USDA

United States
Department
of Agriculture

Forest Service

Rocky Mountain
Research Station

Proceedings
RMRS-P-41

September 2006

Fuels Management—How to Measure Success: Conference Proceedings

28-30 March 2006;
Portland, OR

Andrews, Patricia L.; Butler, Bret W., comps. 2006. **Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR.** Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 809 p.

Fuels management programs are designed to reduce risks to communities and to improve and maintain ecosystem health. The International Association of Wildland Fire initiated the 1st Fire Behavior and Fuels Conference to address development, implementation, and evaluation of these programs. The focus was on how to measure success. Over 500 participants from several countries convened in Portland, Oregon, to discuss approaches to fuels management and to learn from 158 oral and poster presentations.

Sponsors

- International Association of Wildland Fire
- National Interagency Fuels Coordination Group
- Joint Fire Science Program
- USDA Forest Service Research
- The Nature Conservancy, Global Fire Initiative
- National Fire Plan
- Canadian Forest Service
- British Columbia Ministry of Forests and Range, Protection Program
- National Center for Landscape Fire Analysis

Conference Coordinators

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Editors' Note

Peer technical reviews of manuscripts were obtained by the authors before submission. The views expressed are those of the presenters.

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Foreword

1st Fire Behavior and Fuels Conference: Fuels Management—How to Measure Success

Patricia L. Andrews, Conference Chair

The 1st Fire Behavior and Fuels Conference: *Fuels Management—How to Measure Success* was held in Portland, Oregon, March 28-30, 2006. The International Association of Wildland Fire (IAWF) initiated a conference on this timely topic primarily in response to the needs of the U.S. National Interagency Fuels Coordinating Group (www.nifc.gov/fuels).

Fuels management programs are designed to reduce risks to communities and to improve and maintain ecosystem health. The conference addressed development, implementation, and evaluation of these programs, with a focus on *how to measure success*. The scope included not only the *how to*, but also the *what* and *why* of fuels management.

The 500 conference participants represented a wide range of organizations, disciplines, and countries. The conference program included workshops, invited speakers, oral and poster presentations, panels, and vendor displays.

Rather than having a single keynote speaker set the tone for the entire conference, each day began with invited speakers who presented a range of viewpoints. Topics included a broad view of fire as it relates to other "disasters," fire as an ecological process, and fuels management policy and direction of U.S. federal agencies, Canada, Australia and New Zealand, and Europe.

Panels addressed two key topics: "Wildland fire use: it's not just for wilderness anymore" and "How do we define success in fuels management?"

About 250 people took advantage of the optional pre-conference workshops. They attended several of the 10 workshops that described and demonstrated computer systems, models, and methods that can be used in support of fuels management. The short workshops showed how to get additional information, publications, and computer programs.

In addition to the seven invited speakers, there were 151 presentations (97 oral and 54 poster). Presenters described their research and experience on topics including

- modeling, risk assessment, and decision support systems,
- fuel characterization and mapping,
- fuel treatment and prescribed fire,
- fire ecology and fire effects,
- economics and biomass utilization,
- communication and collaboration, and
- case studies.

Sixty-five of the presenters elected to submit a paper for the published proceedings. Some of the papers will also be in a special issue of the International Journal of Wildland Fire. Titles and authors of presentations without papers are listed in the appendix to give an indication of the scope of the conference.

The published proceedings is a partial record of the conference content. An important element was the interactions and sharing of information that occurred outside of the formal presentations. Many of those who responded to the after-conference survey listed "networking" as one of the most valuable aspects of the conference. They noted the mix of managers, researchers, academia, practitioners, and policy makers. The field of fuels management will undoubtedly benefit from the many personal contacts made at the conference.

Special thanks are owed to the steering committee, who formulated the structure of the conference, and to the conference organizing committee, who planned and implemented details of the conference. The conference was a success due to the contributions of dedicated individuals.

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Conference Co-chair:

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- Diane Trethewey, Fire Behavior Research, RMRS Missoula Fire Sciences Lab
- Paul Woodard, IAWF officer, University of Alberta

Fuels Management

Be a Change Agent and Change the Strategy

Jerry Williams[1]

I was invited to speak at this conference on the subject of disasters and the relative importance of wildfires because of the breadth of my experience. The fact that I currently manage a flight school gives me an outside perspective of wildland fire and fuels management.

I have spent a fair amount of time in wildland fire and disaster management. This experience has been in the management of incidents, and in training others to manage incidents. My experience includes wildfires (I quit counting at 600), floods, blizzards, hurricanes, tornados, volcanoes, earthquakes and disease epidemics. I was even on a cruise ship that sank, and my wife and I ended up managing the triage and recovery center.

Disasters have been around since man was there for the event. By UN definition, a disaster is "A natural or human-caused event, which causes negative impacts on people, goods, services and/or the environment, exceeding the affected community's capability to respond."

Over time, events that would not have been disasters, or even emergencies, are now major catastrophes. The increase in world population, the movement of this population to vulnerable areas, has created a situation where 100's of thousands of people die, and 100's of billions of dollars are incurred in response, relief and reconstruction. This results in an on-going cycle of disasters. Around the world, disasters are a growth industry. At any one time there are as many as 40 major relief efforts by US government agencies and non-governmental organizations.

Hundreds of thousands of people on the African continent are dying from AIDS. Millions are dying from civil wars. Millions more are about to die from starvation and disease.

Every year in Bangladesh, 100 thousand children under the age of 5 die from diarrhea. Every day 700 die from malnutrition. I spent 6 weeks in Bangladesh at a research hospital working on a training program for NGO's on the prevention and treatment of diarrheal disease in disasters.

No one knows for sure how many died from the South Asia Tsunami but the number is probably well over 300 thousand.

The death toll from Katrina is still not known and the damages will be in the billions of U.S. dollars. An impact of Katrina and the Florida hurricanes is that the re-insurers are telling the underwriters to cancel policies on structures built on the beaches and outer banks. Allstate just last week announced the cancellation of more than 22 thousand policies in Massachusetts alone.

There is also a worldwide attitude that "the government will take care of me." An Arizona Daily Star (March 22, 2006) AP article told of a California homeowner who cancelled his earthquake insurance because it was too high, saying that he is going to rely on the government to take care of him.

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These major events make the news and some stay in the media focus for months or years. A large wildland fire might stay on the radar for a week or two and then disappear. Hurricane Andrew is still referred to, and Katrina and the Tsunami will be in the news for many years to come.

In the world of disasters, wildfires are a passing thing. Since 1871, the death toll from wildfires is less than 3400. There is no count on structures lost, but then, how many have burned off of the same foundation more than once?

Sixty years ago, we suppressed fires to protect the renewable resources that we were managing for the products they produced, and the economies they supported. Foresters were the good guys in the white hats. The Forest Service was described in management books as a great example of management excellence.

We said fire in the forest was bad. The most successful ad campaign in history put our symbol in everyone's brain. All hail Smokey.

Then the situation changed. Foresters were not able to continue the cultural practices the land needed. We learned a great deal about the effects of fire thanks to some great researchers. So now we said fire was natural and good. The drip torch brigades were on the march.

Then a bunch of folks lost their homes from our "prescribed" fires. The system went awry. But since we thought we were still the good guys in the white hats, we said, "Hey, we're from the government and we know what is best." The public has lost trust in the government to do the right thing in a disaster. Another impact of Katrina and the Florida hurricanes is that the American public now has no trust in the ability of their government to respond in disasters. A recent media survey indicated only 15 percent had any confidence at all (AP, Tucson Citizen, March 3, 2006).

Today houses are wrapped in aluminum foil to protect them from the results of our actions, or non-actions, over the years. In my opinion, if people want the experience of living in the woods, they should have an opportunity to get all of the experience. Just as the wilderness hiker has the opportunity to be eaten by a grizzly, maybe the wildland homeowner should have the opportunity to get burned up.

We have fire managers that are afraid to fight fire aggressively. The courts and the agencies have put in "rules of engagement" that make an Incident Commander (IC) think long and hard about taking action. In the old days, if we had two firefighters and a couple of tools, we set an anchor point and started making line. If we were lucky we had some C-rations and maybe a ham and cheese sandwich that the ladies in the office made and sent out. We didn't have TV and foosball and movie set catering services in our fire camps. The idea that a fire boss would wait ten days to establish an anchor point and start building line just baffles me. And you know what, the public knows this too.

Those big air tankers full of money sure do make good clips on the evening news but somebody has to still build line.

There is a well known axiom of management, "If you do things the way you have always done them, you will get the results you have always gotten." If you like sitting in the office doing those Environmental Impact Statements (EIS) and all the other stuff you do, don't change a thing. Otherwise, it's time to find a new approach and a new horse to ride. When the insurance companies stopped paying for burned down buildings in Boston and Butte, the urban renewal stopped. When the insurance companies stopped paying for blown down houses in the Caribbean, the people started following the building codes to build new ones. The same thing is happening in Florida and now the Gulf Coast.

In Latin America, the West Indies and the South Pacific, business and government are working together to reduce the risk of disaster by eliminating hazards where possible and really focusing on reducing vulnerability. The best results have been obtained at the individual and community levels.

The Fire Safe Councils and Firewise programs are a good start but they need a bigger stick to wield. A recent article in the Arizona Daily Star (March 5, 2006) about a Firewise effort said "It would be heartbreaking to see one homeowner's effort be overcome by a neighbor who didn't participate in Firewise."

Instead of asking for money for Public Relations programs, ask for positive action. The insurance companies, the banks and lenders, the power companies, all have a financial interest in reducing the losses due to wildfires. They need to support the enforcement of strong codes for location and construction of structures in fire prone areas. After the fires on Mt. Lemmon near Tucson, Arizona, Pima County wrote new codes and guides for construction in wildland areas. The insurance companies are supporting the effort by not paying for reconstruction and not reinsuring structures, or their contents, that do not meet the codes.

These financial institutions also have an interest in good land management using the best cultural practices. You can't lobby congress, but they can, and they do. If every local insurance agent and lender went to company meetings and pushed for corporate action, action will happen. These companies have tremendous political and economic power. I know this from my work with the insurance companies and lenders in the aviation industry.

The world of general aviation, where I am, is changing dramatically. Technology that was only available to the military and airlines is now available in virtually every small airplane. I have a new Cessna 172 trainer coming next week that has the latest in glass cockpit technology. This is the same technology that's in the most sophisticated commercial jets. And, soon to be at an airport near you are the small personal jets.

The Federal Aviation Administration, that large monolithic agency made of stone, has great concern that this technology is overwhelming the average pilot and causing accidents. And they are correct. They could not do their usual approach of writing regulations to make something happen, but the insurance companies could, and have, with minimum qualification training and recertification requirements for insurance coverage.

The FAA has proposed a whole "new" approach to reduce the risk of general aviation accidents. And it is not regulation. We are going to change the way we teach people to fly. The FAA has asked me to develop a whole new course of instruction using a lot of the techniques we learned in the wildland fire training program during the past 30 years. We have already started implementing the use of scenario based training and advanced aviation training devices.

The insurance companies are a key player in this effort with the requirement for pilots to be recertified annually to fly complex aircraft. I have been meeting with the major aviation underwriters this past month and we are beginning to do insurance company recertifications using the same strategies. They reward the pilot and business that have risk reduction programs and increase rates on those that do not. I have had an 18% reduction over the past two years.

The following is a review of my thoughts in the form of some brief statements:

1. We created this situation with our fire suppression success and loss of management options.
2. The traditional PR programs (e.g., Smokey Bear) are not working.
3. A new approach to risk reduction is needed and the government isn't going to be able to make it happen.
4. The public understands the economics and options of high insurance costs and premium breaks.
5. The folks at the local level ultimately have the power to make something happen. The lenders and the insurers have to take action.
6. A change is needed and you have to make it happen.

There are a lot of very creative folks in the wildland fire business. Quite frankly, it's time for you to get off your bureaucratic backsides, become change agents, and get on with it. I'm going home and change the way people learn to fly airplanes. What are you going to change?

U.S. Federal Fuel Management Programs: Reducing Risk to Communities and Increasing Ecosystem Resilience and Sustainability

Tim Sexton[1]

There is no doubt that wildland fuel conditions on large portions of federal wildlands in the United States have changed significantly over the last 100 years. The changes include:

- Increased density of woody species
- Artificial fragmentation of fuel mosaics
- Exotic species invasions
- Structural changes which reduce ecosystem resilience to fire

Fire suppression, especially in plant communities which evolved with frequent fire, has allowed fuel to accumulate to levels far above what would have existed without fire suppression. The fire suppression era also contributed to forest densification. Many more stems of living shrubs and trees occupy landscapes today than would have existed without fire suppression. Forest densification tends to predispose areas to insect and disease mortality, further loading up the dead fuel mass.

Roads, farms, cities and other human developments have broken up fuel mosaics. Fragmented fuels inhibit fire spread and contribute to fuel accumulation.

Exotic species such as cheat grass, phragmites, salt cedar (tamarisk), and others have added to live fuel mosaics or even completely replaced previous plant communities. Many exotics (such as those listed above) are much more flammable than the native species that would otherwise occupy sites. The increased flammability has resulted in larger and more damaging wildfires in these invaded areas.

Logging, grazing and other human activities have altered plant community structure and composition. In many cases the new structure is more susceptible to fire damage and/or more flammable. Small trees are fire-killed more readily than large trees and provide a more effective "ladder" for a surface fire to climb into the crowns.

Last, but not least, social changes in the United States have caused a huge change in the potential *consequences* of wildfires. Homes, infrastructure, and public use have become embedded in these altered, volatile fuel mosaics.

The last twenty years have witnessed a significant increase in large, costly wildfires which have damaged natural resources and improvements on public and private lands. A great deal of scientific research points to increases in wildland urban interface, fuel accumulations, alteration of species composition, and changes in plant community structure as principal reasons for these costly, damaging wildfires.

The National Fire Plan and associated initiatives have provided a framework for managing fuels to reduce impacts from wildfire. The primary five federal agencies with wildland fire management responsibilities (US Forest Service,

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Bureau of Land Management, National Park Service, Bureau of Indian Affairs, and US Fish and Wildlife Service) are coordinating efforts to manage fuels. The National Interagency Fuels Coordination Group (NIFCG) with representatives from these five federal agencies has been tasked to coordinate federal strategies for mitigating wildfire hazards through fuel treatments. NIFCG is currently composed of Dennis Dupuis (BIA), Erik Christiansen (BLM), Dick Bahr (NPS), John Segar (USF&W), and Tim Sexton (USFS).

I encourage you to engage these agency representatives when you have issues with national policy rather than simply complain to your counterparts. We need to know how our efforts are working. You need to tell us. We have a website which can be accessed through the National Interagency Fire Center home page. This website is intended to be a resource for keeping the field informed on our actions and proposed changes to our business.

The primary goal of federal wildland fuel management is to reduce the unwanted impacts from wildfire, including threats to public safety, suppression costs, damage to natural and cultural resources, and damage to public and private improvements. It must be clear that we are not trying to reduce the number of acres burned by wildfire. In fact, we will likely facilitate an increase in acres burned by unplanned ignitions. Wildland Fire Use and less aggressive attack on many suppression-objective wildfires present opportunities for suppression cost savings, reduced exposure of firefighters to hazards, and reductions in hazardous fuel.

The federal wildland fire agencies have agreed on several key action areas in support of the goal to reduce impacts from wildfires. These action areas include:

- aligning federal fuels management policies, practices, and procedures
- prioritizing fuel treatments which:
  - have been identified as key components of Community Wildfire Protection Plans,
  - provide by-products for local economies and energy production,
  - reduce hazard on a landscape scale, and
  - are cost-effective
- expanding wildland fire use as a means of treating fuels
- providing support for development and deployment of technologies (such as LANDFIRE and associated planning tools) for facilitating planning and implementation of fuel reduction projects
- managing ecosystems so that they are resilient to disturbance and sustainable in the goods and services which they provide to the American Public
- development of a work force which has the capacity and the capabilities to strategically manage fuels to obtain the greatest reduction in impacts from wildfire

Successes

In fiscal year 2005 more than 4 million acres of hazardous fuel were treated on USDA and USDI lands. We recognize that gross area treated is not a particularly good indicator of progress toward the goal of reducing unwanted impacts from wildfire. However, it *is* a good indicator of our increasing capability to implement treatments. We believe that LANDFIRE will enable us to develop metrics which will correlate more closely with progress toward our goal.

We have many accounts of wildfires which were contained or where communities were prevented from burning by the fuels treatments accomplished since the National Fire Plan was developed.

In July 2004, the Waterfall Fire, near Carson City, Nevada burned over 8,700 acres. Fifteen homes were destroyed. However, many times that number were saved due to reduced fire behavior in fuel treatment areas on BLM lands adjacent to subdivisions.

Recently, the February Fire on the Tonto National Forest in Arizona was contained at about 4,200 acres due, in part, to a recently completed fuel treatment area. Post fire review indicated that the containment opportunity afforded by the fuel treatment area contributed to protecting many homes in the fire area including one owned by Mike Johns, US Attorney and frequent defender of us in fire-related litigation.

In October 2004 on the Eldorado National Forest, the Fred and Power Fires burned over 20,000 acres near the communities of Kyburz and Silver Fork, California. Fuel treatment areas in the wildland urban interface enabled firefighters to protect all homes in these communities.

One of the best examples of successful fuel treatment is the Cone Fire which burned on the Blacks Mountain Experimental Forest in northern California in 2002. This fire burned through several well documented fuel treatment areas, enabling comparisons of burn severity related to treatment type and intensity.

While these are impressive accomplishments we need to do more. We continue to see many examples of urban interface and intermix in extremely vulnerable fuel conditions. Beyond the WUI, we see extensive areas of overly dense forests; cheat grass-invaded rangelands, and watersheds which have been left to develop multi-story flammable conditions. Historically, an average of over 25 million acres burned annually from wildfire on lands that are now managed by these agencies in the coterminous United States. Some national analyses have suggested that we need to double our efforts in order to make significant progress in reducing the impacts of wildfire. Other analyses indicate that strategic placement of treatments might achieve that same significant progress with much less area treated.

We have had a few failures along the way. In early 2006 the US Forest Service has experienced two large, damaging escaped prescribed fires. In January, on the Cleveland National Forest, the Sierra Prescribed Fire escaped eventually burning about 12,000 acres and costing over 7 million dollars to suppress. In February on the Shasta-Trinity National Forest the Hot Lum Prescribed Fire escaped burning 3,000 acres and a residence.

We are working hard to determine the reasons for the escapes and any unit-level or programmatic actions which would prevent additional escapes. We are using Learning Organization concepts so that we, as an organization, can benefit from the losses.

Future

What do we need to do to become more effective in managing fuels and unwanted impacts from wildfire? The NIFCG is working to improve our organizations and business practices so that we have:

- Increased capacity
    - Utilize our agency and partners workforces

- Increased capabilities
  - Skills in using new technology and recently developed science
- Internally integrated Fuel and Other Resource management programs
- Logic-based allocation process for prioritizing funds from National to Regional/State and then to local unit levels
- Improved Collaboration with all stakeholders
- Interagency Fuels Training Strategy
- Enhanced planning skills
  - SPOT
  - LANDFIRE has great promise for increasing our abilities to develop strategic fuel treatment plans
  - Treatment longevity
  - Treatment effectiveness
  - Treatment cost efficiency
  - Trade-off analysis
  - Smoke management
- Focused science needs and delivery
  - Risk quantification
  - Treatment effectiveness longevity
- Streamlined, “enabling” policies such as might be developed through a doctrinal approach
- Programs at National, Regional, and local levels which are “opportunistic”

What can you do? Keep current on national initiatives such as LANDFIRE, FPA, FRCC, the revised ten year implementation plan, and others. Most of what is initially put forth has room for improvement and thoughtful critiques are welcome. The most effective improvements will come from field-level folks who are being asked to implement these initiatives.

In summary, the US federal fuel management policies provide guidance and support to manage fuels to reduce the unwanted impacts from wildland fire and to manage plant communities so that they are resilient to disturbance and can continue to provide the socially-desired goods and services in the long run.

Canadian Wildland Fire Strategy: A Vision for an Innovative and Integrated Approach to Managing the Risks

Canadian Wildland Fire Strategy Project Management Team[1]

Abstract—*The Canadian Wildland Fire Strategy (CWFS) provides a vision for a new, innovative, and integrated approach to wildland fire management in Canada. It was developed under the auspices of the Canadian Council of Forest Ministers and seeks to balance the social, ecological, and economic aspects of wildland fire through a risk management framework that emphasizes hazard mitigation, preparedness, and recovery as well as efficient fire suppression and response. This strategic and holistic approach is needed to address both the root causes and symptoms of current and future wildland fire management challenges.*

The desired future state advocated in the CWFS consists of communities that are empowered to enhance their own safety and resilience, forest ecosystems that are healthy and productive, and wildland fire management agencies that utilize modern business practices. To foster change in attitudes, policy, and practices, the provincial, territorial, and federal governments are currently working collaboratively to create a joint cost-shared program in excess of 1 billion dollars over 10 years to address 4 strategic objectives: (i) pan-Canadian FireSmart initiative, (ii) wildland fire preparedness and response capability, (iii) public awareness and risk and policy analysis, and (iv) innovation. The underlying tenet is that managing the risks from wildland fire is a shared responsibility of individuals, stakeholder groups, the private sector, and all levels of government and therefore requires integrated and cooperative actions.

Introduction

Each summer the news media carry stories of wildfires raging across the Canadian landscape, threatening our communities, causing evacuations, and at times burning public and private property. This portrayal of fire as a menace to society is often accurate but it is only part of the story. In Canada, fire is nature's primary way of keeping the wildlands (including forests, grasslands, and parks) healthy and productive. As a result, policy makers and practitioners are faced with the complex and difficult task of managing wildland fires so that their environmental benefits are maximized and simultaneously the risk to people and property is minimized.

Recognizing that the challenges of today and the future cannot be solved by simply using the thinking and methods of the past, the provincial, territorial and federal governments have worked together under the auspices of the Canadian Council of Forest Ministers (CCFM) on a new Canadian Wildland Fire Strategy (CWFS). Based on the principles of risk management, the CWFS will address the symptoms and the root causes of wildland fire management by modernizing approaches and capabilities. It provides a comprehensive vision of integrated activities that will increase public safety, improve the health and productivity of Canadian forests, enhance intergovernmental cooperation, and apply public funds efficiently.

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Fire and Fire Management in Canada

The Role of Fire in Canada's Forests

Fire has been a very dominant feature in Canada's forests since the last Ice Age, particularly in the vast boreal region that stretches from the Yukon to Newfoundland. Many plant species — such as pine, spruce and birch, to name just a few — have not only adapted to fire but rely on it for their renewal. Fire has also created a mosaic of habitat types and ages, which are needed by various animal species. Wildfires burned freely in most of Canada until the late 19th century after which European-influenced views of fire and forestry resulted in policies that sought to suppress all fires. In recent decades there has been a growing recognition that fire exclusion is neither ecologically desirable, nor economically possible, to eliminate all fires from our wildlands.

The Risk from Wildfire

Currently in Canada there is an annual average of 8,600 fires that burn 2.5 million hectares, or an area larger than Lake Ontario. Provincial and territorial agencies and Parks Canada are world leaders in forest fire suppression, controlling 97% of all wildfires when only a few hectares in size. But just as with hurricanes, floods, and tornados, there are times when Mother Nature presents conditions that make wildfires unstoppable. As more Canadians live, work, and recreate in or near flammable vegetation, wildfires are posing an increasing threat to public safety. Over the past 10 years more than 700,000 people have been threatened by wildfires in over 200 communities – many of which are inhabited by Aboriginal peoples. A recent, vivid example was in western Canada in 2003, when hundreds of homes were lost, tens of thousands of people were evacuated, and combined damage and firefighting costs exceeded $1 billion.

The Looming Crisis

Extensive analysis conducted by federal, provincial, and territorial government officials has found that the vulnerability of people, property, and natural resources to wildfire has reached an unprecedented level and is projected to continue to rise rapidly. The main reasons for this include more frequent and intense fires resulting from severe droughts and climate change; insect infestations that leave dead and highly flammable forests in their wake; and the growing number of homes, cottages, businesses and activities located in or near flammable forests. Meanwhile current wildland fire suppression capacity is eroding as aircraft, facilities, and equipment age and experienced firefighting professionals retire. Many believe it is only a matter of time until another major fire season occurs again in Canada and the greatest concern is that next time the tragic consequences may include the loss of human lives as seen recently in other parts of the world.

Moving Forward

Taking a Strategic Approach

To address current and emerging challenges, the CWFS recommends expanding the toolkit available to wildland fire managers to include hazard mitigation, preparedness, and recovery programs that complement an efficient fire suppression and response system. New ways of sharing and managing the risks are also required.

To put this another way, on a personal level all Canadians, in their daily lives, face decisions about risks from house fires and how to deal with them. Some people buy insurance, others purchase smoke detectors, and many schoolchildren have helped their families plan escape routes from a burning home as part of a homework assignment. At the community level, local governments invest in firefighting equipment and the training of firefighters to stop fires, if possible, before they become devastating. However, perhaps most important has been the considerable effort that has gone into creating building materials that are increasingly fire-resistant and the rigourous use of building codes that demand high standards of fire protection in the construction of residential homes and office buildings. The principles that have worked in our homes and communities for house fires can also work in the Canadian wildlands to reduce the risk from unwanted wildfires.

Action Plan

In October 2005, the provincial, territorial, and federal forestry ministers signed the CWFS Declaration and committed to a shared vision and common set of principles for wildland fire management in Canada (see www.ccfm.org). They also agreed to approach their respective governments to invest over $1 billion dollars over the next 10 years to implement the CWFS. Working with relevant partners and stakeholders, a joint cost-shared program would target four main initiatives:

(1) pan-Canadian FireSmart activities that empower individuals and communities to directly reduce the risk from wildfire;
(2) improved preparedness and response capability through, for example, replacement of aging aircraft and equipment, plus a stepped-up recruitment and training program to create the next generation of professional fire management staff (including extensive capacity building in aboriginal and rural communities); and
(3) a public awareness campaign about the role of wildland fire and the associated risks;
(4) innovation that includes the development and application of new science and technology in support of early warning systems, better predictive models, and the increased use of prescribed fire.

All of these actions build upon a strong spirit of intergovernmental cooperation that has existed in the wildland fire community for many years, and is evidenced in the thousands of fire fighting resources that are exchanged among agencies during times of need.

The CWFS is an ambitious initiative, but one whose time has definitely come. At first glance it may appear costly; however, in the face of increasing threats from wildfires, it is an investment that will avoid escalating costs and losses in the future. When implemented, the CWFS will make Canada's wildland fire management policies and programs among the most progressive in the world – thereby enhancing the safety of Canadians, facilitating forest sustainability, and ensuring the efficient use of public funds.

Fuel Management—An Integral Part of Fire Management: Trans-Tasman Perspective

Jim Gould[1]

Abstract*—Although Australia and New Zealand have quite different fire climates and fuels, the common understanding of fire behaviour underlies many facets of fire management in both countries. Fire management is the legal responsibility of various government land management agencies that manage public lands and individuals, local governments or corporations that manage private land. Volunteer bushfire/rural brigades have been formed throughout rural and peri-urban areas and are coordinated by rural and metropolitan fire authorities for specific activities such as fire suppression and fuel management. During the last two decades there has been an increasing interaction between Australia and New Zealand rural and land management fire agencies exchanging fire management practices, lesson's learnt, common incident command systems and more recently, through partnership in their research programs.*

Both countries face a similar array of challenges in meeting their fire management objectives and the task is becoming increasingly difficult. As overarching services provided by governments, fire management has been subject to financial pressures, resulting in staff reductions and erosion of traditional levels of fire management resources. Resources are declining at a time when demands for protection by the general community are increasing. Concurrently, the demands for ecologically appropriate fire management practices and concerns about the long-term impacts of prescribed burning have led to the suggestions that, in some areas, fire is adversely affecting biodiversity and long-term sustainability of natural ecosystems. These issues are overlain by debate about how fire can affect climate change, greenhouse gas balance at the landscape and national level, and whether such changes are being exacerbated by managed and/or wildland fires.

Australian Fire Environment

Bushfires have been part of Australia's environment for millions of years. Australia's natural ecosystems have evolved with fire, and the landscapes and their biological diversity have been shaped by both historical and recent patterns of fire. Because of the climatic variation across Australia, at any time of the year some part of the continent is prone to bushfires. Thus, bushfire occurs throughout Australia, although they may be very infrequent in some climatic zones, such as those dominated by rainforest or wet eucalypt forests. In any give year, the greatest extent of bushfires is in the tropical savannas regions of northern Australia; in some seasons these extend into the semi-arid and arid interior regions (Luke and McArthur 1978). Table 1 shows area of Australian burnt between 1997 and 2003 and percentage of total land area fire affected (Ellis and others 2004).

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Table 1—Approximate fire-affected areas across Australia, 1997 to 2003[a].

Calendar year	Area (million hectares)	Percentage of total land area fire affected	Percentage of fire-affected area that is tropical savanna[b]
1997	48.3	6.3	86
1998	26.3	3.4	92
1999	60.0	7.8	86
2000	71.5	9.3	65
2001	80.1	10.4	84
2002	63.8	8.3	63
2003	31.6	4.1	85

[a] Source: Western Australian Department of Land Information in Ellis and others 2004.
[b] Defined by the Department of Land Information, Western Australia, for the purposes of monitoring fire-affected areas, as being the area north of 21°S and east of 120°E.

Planned fires to achieve specific objectives (ecological, fuel reduction, etc) have been and remain a fundamentally important land management tool for Australia's land managers and firefighters. Australians who work with bushfires- indigenous Australians, farmers and pastoralists, fire fighters, public land mangers and scientists- recognise that there are good, as well as bad, bushfires. Good bushfires help to meet land management and fire mitigation objectives without adverse impacts on people, property or the environment; bad bushfires threaten lives, property or environmental assets and do so in ways that are difficult to control (Ellis and others 2004).

Since European settlement nearly 70 percent of Australia has been occupied by agricultural, forestry and livestock grazing enterprises resulting in the extensive modification and conversion of forest woodland, open woodland, shrubland and grassland systems (Thackway and Lesslie 2005). The native forests cover is classified into three classes by the density of their crown cover (National Forest Inventory 2001). Thus, there are:

- 118 million hectares of woodland (tree crowns cover 20 to 50 percent of the land area when viewed from above), including just under 10 million hectares of woodland mallee;
- 43 million hectares of open forest (51 to 80 percent crown cover), made up of 38 million hectares of what are commonly called wet and dry sclerophyll forests and 5 million hectares of open forest mallee; and
- 5 million hectares of closed forest (81 to 100 percent crown cover), made up of over 4 million hectares of rainforest and almost 1 million hectares of mangroves.

Most of the woodland and open forest areas of Australia, composed of fire-dependent and fire-adapted species and ecosystems, have evolved in the presence of a fire regime driven originally by natural sources of fire ignition (i.e. lightning) and by cultural practices of aboriginal people. The forests are a source of raw material for the forest industry, and a source of many tangible and intangible products and services including recreational and cultural opportunities for all Australians. In recognition of these values, forest protection efforts commenced in the early 1900s, and have steadily developed to the point where Australian State public land management agencies are recognized among the world's leaders in fire management.

Forest fire management in Australia is the responsibility of the State and Territorial governments. Fire management on public lands (e.g. State forests, National parks, State parks, Crown lands, etc.) is the responsibility of the State agency charged with managing those areas. Fire suppression may be carried out by individual agencies or placed with one agency, e.g. in Victoria suppression on all State lands is carried out by the Fire Management Section of the Department of Sustainability and Environment. Fire management on private lands is carried out by volunteer bushfire brigades or industry brigades that are co-coordinated and supported by the State rural fire agencies. In recent years there has been an increase in the corporatisation of State-owned plantations and the fire management responsibility for these forests, along with new plantation forests established on private land, rests increasingly with the State rural fire authorities. This shift in fire responsibility has mainly occurred in South Australia and Victoria over the last five years.

Most of the States provide fire management directly as a government service, generally by the departments that manage lands, forests and other natural resources. Their fire management programs provide for varying levels of planning, fuel management (i.e. prescribed burning), detection, pre-suppression and suppression operations. The level and type of activity in each category varies with each agency's natural resource polices, protection priorities, financial resources and, in particular, the ecological and biogeographical conditions of the forest itself. Consistent with the statutory obligations and policies of public management agencies, their fire management objectives include:

- Protection of people from bushfire.
- Protection of buildings and facilities from bushfire.
- Prevention of bushfire burning onto neighbouring property.
- Conservation of natural and cultural values including:
  - Native plant and animal species, habitats and communities;
  - Soil and water resources;
  - Scenic and landscape values; and
  - Aboriginal and European heritage values.

All agencies deliver an organised detection program. Fire towers are the most common detection system offering regular surveillance of high-value areas and community assets. The used of fixed wing aircraft for detection has increased in the past 15 years. There are recent attempts to use satellite-based remote sensing as a tool for fire detection.

Suppression strategies use a mix of resources from the land management agencies with support from rural bushfire authorities. Ground crews using fire appliances (fire tankers), heavy equipment (dozers) and hand tools are the backbone of the suppression system. Aircraft for aerial suppression have been used in Victoria for more than thirty years, and over the past decade other land management agencies have increasingly used air attack on bushfires.

Different suppression strategies are used by the agencies, which are based on the nature of the forest and fire regimes that they deal with and, to some extent, on the organisational philosophy. Some agencies, such as those in Victoria and Western Australia, have relatively large full-time fire management organisations compared to those in other States.

New Zealand Fire Environment

Although not having one of the most severe fire climates in the world, New Zealand has as a long history of large and damaging wildfires. Northern and eastern New Zealand are characterized by a mix of flat and steeply divided terrain, occasional drought, strong wind conditions and flammable grass and scrub fuels. New Zealand climate ranges from subtropical in the far north to cool temperature in the south, but the steep and divided relief causes dramatic variation along the length of the country. As frontal weather systems approach New Zealand, the winds preceding it often reach gale force and are force to rise over the Southern Alps resulting in hot dry fohn winds in the eastern part of the South Island. These regions in the South Island Canterbury Plains can experience extreme fire weather on more than 40 days per year (Pearce and Majorhazi 2003).

The approximate cover of different land uses in New Zealand is listed in table 2. Natural and plantation forests cover 23 percent (6.2 million hectares) and 7 percent (1.8 million hectares) of the New Zealand land area respectively (New Zealand Ministry of Agriculture and Forestry 2005). Areas of pastures, arable land and other non-forested land (tussock and scrub vegetation) cover approximately 70 percent (18.9 million hectares). These areas of tussock and scrub fuels are very flammable, and recent research results show that extreme fire behaviour will often occur under Low to Moderate forest fire danger conditions (Fogarty and others 1998).

New Zealand native vegetation consists of species that are not specifically adapted to fire, but there are xeromorphic elements thought to be adapted to disturbance from longer term climatic fluctuations. Margins of beech (*Nothofagus* spp.) and podocarp forest are sensitive to fire and after fire or other disturbance (e.g. landslides), flammable species (e.g. *Leptospermum* spp. and *Dracophyllum* spp.) invade the site such that the potential for decline and fragmentation by fire is increased (Fogarty and Pearce 1995).

New Zealand experiences approximately 3,000 vegetation wildfires each year and these fires are attended by the Department of Conservation, forest companies or local government Rural Fire Authorities make up of both permanent (land management) staff and volunteer fire fighters. These fires are primarily human-caused and many continue to occur as a result of escapes from (both permitted and unauthorised) prescribed burning activities and increasing arson (Pearce and Majorhazi 2003).

The number of hectares that are burnt annually by wildfires varies considerable being driven predominantly by the weather conditions during the summer season. The summer of 1946 represents the most disastrous fire year in New Zealand history when, following periods of drought in the north east central regions of the North Island, over 200,000 ha of indigenous forest, exotic plantations, cutover forest, tussock and scrub were burnt. More recently, the 1998/99 fire season resulted in 18,000 ha being burnt. Since 1988/98 there has been an annual average of 7,000 ha of rural lands (including forestry) have been burnt (Fogarty and Pearce 1995).

Large and devastating bushfires occur relatively infrequently in New Zealand when compared with Australia, Canada and USA. However, the

Table 2—Different land uses in New Zealand.[a]

	Hectares (millions)	% of total
Pasture & arable land	11.8	44%
Natural forest	6.2	23%
Other non-forested land	7.1	26%
Plantation forest	1.8	7%

[a] Source: New Zealand Ministry of Agriculture and Forestry, 2005.

potential exists in most parts of the country for significant events to occur (Pearce and others 2004, Fogarty and others 1998). Like Australia, New Zealand will face an increase in the severity and impact of bushfires in the next decade and beyond. The increasing trend in the expansion of the rural-urban interface is one of the major factors contributing to increased future risk from wildfires. Also, changes in forestry and land management practices may increase the likelihood of major wildfire events. This includes potential changes in long-term fire danger such as those associated with projections of future global warming and climate change (Pearce and others 2005; Hennessy and others 2006).

Fuel Management Strategy

The damage caused by wildfires and the ability of suppression forces to control them is strongly linked to fire intensity, which is governed by fuel, weather and topography. Of these factors, only the fuel level can be manipulated, and fuel management is the basis of wildfire prevention throughout much of Australia. New Zealand is beginning to consider use of fire to manage fuels (for fuel reduction or ecosystem management) despite a long history of using fire as a land management tool for land clearing and forest establishments. In the natural landscape, this requires the periodic removal of part of the surface litter and understorey vegetation. This can be achieved by manual, mechanical, or chemical methods or through the use of fire.

Prescribed burning is defined as the burning of vegetation under specified environmental conditions and within a predetermined area to achieve some predetermined objective. The objective may include habitat management for native fauna, species regeneration, maintenance of specific eco-types or hazard reduction, etc.

Studies conducted by McArthur (1962), Peet (1965), and others since the 1960s (Cheney and others 1992) have provided the technology for fire to be used effectively to manage fuels. These studies enable the behaviour of fires that are lit under given conditions to be predicted. A range of operational procedures provide a high level of security against fire escape. Due to the improvements in techniques and the application of fire behaviour knowledge, prescribed burning has become a reliable fuel management tool. To date the only effective way of reducing fuels over large areas is through the use of low-intensity prescribed fires and, in Australia, this is generally synonymous with broad-area fuel reduction. In most of the eucalypt forest the aim of fuel-reduction programs is to keep the load of fine fuel (fuels less than 6 mm in diameter) on the forest floor to less than 10 tonnes per hectare (t ha^{-1}). This will prevent the development of crown fires in medium to tall forests and will limit the rate of spread and damage done by wildfires. The frequency of burning is determined by litter accumulation rates so that burning rotations to manage fuel reduced areas are normally between 5 and 10 years.

Prescribed fire is also used in native forests to remove slash accumulations and to prepare a seed bed for the regeneration of native forest species, and more recently to regenerate understorey species and manipulate vegetation to provide suitable habitat for native fauna. Although these operations also remove fuels, they are generally of higher intensity than low-intensity prescribed burning specifically for fuel reduction and the intensity prescribed is determined by the requirements for good regeneration.

Hazard reduction burning—Hazard reduction burning will reduce the total load of fine fuel and is also effective in reducing the height and flammability of elevated fine fuels such as shrubs and suspended dead material. Burning is the only practical way of reducing the fibrous bark on trees, which is the prime source of firebrands that cause spotting. Hazard reduction reduces fire behaviour by:

- reducing the rate of development of growth of the fire from its ignition point;
- reducing the height of flames and rate of spread;
- reducing the spotting potential by reducing the number of firebrands and the distance they are carried downwind; and,
- reducing the total heat output or intensity of the fire.

Prescribed burning is not intended to stop forest fires but it does reduce their intensity and this makes fire suppression safer and more efficient. Prescribed burning does not provide a panacea, nor does it work in isolation. It must be used in conjunction with an efficient fire fighting force.

Hand crews can suppress a fire up to a maximum intensity of 1000 kilowatts per metre (kW m^{-1}) (Loane and Gould 1986). If the fuel load is greater than 15 t ha^{-1} (which is typical of dry eucalypt forests between 8 to 15 years since the last fire) this intensity will be exceeded under low to moderate fire danger conditions. If the fuels are reduced to 10 t ha^{-1}, fires will not develop an intensity of 1000 kW m^{-1} until fire danger gets into the moderate to high range. This means that the range of weather conditions that fire fighting with hand tools is effective is increased and more time is available to bring the fire under control. If the fuels are reduced further to less than 7.5 t ha^{-1} then suppression with hand tools is effective under weather conditions of very high fire danger. Under extreme conditions, provided there is sufficient fuel to carry fire, fire suppression by any means is virtually impossible because the strong dry winds associated with conditions will cause burning embers to breach any fireline. Nevertheless, the result of the lighter fuel load will reduce the rate of spread of the fire and the area burnt so that the fire suppression task will be easier when the weather conditions ameliorate.

Silvicultural burning—Silvicultural burning is usually a moderate-intensity prescribed burn carried out after a partial-cut logging operation designed to remove logging slash, prepare the seed bed and stimulate regeneration and/or the growth of rootstock regeneration. Silvicultural burning is conducted in the jarrah forest of Western Australia and the silvertop ash forests of New South Wales.

Ecological burning—The main aim of using fire for ecological management is to provide an appropriate fire regime (of specific fire frequency, intensity, seasonality and patchiness) to meet specific goals for the management of a particular species, populations or communities (e.g. as part of a recovery plan for a threatened species). Since fire has a fundamental role in the development of forest ecosystems, it follows that fire has a place in maintaining them. Good (1981) indicated that because fire is the major and only environmental factor over which some control can be exercised, and many native species depend on fire for their continued existence, and the use of fire will always have a place in ecological management. Fire has a place in both flora and fauna management but its effective application in Australia has been infrequent.

Application of prescribed burning—There is a perception among people unfamiliar with fire management that prescribed burning is simply lighting fires to burn-off the undergrowth and that this can be carried out with only a basic understanding of fire behaviour. Indeed, where burning-off has been carried out in this way the results have been less than optimal and have resulted in escapes, injury and/or death (e.g. Kur-Ring Gai National Park, New South Wales 2000). Like any land management operation, prescribed burning requires the setting of clear priorities and objectives, planning and the application of technical guidelines to meet those objectives. In general terms the process of conducting a prescribed burn is as follows:

- Set the objectives and desired outcome for the fire.
- Determine the fire intensity and the associated heat pulse that is required to meet that objective (in forestry and for fuel management this may be determined by an acceptable height of scorch of the overstorey canopy or an acceptable level of heat damage to the cambium of regenerating trees).
- Determine the level of fire behaviour (for example flame height, intensity) that will produce this heat pulse for the particular fuel type.
- Determined the weather conditions and the ignition pattern that will produce this fire behaviour.
- Light the fire in a planned way when prescription conditions are met and confine it to a predetermined area.

The key to conducting the operation is a good fire behaviour guide that predicts fire behaviour in the selected fuel type. In Western Australia, the Department of Conservation and Land Management has been conducting prescribed burning to meet fire protection, forestry and ecological objectives in a scientific way since mid-60s. The planning process starts seven years in advance of each prescribed burn. Individual burning guides have been developed through empirical research for all their major fuel types including dry jarrah forest, tall wet karri forest, conifer plantations and mallee shrublands (for example Sneeuwjagt and Peet 1998).

In the eastern states prescribed burning is largely carried out using rules of thumb based on a McArthur's original burning guide for dry eucalypt forests produced in the 1960s (McArthur 1962). However, in one case a new burning guide has been developed and that was for burning under young regeneration of silver top ash in New South Wales State Forests (Cheney and others 1992). Clearly, if prescribed burning is to be conducted in a more professional way in there is an urgent need for new and better burning guides that can be applied to a whole range of different fuel types.

Advances in fuel management—The development of more sophisticated burning guides requires a better understanding of fire behaviour in fuels of different structure and composition. Recent work undertaken by CSIRO and Department of Conservation and Land Management Western Australia as part of Project Vesta (Cheney and others 1998, Gould and others 2001, McCaw and others 2003) has identified the importance of fuel structure in determining fire behaviour and has developed a system for quantifying fuel structure with a numerical index that can be used as a fuel predictor variable to replace fuel load.

Although fuel structure is difficult, if not impossible, to measure reliably and consistently, all natural fuels can be divided into easily recognisable layers. It is the characteristics of these layers that determine the particular fuel type and its characteristic fire behaviour and the difficulty of suppression. For example, the simplest fuel type is annual grassland like wheat. This is a single layer of relatively uniform compaction. The main factor that determines rate of spread is the continuity of the grass. Although height of the sward the affects the flame height, and thereby the suppression difficulty, it has only a minor effect on the rate of spread. In contrast dry eucalypt forest with a tall shrub understorey has fuels that can be identified into several layers of different compaction. These are in order of decreasing compaction:

- Compacted surface litter bed of leaves twigs and bark that makes up about 60 percent of the total fuel load,
- Near surface layer above it of the low shrubs containing suspended litter and bark,
- Elevated layer of tall shrubs,
- Intermediate layer of small trees,
- Fibrous bark of the overstorey trees, and
- Canopy of the overstorey trees.

All of these layers make an important contribution to the fire behaviour and each layer becomes progressively involved in fire as the intensity increases. A visual hazard rating system is being developed (Gould and others 2001) takes into account the height, continuity and fraction of dead flammable material in each layer. The latter that appears to be most important in determining fire spread is the near surface fuel layer and the best fuel variable for predicting the rate of spread is an index based on the hazard score and height of the near surface fuel layer (Gould and other 2001, McCaw and other 2003).

Effectiveness of fuel reduction over time—The period of time over which fuel reduction remains effective in assisting suppression depends upon the number of fuel layers involved, the rate of accumulation of fuels and the time that it takes for the key layers to build up to their full potential hazard for the site. This may be a relatively short time for fuels with a simple structure or take many years in more complex fuel types (table 3).

Table 3—Period that fuel reduction burning will assist suppression activities and the main factors that contribute to difficulty of suppression.

Fuel type	Persistence of reduced fire behaviour (years)	Factors contributing to difficulty of suppression
Annual grass	1 (year of burning)	
Tussock grassland	5	Development of persistent tussock fuel
Tall shrubland	10 to15	Height of shrubs accumulation of dead material (ROS, flame height)
Forest, short shrubs, gum bark	10 to 15	Surface fuel, near-surface fuels structure (ROS flame height)
Forest, tall shrubs, stringybark	15 to 25	Near-surface fuel, shrub height and senescence, bark accumulation (ROS, flame height, spotting potential

Although the effect of prescribed burning may persist for a considerable time, most fire management agencies consider that sufficient fuels have accumulated after 5 to 8 years to warrant re-burning.

Trans-Tasman Partnership

Australia and New Zealand have had a long history of sound fire management through a number of coordinating organisations. Building on this history and accumulated relevant fire management expertise, fire managers in Australia and New Zealand have been able and will continue to contribute the technical capacity of fire management in Australasia and internationally. In addition to the obvious positive economic and environmental outcomes from fire management their contributions have complementary social benefits to both countries. The major Trans-Tasman co-ordinating bodies include:

Forest Fire Management Group (FFMG)—is a committee of Australian and New Zealand land management agencies with responsibility for forest fire management together with representatives from research, education and the forest industry. FFMG reports to the federal government Forestry and Forest Products Committee (FFPC) which is comprised of the heads of federal, state, and territory and New Zealand government forestry agencies. The FFPC is a sub-committee of the Primary Industries Ministerial Council. FFMG's aims are to provide a centre of expertise on forest fire management and control, and particularly to:

- Provide a high level of technical and policy advice on fire management and fire control matters to the Forestry and Forest Products Committee through the Primary Industries Standing Committee;
- Assist interstate and international liaison and consultation between fire controllers and managers; and
- Assist in the development of effective fire management and control philosophy and proficiency.

Australasian Fire Authorities Council (AFAC)—is the peak representative body for fire, emergency services and land management agencies in the Australasian region. It was established in 1993 and has 26 full members and 10 affiliate members. AFAC's mission is to improve collaboration between the fire, emergency services and land management agencies in the Australasian region, particularly in the exchange of strategic information and the sharing of expertise.

As the national peak body, it is also committed to:

- Developing national standards for the fire industry;
- Advocating to State and Federal government on behalf of its member agencies;
- Creating national policies on a range of issues;
- Acting as an industry peak body on issues of national importance.

Research partnership—The resources of Australia's and New Zealand's pre-eminent forest research organisations has come together in a world leading joint forest research venture. Ensis- the joint venture between Australia's CSIRO Forestry and Forests Products and New Zealand's Scion (formerly Forest Research) - combines and enhances the breadth, depth and scale of Australasia's bushfire research and development capability. This research capability is also enhanced by the research partnership with the Bushfire Cooperative Research Centre (Bushfire CRC). The integrated Ensis bushfire research group created a strong Australasian bushfire science capability with significant benefits to end users in Australia and New Zealand, including:

- Gaining critical mass, economies of scale, and enhanced overall capability, with immediate benefits in the areas of bushfire science.
- A significant increase of expertise available to New Zealand in terms of fire behaviour, fuel assessment and suppression research. Integration of the bushfire research groups has increased its research capabilities in the Bushfire CRC.
- An increased capacity to quickly deal with the various activities generated from major wildfire events which in most cases assume top priority.

Conclusion

Australia and New Zealand have quite different fire environments and diverse land cover but the importance of understanding fire behaviour is recognised in both countries as an aid to fire management. Fire management agencies in both countries face a similar array of challenges in meeting their fire management objectives and the task is becoming increasingly difficult. As a government service, fire management has traditionally been combined with other forest management skills, notably sustainable timber production. Financial pressures and changes in policy relating to timber production from native forests are resulting in staff reductions and erosion of traditional levels of the fire management skills base and resources. Resources are declining at a time when demands for protection by the general community are increasing. Concurrently, the demands for ecologically appropriate forest management practices and concerns about the long-term impacts of prescribed burning practices have led to the suggestion that, in some areas, fire is adversely affecting biodiversity and long-term sustainability of forest ecosystems. It is also widely recognised that there will be increase in the severity and impact of bushfires in the next decade in the Australasian region. This includes potential changes in long-term fire danger such as those associated with projections of future global warming and climate change. These issues are overlain by debate about how fire can affect climate change, greenhouse gas balance at the landscape and national level, and to whether these changes are being exacerbated by managed and/or wildland fires.

Accurate interpretation of the effect of fire management practices on forest management requires not only accurate measurement of area burnt but also the classification of all fires by vegetation type and burning conditions, the measurement of the fuel dynamics and equilibrium fuel loads for each type and the measurement of consumption rates under a wider range of burning conditions than is currently available. Also, fuel management using prescribed fire has an important role in protection of forests, community assets, other valued resources and biodiversity. Forest and rural landscapes in Australia and New Zealand are becoming increasingly more fragmented because of human activities, is also having an impact on the fire management practices that could contribute more to the amount of area burnt by wildfires. The critical role of fire management and using fire as a management tool for fuel management requires a better understanding of fuel characteristics and fire behaviour leading to the development of improved guides for prescribed burning in different fuel types.

Acknowledgments

I would like to thank British Columbia Ministry of Forests and Range for sponsoring the invited speaker to the First Fire Behaviour and Fuels Conference- "*Fuel Management- How to Measure Success*". The shared views from my colleagues of the Forest Fire Management Group and Phil Cheney have been wonderful sounding board and contributor for many years on this subject are greatly appreciated. Formal internal review for CSIRO and Ensis- Bushfire Research before submission was carried out by A. Sullivan and G. Pearce.

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Forest Fuels Management in Europe

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Abstract—*Current fuel management practices vary considerably between European countries. Topography, forest and forest fuel characteristics, size and compartmentalization of forests, forest management practices, land uses, land ownership, size of properties, legislation, and, of course, tradition, are reasons for these differences.*

Firebreak construction, although not as clearly favored as in the past, is still a prominent fuel management technique. Fuelbreak construction has been adopted quite extensively in the last decades. Fuel treatments along the sides of roads are common. Use of prescribed burning is generally very limited. However, in most countries, shepherds use fire quite extensively, but illegally. Furthermore, stubble burning is a very common type of fire use, which often becomes source of wildfires. Grazing of cattle, sheep and goats is a traditional practice in the wildlands of Mediterranean countries. In spite of many recent social changes, it is still prevalent. Although its effect is often negative, when the carrying capacity of the land is exceeded, it does offer a significant contribution toward controlling fuel accumulation. In some cases animal herds are actively used as means for controlling vegetation re-growth in areas of fuel treatment. This paper is an effort to provide an overview of current fuel management activities in the European countries, mainly those with Mediterranean climate.

Introduction

Europe is a diverse continent with a large number of nations and countries that differ significantly from each other. Their differences range from the characteristics of their people to the prevailing environmental conditions, and from their culture and heritage to their social and economic structure. The European forest cover is characterized by a great diversity of forest types, extent, ownership structure and socio-economic conditions. However, in regard to forest fires, things are much simpler: the countries in northern Europe are not really concerned with fires. On the other hand, the southern European countries (Portugal, Spain, the south departments of France, Italy, Greece and Cyprus), most of them lying next to the Mediterranean Sea, face a profound forest fire problem. The Mediterranean countries contribute 94% of the total burned area in Europe, according to an analysis of the 1975-2000 statistics by the European Forest Institute. Fire is the most important natural threat to forests in Southern Europe.

The countries of Southern Europe have seen their fire problem getting worse in the second part of the 20th century. Abandonment of rural areas, prolonged protection of forest lands, and expansion of fast growing species that are highly flammable (mostly pines and eucalypts) have aggravated fire

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hazards. Tourism growth and development of extensive wildland-urban interface areas have sharply increased fire incidence and disaster potential. The annually burned area has more than doubled since the 1970s.

Realizing they had a problem but not fully understanding the reasons behind it, all south European countries responded by increasing their fire suppression capacity, especially through the 1990s, necessarily increasing their firefighting budgets. The outcome of this effort is a reduction in total annually burned area in relatively easy fire seasons. However, the potential for major disasters is still there. As more fuels accumulate, in difficult fire seasons, the burned area climbs again to high levels. Furthermore, the damages are very high as fires often originate or easily reach the extensive wildland-urban interface areas that have emerged in all these countries, mainly close to the coastline. This has been demonstrated very clearly in the last three catastrophic fire seasons in Portugal (2003-2005), with the occurrence of extremely large (over 10,000 ha) and destructive fires. Currently, the need for reducing fire hazard through active fuel management is becoming more and more obvious, but, to this day, the funding that is diverted from suppression to fuel treatment and general fire prevention is limited.

Fuel occupies one of the three sides of the fire triangle. Heat and oxygen form the other two sides. In the forest, fuel can be manipulated effectively before the start of a fire, influencing the probability of fire ignition and potential fire behavior. The other two contributing factors to fire behavior (weather and topography) cannot be altered by fire managers. Thus, forest fuel management is one of the cornerstones of successful fire management.

There are many definitions of fuel management in literature, most of them quite similar to each other. According to the one adopted by the Food and Agriculture Organization of the United Nations, fuel management is the "act or practice of controlling flammability and reducing resistance to control of wildland fuels through mechanical, chemical, biological, or manual means, or by fire, in support of land management objectives."

Managers can modify the load and the arrangement of both live and dead fuels. Available options are quite well known. They include horizontal isolation of fuel through firebreaks, fuelbreaks and greenbelts, fuel reduction through physical removal, prescribed burning and intensive utilization, change of fuel bed compactness by methods such as lopping and scattering (manually or by tractor crushing) and chipping, breaking vertical continuity through pruning and surface fuel reduction, and change of fuel moisture content through dead fuel removal and even local irrigation (Chandler and others 1983). Fire-aware silviculture is yet another broad option. The choice of which methods are used varies depending on factors such as vegetation type and characteristics, seriousness of the fire problem, available funds, available experience and expertise, tradition, social concerns, etc. How these factors weigh in the final decision has a direct effect on the selection of fuel management methods and the scale of their application. This is where differences exist between Europe and the other continents, as well as within Europe.

Most of the above mentioned methods of fuel treatment are used somewhere in Europe. This paper provides an overview of current fuel management practices in European countries, mainly those with Mediterranean climate, based on literature and on the personal knowledge of the contributing authors. In doing so, we tried to explain the reasons that have led to the current practices.

Fuel Management Practices in European Countries

Horizontal Continuity Disruption

Firebreaks—Firebreak construction was the most widely applied fuel treatment in the past. It still is to a large extent but it is not as clearly favored anymore. The preference for creating firebreaks can be explained by the obviousness of their objective (to stop the fire through fuel continuity disruption) that is visible to laymen and politicians alike. However, through time, a number of disadvantages became evident: high construction cost, high maintenance cost (need for annual clearing), poor aesthetics and significant potential for erosion when built on medium to steep slopes. Furthermore, their effectiveness proved to be quite limited. They may help to stop small fires with little firefighting support under mild weather conditions, but they are easily breached through spotting under strong winds and low relative humidity. The relatively small extent of forests in Europe, presence of villages and agricultural properties, and concerns about aesthetics and erosion, practically preclude construction of very wide firebreaks. The width (30-40 m) is often inadequate for averting breaching by direct flame contact when crown fires are fanned by strong winds.

Currently firebreak construction is a regular practice in Portugal, Spain, France, Greece and Cyprus. In Italy it exists as a practice but its use is not as regular. It should be pointed out that in some of these countries, especially in Spain (where the regions are largely autonomous) and in Italy, there are significant differences in the natural environment (colder north vs. warmer south, elevation influence, maritime influence, vegetation composition), in the societal structure and in the overall political management practices, including budgeting. This is reflected to a large extent in the decisions made on fuel management in general and in firebreak construction in particular.

Building firebreaks is only a start. Maintaining them is much more difficult as budget shortages often make it impossible to keep them free of low vegetation (mainly grasses and shrubs) on a short period (usually annual) basis. The longer the firebreak network, the more the yearly budget required for maintenance. With poor maintenance firebreaks cannot serve their purpose.

Fuelbreaks—Fuelbreak construction has been adopted quite extensively in the last two decades. Sometimes fuelbreaks are built "by the book" trying to permanently convert vegetation to a cover of low fuel volume and/or low flammability (Chandler and others 1983). In general this is not easy when dealing with Mediterranean shrubs, either in an open shrubland or under the canopy of trees, because most of these shrubs are vigorous resprouters. On the other hand, use of phytocides has been tried experimentally in various situations with interesting results but their costs and the associated risks make this practice difficult to accept in both ecological and economical terms (Rego 1997).

In the European countries road networks are quite dense. Clearing vegetation on the sides of forest and rural roads, either manually or mechanically, results in fuelbreak-like belts of reduced fire hazard from which firefighters can try to stop a fire, for example, by lighting a backfire. Also, when understory vegetation is removed along the sides of the roads, usually up to a distance of 30 m on each side, the spread of a fire that starts by the road is slowed down. Crown fire initiation is also delayed increasing the probability of successful initial attack.

Regular fuelbreak construction is common in Spain, France and Italy, while it is less common in Portugal and quite uncommon in Greece.

Greenbelts—Chandler and others (1983) referred to greenbelts as "the next logical progression after the fuelbreak." They defined greenbelt as "a strip that has been converted to a nonflammable cover type and is maintained in that state by irrigation and mechanical treatment." They suggested a golf course as an example of a greenbelt, but admitted that greenbelts are prohibitively expensive for a forestry organization.

In Southern Europe, however, some agricultural cultivations play the role of breaking horizontal fuel continuity by providing a strip of nonflammable cover type. The abundance of such fields around villages is one of the reasons for reduced fire damages in the past. Vineyards are one of the commonly encountered cultivations that can function as a greenbelt. Orange and lemon orchards are another. Even olive groves, when properly cultivated, with grass and other surface fuels removed, can stop a fire effectively. However, as much of the rural population abandons agriculture and leaves for the cities, the effectiveness of these greenbelts is greatly reduced. Their size decreases and without the usual treatment of grasses under the cultivated woody plants the fire can easily breach them. Olive groves are the most pronounced example of this change: when left with grasses in the understory they become a major problem for firefighting because the olive trees, once ignited, are very hard to extinguish completely.

Fuel Reduction

Physical fuel reduction—Fuel reduction by manual or mechanical means is the main method used by fire protection organizations for the creation of firebreaks and fuelbreaks. However, the cost of such treatments is generally very high and the area that can be treated is quite limited.

Prescribed burning—Prescribed burning was introduced in Europe—Portugal, Spain and France, in the early 1980s (Botelho and Fernandes 1998). However, after 25 years, its operational use remains very limited. In some cases, as in Greece, it is not possible as there is no provision for it in the existing laws. There is neither long-term experience in the fire management organizations nor much willingness to assume the risks associated with this practice. The existence of towns and villages, agricultural lands and other private property imposes significant restrictions in regard to smoke management, liability issues and safety. Furthermore, since any type of fire in the forest has been described in all fire prevention campaigns as bad in the past, there is concern of the public receiving mixed signals if prescribed burning is not introduced properly.

Currently, the European Union (EU) is trying to improve its knowledge on prescribed fire as applied in European ecosystems, hoping to expand its usage where it could be beneficial and offer practical solutions. An EU funded Integrated Research Project titled "FIRE PARADOX" was started in the beginning of 2006 and will continue until 2010. It involves 31 institutions from 13 countries, including in addition to the European partners, institutions from Northern Africa (Maroc and Tunis). The aim of the project is to study the use of prescribed fire and the application of backfire in Europe

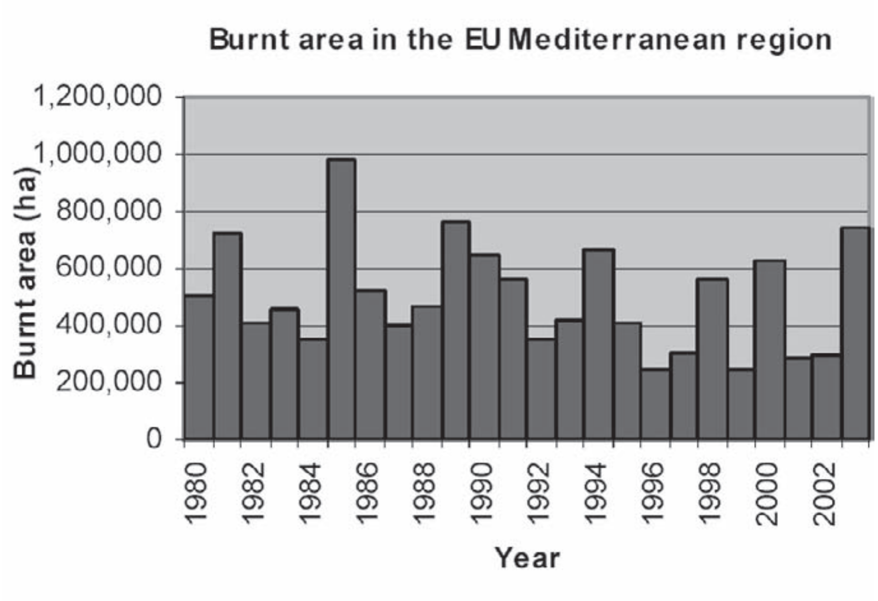

Figure 1—Burnt area in the EU Mediterranean region in the 1980-2003 period (European Communities 2004).

in four main domains: Prevention, ignitions, spread and suppression (www.fireparadox.org).

Shepherds often do what is not done by fire management organizations in regard to fuel reduction by fire. It is a long-standing tradition for them to set small fires at times of low fire danger that burn patches of land, stimulating new succulent growth of grasses and (mainly resprouting) shrubs for their animals. This procedure could be considered as a management scheme under certain conditions as it is profitable for the shepherds and also reduces fuel hazard. However, in recent years it has become a problem, often leading to desertification. The reason for this is an increase of the number of animals to levels far beyond the carrying capacity of the available land. EU subsidies to shepherds, in the 1985-2000 period, were based on the number of animals they had, becoming a motive for increasing the size of their flocks. This policy has been changed nowadays after its detrimental effects became evident. The large number of animals quickly reduced available forage, making shepherds reburn the land every 1-4 years. Such a frequency, combined with immediate overgrazing of the young vegetation, quickly denuded many sites leaving them covered with non-palatable, mostly thorny, plants, and having a significant soil erosion problem.

Although "effective" for fuel reduction, this method also has a side effect. As firefighting organizations easily manage to stop shepherd fires in the low fire danger season, it has been observed that the shepherds turn to new lands where they start fires on high danger days.

Biomass utilization—Fuels accumulate in forests when biomass production through photosynthesis is higher than the rate of decay. This is common in most ecosystems but the rate at which such accumulation occurs, varies depending on the characteristics of the ecosystem and its environment. When fuels accumulate beyond a certain point fire becomes the alternative that breaks down the biomass and initiates a new circle of life. Biomass utilization is a third alternative that can maintain balance and reduce the probability of fire.

In the Northern European countries active forest management with good timber utilization that leaves relatively little slash behind is key to keeping the potential for fire disasters low. Timber production is one of the main products fueling the economy of the Scandinavian countries. With such practices, fires like those in the boreal forests of Alaska, Canada, and Siberia are highly unlikely in Sweden or Finland.

On the other hand, in Mediterranean ecosystems fuels accumulate quite fast as biomass production is quick and decay is slow. Active forest management for timber production with appropriate silvicultural practices is mostly carried out where there is financial incentive: the forest products have a higher value than the cost for managing the forest. Examples are the eucalypt plantations in Portugal, the *Pinus nigra* forests in Greece and the *Pinus pinaster* and *Pinus sylvestris* forests in Spain. In many cases, however, as with the forests of *Pinus halepensis* and *Pinus brutia* in Greece, the active management of forests is not economically viable. Without biomass utilization these forests are expected to burn with relatively high frequency. Traditionally, much of the biomass produced by these forests and the evergreen Mediterranean shrublands was harvested and used as an energy source for cooking and heating by the rural populations living close to the forests. Also, resin collectors managed these pine forests in a traditional way, guarding them, maintaining access trails and removing old and non-productive trees to be used as fuel wood, in an effort to create open spaces for regeneration of new clubs of trees. In this way, a balance was maintained, at least close to the numerous villages, where approaching fires were easy to control. The migration of these populations toward the cities and the substitution of other energy sources (electricity, oil, gas) for wood upset this "natural" balance and led to the current worsening condition and the need for fuel management for fire hazard reduction.

Currently, grazing in the shrublands is the most common form of biomass utilization in the non-timber producing forest lands in the Mediterranean. When this practice is planned and controlled at appropriate levels it functions as a very effective and productive method of fuel management.

A Short Summary for Each Country

France

France is the most active southern European country in regard to fuel management. The French approach is that firefighting implies strategy, and good strategy means preparing wildlands for firefighting to achieve efficiency of suppression operations and safety of fire crews. In this respect, the core of French strategy in fire management is "wildland partitioning" (Figure 2).

The "tools" for achieving wildland partitioning are fuelbreaks and fire fighting areas. Furthermore, as part of the overall strategy, protection of human assets is a priority. A "let it burn" policy is applied on a very limited scale. It is very difficult to apply such a policy in France, because human assets are too many and interspersed in most forests.

A "fuelbreak working group" has been established in France. The Group works on:

- Building fuelbreaks

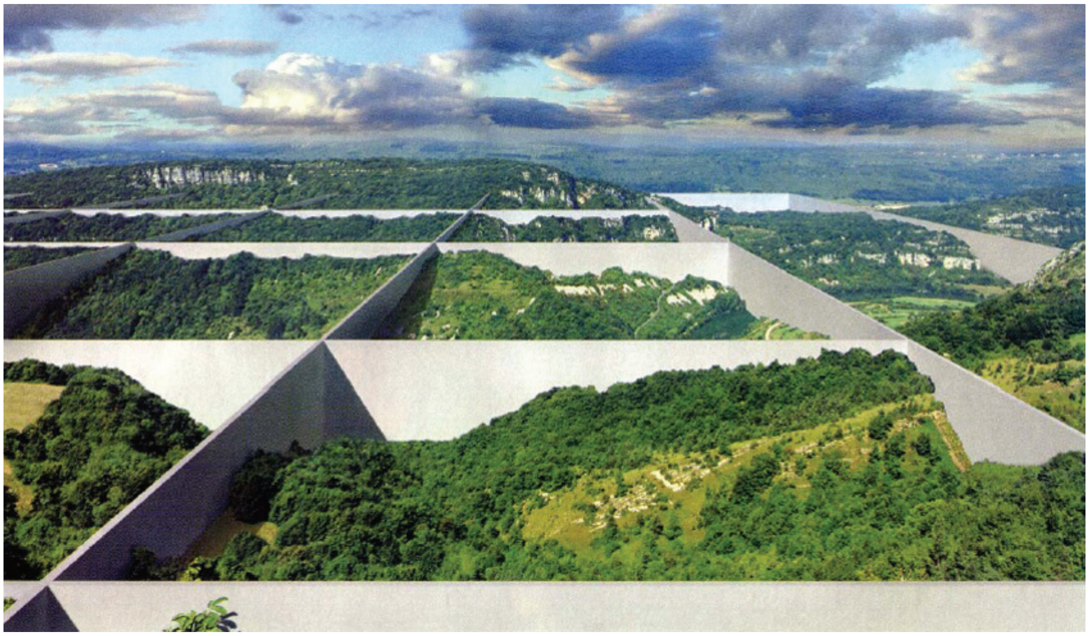

Figure 2—The concept of "wildland partitioning" in France.

- Fuelbreak maintenance
- Real study cases analysis
- Economic assessment of fuelbreaks
- Preparing national standards for the "tools" of fuel management (such as firebreaks) that are applied in the field

In France, fuelbreaks are categorized in three types according to their objective:

- Type 1: The objective is to limit fire ignitions: fuel management aims to decrease ignition hazard and to increase success of early fire fighting operations. It is mostly applied in or around Wildland Urban Interface areas.
- Type 2: The objective is to limit fire effects on assets: fuel management focuses on making the circulation of firefighting crews and the public easier and safer (safer escape routes). It is mostly applied in or around Wildland Urban Interface areas. Fuel management for forest autoprotection (i.e. to avoid stand replacement fires) is included in this type of fuelbreak.
- Type 3: The objective is to limit the size of burned areas by breaking forest continuity. These are fuelbreaks built at strategic locations to help firefighters control the head or the flanks of probable fires. They are generally built between 2 non-burning (usually agriculture) areas. In building type 3 fuelbreaks two objectives are:
    - o To provide at least a safety zone for fire crews.
    - o To enable efficient fire suppression actions.

Scenarios that must be taken into account include the case of a large fire and fires under severe fire weather conditions (Figure 3).

Fuelbreaks are built by forest authorities but in cooperation with the firefighters (Civil Protection) in order to take their requirements into

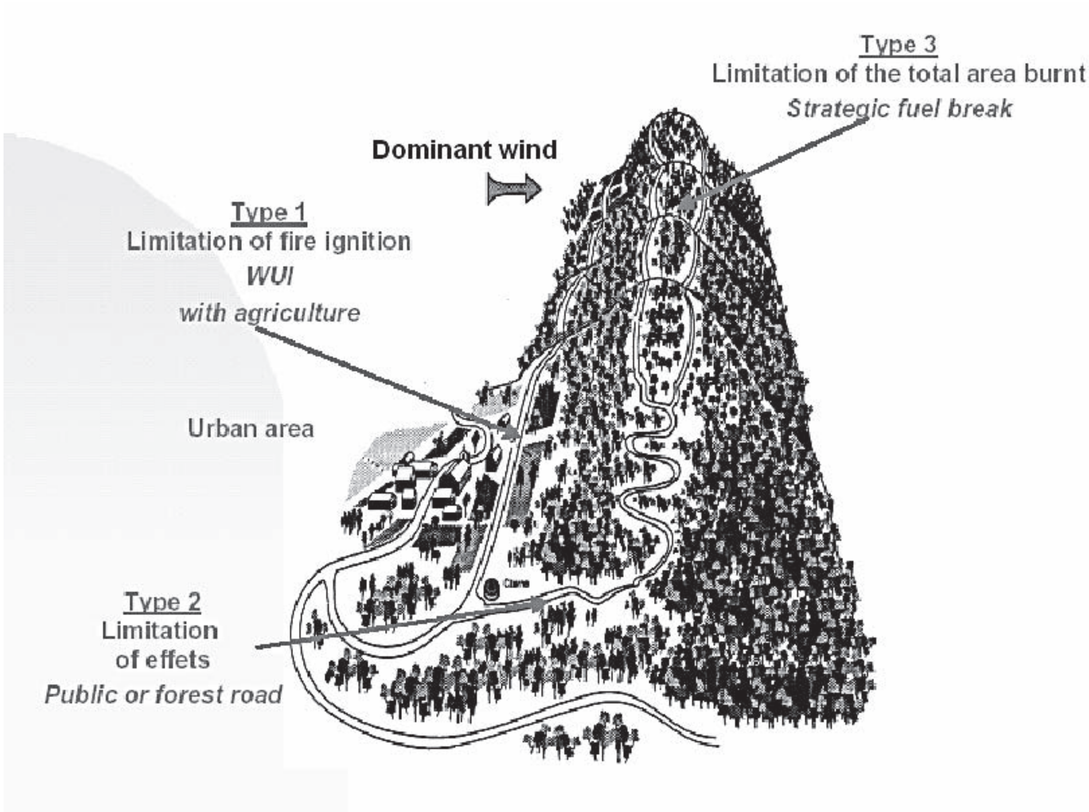

Figure 3—The concept of a fuelbreak network in France.

consideration. Their construction takes into account the firefighting strategy. Necessary elements, such as water supply, access (roads), road signs, etc., must be available along a fuelbreak.

The standard approach for fuelbreak maintenance is mechanization. When possible, grazing and agriculture are also used. Prescribed burning is also used to some extent and its application is increasing. Of course, social constraints have to be integrated when choosing to use it.

In a 1999 study of nine fuelbreaks in France, which took into consideration the cost of construction (amortizement), maintenance, outcomes from grazing (production) and external costs, over a 5 to 15 year period, it was found that the annual cost of a 30 to 40 ha fuelbreak is equal to one hour of aircraft flying time delivering three retardant drops.

Portugal

The Portuguese Forest Services structure is based in a Central Office at Lisbon and three regional offices, each with 7 sub-regional offices. These sub-regional offices have the responsibility of promoting the Regional Plans of Forest Management. Recently, a Sub-Directory for Forest Fires Prevention was created under the General-Directorate of Forest Resources, to accomplish the execution of the National Plan for Forest Fire Prevention and Management. The Regional Plans of Forest Management also define the primary and secondary fuels break network planning, to promote rural landscape fragmentation and control the spread of large fires.

There is the assumption that the solution to the forest fire problem relies on the promotion of private forest management, although this is a mid-term solution. Several incentives are now being developed, such as reduction of the Value Added Tax (VAT) for preventive silviculture services and funding support for the installation of “Integrated Forest Zones”, that unite, for management purposes, a large number of small size private forest parcels. These zones have a size of at least 1,000 ha, a size that is considered as the minimum needed for professional management of the forest resources and for fire prevention planning at the landscape level.

At the municipal level, Forest Fire Prevention plans include characterization of hazardous areas and set the fuels treatment strategy. Techniques like prescribed fire, grazing and localized mechanical interventions are defined in those plans. Fuel treatments in the forest/urban interface are also planned, as well as pre-suppression infrastructures (water points, lookout towers, forest roads and fuelbreaks).

Firebreaks are the most widely used fuel management technique in Portugal, mostly in the mountainous areas, in the public lands and in the eucalypt plantations of the pulp and paper companies. Directed grazing for cattle at the landscape level is starting to be promoted. Localized manual fuel treatment by hand crews is another technique used in strategic areas. Recently, Portugal puts an emphasis in the reintroduction of prescribed fire and for this purpose has started a broad training program of foresters and support crews. A technical exchange program with the U.S. Forest Service (USFS) is being prepared to support this initiative (Figure 4).

Figure 4—One of the first prescribed burns executed in 2006 in Portugal with the cooperation of USFS prescribed fire specialists (Photo: Mike Crook (USFS)).

Spain

In Spain the responsibility for forest fire prevention belongs to the 17 autonomous regions (Autonomies). Every region has its own regulation and rules for forest fuel management, hence the methods, intensity and allocated budget varies from region to region.

Out of the 26 million hectares classified as forest land, about 18 million are privately owned. Landowners are in charge of the exploitation and maintenance of the ecosystems, and also responsible for the forest fuel treatments. Although specific regulations apply in the regions most affected by forest fires, landowners do not respond in the same way in regards to fuel management. Hence the methods, extension and intensity vary within the regions as well.

Every region, by law, has to provide a forest fire defense plan, including a chapter for preventive measures, which include operations on the forest fuel. However, common objectives are followed, mostly thanks to the yearly CLIF meeting which is hosted by the Ministry of Environment and in which main target priorities are discussed and set among all autonomous regions.

In the last two decades, an important change in fuel structure and load has occurred, mostly caused by the de-population of rural areas. Land use change, in many cases followed by the abandonment of activities in the forested lands, has brought about an increase of burnable biomass in grasses and shrubs, and the modification of the vegetation structure, favoring horizontal and vertical fuel continuity.

Three areas can be considered in terms of fuel structure and load, hence giving an idea of the requirements of forest fuel treatments.

In the Atlantic zone, which is humid, there are several vegetation structures. The forested areas frequently have an overload of flammable fuels creating explosive situations. This is caused by the low budget invested in the forest stands, and the poor investment of landowners in fuel treatments. The situation is aggravated further by the fact that the shrubs in this zone regenerate quickly, leading to heavy accumulations of very flammable biomass in a short time after fires or fuel treatments. The agricultural lands have mostly been abandoned. Natural vegetation has invaded these lands, mostly in the interior. The situation is made worse by the uncontrolled use of fire in an effort to control the invading vegetation. Removal of forest fuels in the Atlantic zone is costly due to the high rate of biomass production, and is traditionally limited to the removal of fern and grasses. Their biomass is normally burned in piles. Today, a new practice is being explored: it is the mechanical removal of the fast growing shrubs and their use in biomass-energy production plans. In the Atlantic zone, it is normal to apply systemic herbicides on firebreaks and cleared zones built along the perimeter of forest lands to reduce future regeneration of shrubs and tree sprouts. Although very efficient as a vegetation control tool, Administrations are generally reluctant to use prescribed burning, perhaps due to the many agricultural burnings that end-up as large forest fires. As a result, at least in the vicinity of large and/or dense forest stands, prescribed burning is avoided, although is the most efficient and cheap method of forest fuel removal. In the Atlantic zone, grazing is not applied systematically for fuel control.

In the Mediterranean zone, Spain has a mosaic of forest land patterns, including young forest stands and reforested areas, abandoned agricultural lands, and mature forest stands. They are always subject to the pressure of shrub species. Most forests have a more or less dense shrub understory. In this zone, silvicultural and other treatments of the forest fuel are generally economically unfeasible for widespread application. Hence, hazard reduction efforts are localized and more focused. A combination of silvicultural treatments and livestock grazing is the measure of choice.

In calculating risks in the Mediterranean zone, it is very important to consider soil erosion and other hydrological phenomena, which could take place under sparse vegetation coverage. Large forest stands are infrequent, and when they exist, they are protected by a strip of low combustibility around their perimeter. Networks of firebreaks are combined with other low-load vegetation patterns (i.e. agriculture) to avoid horizontal continuity, while taking into consideration the protection of settlements and housing areas in the increasing wildland-urban interface domain. Planning the extent and location of fuel management takes into consideration the quality and extent of the various ecosystems, regeneration capacity, vegetation coverage and special protection priorities, if any.

In the Southern zone of Spain, the forest structure is very variable and has a direct correlation with the ownership regime. The forest stands belonging and managed by the Administration are subject to periodic silvicultural treatments, such as thinning, pruning and understory removal. In contrast, in privately owned forests the response is quite poor, except for some cases, in which several owners associate and cooperate in managing their forest. In this Southern zone, the most common fuel management practices applied are grass and shrub removal, prescribed burning and grazing. Due to budget restrictions mechanization is still not totally achieved.

Firebreak construction is perhaps the most common fuel control measure in Spain. All fire-prone areas in Spain are criss-crossed by a network of linear firebreaks. The main objective is to fragment the territory into cells to minimize the spread of large fires. Regardless of whether they serve their purpose well, firebreaks are unpopular among citizens in Spain, mostly due to the visual impact on the landscape, although the rural population has accepted them more quickly due to the forest protection benefits they offer. Maintenance of firebreaks, which is required, takes a large part of the fuel treatment budget. Often, budget constraints lead to poor maintenance in certain regions. However, in some regions, such as Valencia, application of intense grazing by goats in firebreaks keeps costs low and helps to maintain the firebreak network.

The standards for building new firebreaks are summarized below:

- Width of firebreak has to be two and a half times the dominant canopy height, with a minimum of 15 m in the vicinity or forest stands.
- Width of firebreak has to be 10 m in the vicinity or inside of shrublands.
- Width of firebreak has to be 5 m in the vicinity or inside grasslands.
- In all cases, firebreak vegetation has to be totally removed to mineral soil.

In areas where lightning is a main cause of forest fires, firebreaks are often built along mountain crests where they serve as an efficient transport corridor for ground forces in addition to hindering fire growth.

Fuelbreaks are becoming more popular in Spain lately. They are favored by many because they have a more natural-looking structure. Their width is normally about 30% more than that required for the firebreaks.

Prescribed burning is not a generalized and accepted practice for forest fuel reduction. It is regulated and applied in some regions (i.e. Andalusia), it is slowly being accepted in others, such as Catalonia and Castilla Leon, but it is totally banned in several others, such as Madrid. In general, it is a rather unpopular practice, perhaps due to the fact that the use of fire as a tool in agricultural activities has frequently been the cause of large and very destructive fires (Vega and Velez 2000).

The frequency of burning for grazing by shepherds varies between regions but it is more or less general practice in Spain to obtain pasture by burning shrubs. This practice is more prevalent in the Atlantic zone as mentioned above. Grazing of cattle, sheep or goats is a common practice for fuel reduction in Valencia and other provinces of the Mediterranean zone. In Galicia, Castilla Leon and many other regions of the Atlantic zone grazing is used just to contain shrub sprouts. Other fuel management practices include mechanical and manual clearance around heavily traveled roads, and under high-voltage (1,000 to 220,000 V) power lines. Furthermore, silviculture in Spain takes into consideration the need to reduce fire hazard. Treatments include shrub removal, tree thinning, and pruning of lower branches and are often applied at locations of special interest (Figure 5).

Figure 5—An example of a silvicultural treatment that also aims at crown fire potential reduction on Tenerife Island, Spain.

Italy

The 20 Italian Regions have unique administrative competencies concerning wildland and forest management in their territory. They are also in charge of forest fire protection, supported by the State Forestry Corps through special agreements at regional level.

Law dispositions on wildland fires in Italy are mainly established by the national law 353/2000. This law states that each Region is in charge of setting up a Fire Management Plan for its regional territory. The plan should identify priorities and arrange all fire protection activities, including interventions on woodlands. The national law is inspired by the principle that the best approach to protect forests from wildfires is to promote and provide incentives for prevention activities, instead of just focusing on suppression. In spite of this declared goal, neither the law nor its specific guidelines discuss in detail the subject of fuel treatment and management for wildfire prevention. The law simply states that each regional plan must provide for silvicultural activities to clean and manage woodlands. The greatest investments are still made in fire fighting, with a varying amount destined to prevention activities from Region to Region.

Each Region must plan, realize and maintain fuelbreaks (and other structural and infrastructural interventions), establishing typologies and standards according to its environmental characteristics. To reduce the risk of fires spreading from agricultural areas to forests, within some Regions, plowed or mowed buffers are realized along cultivated and abandoned fields located next to forests (Figure 6).

Figure 6—Mowed buffer strip separating a forest from agricultural land in Italy.

Each regional plan also has to design all forest cleaning and management interventions for those areas with the greatest wildfire risk. These interventions must specifically aim at:

- Reducing fuel biomass and removing coarse woody debris.
- Creating mixed and well structured stands, with a heterogeneous forest composition.
- Favoring, where possible, coppice conversion to high forest.
- Favoring natural regeneration.
- Thinning old and too dense coniferous plantations.
- Slashing, mowing and cleaning in the proximity of railway lines, forest and ordinary roads and road banks, especially if they are located next to forested areas.

This last treatment is mainly applied in the summer. It is realized by the organizations responsible for the road network and railway management. Along railroads chemical weeding is a common practice, while around roads both manual and mechanical clearance are applied.

In Italy there is clearly lack of experience concerning prescribed burning; moreover there is not a clear set of rules that would define for all the country the use of fire for ecological and management purposes. The national law does not mention the possibility to use prescribed burning; thus, it is up to each Region to adopt the use of prescribed fire in its fire management plan. Only a few Regions currently have plans that allow and regulate the use of the prescribed burning technique. For these reasons and because of a widespread mistrust of fire for ecological and management purposes, in Italy prescribed burning is not applied. Recently some experiments were conducted by the Agroselviter Department of the University of Torino to investigate the use of prescribed burning both for the management of particular biotopes and to reduce fuel load (Ascoli and others 2005).

The practice of burning for grazing by shepherds was more widespread in the past; currently it is quite limited and is exercised mainly in a few areas of the southern regions and in the islands (mostly Sardinia). Stubble and shrub burning is instead a traditional practice adopted by farmers; it is one of the most frequent sources of wildfires.

Grazing of cattle was also more common in the past. Recently some attempts are being conducted to use sheep grazing to reduce fuel biomass within fuelbreaks, instead of mechanical treatments (Antona and others 2003).

Greece

In Greece, the responsibility of firefighting passed from the Forest Service to the Fire Service in 1998 (Xanthopoulos 2004). As a result, prevention and suppression are not seamlessly tied anymore. The cost of firefighting tripled in the years that followed. Funding for prevention decreased. Subsequently, fuel management efforts are relatively limited today.

The General Secretariat for Civil Protection which was established in the late 1990s tries to organize cooperation of all organizations involved in fire management. It organizes public education and fire prevention campaigns every summer, co-ordinates general planning and, in regard to fire hazard reduction, it distributes some prevention funds to local authorities for fuel management work, mainly in the vicinity of settlements and along roads.

Firebreaks are the most common fuel management measure taken by the Forest Service. Forestry officers struggle to keep them clear of vegetation re-growth before every fire season with the limited funding they get.

In Greece, few fuelbreaks are built "by the book" (i.e. trying to permanently convert vegetation to a cover of low fuel volume and/or low flammability). The road network in the forests is quite dense. Clearing vegetation on the sides of forest and rural roads, either manually or mechanically, results in fuelbreak-like belts of reduced fire hazard from which firefighters can try to stop a fire (Figure 7). The cost of this work, when performed manually, has been studied in Greece by Xanthopoulos (2002).

Grazing of sheep and goats is very common in the wildlands of Greece. In all regions of the country, the number of animals exceeds the carrying capacity of the available grazing land. This high grazing pressure has obvious negative ecological effects but also keeps fuels under control. On the other hand, fires lighted by shepherds to rejuvenate vegetation in the overgrazed shrublands are a significant problem as they constitute more than 10%, probably close to 20% if fires listed as "of unknown cause" are considered, of all wildfires in the country (Figure 8).

Figure 7—An example from mount Parnis, near Athens, of shrub understory removal around heavily used forest roads, chipping the resulting biomass.

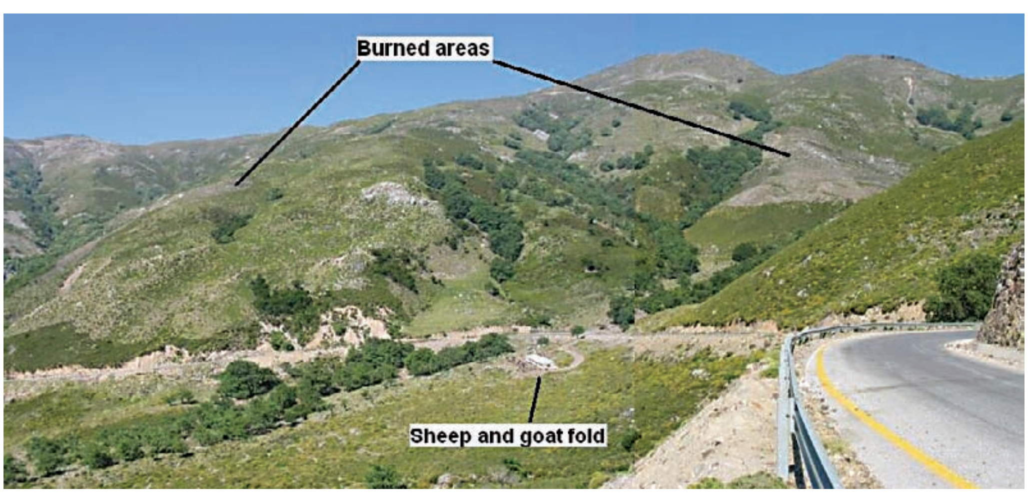

Figure 8—Two small burned areas near a sheep and goat fold in western Crete, Greece.

Conclusions

Table 1 summarizes the fuel management methods in the southern European countries. In spite of the differences between them, there are many similarities worth noting here:

- Firebreak construction, although not as clearly favored as in the past, is still a prominent fuel management technique.
- Fuelbreak construction has been adopted quite extensively in the last decades. Fuel treatments along the sides of roads are common.
- Use of prescribed burning is generally very limited. The existence of villages and other infrastructures within and around forests is one of the reasons discouraging its adoption. It can be concluded that efforts to expand its use are underway.
- In most countries, fire is used quite extensively, but illegally, by shepherds.
- Stubble burning is a very common type of fire use, which often becomes source of wildfires.
- Grazing of cattle, sheep and goats is very common in the wildlands of Mediterranean countries. In spite of many recent social changes, it is still prevalent. Although its effect is often negative, when the carrying capacity of the land is exceeded, it does offer a significant contribution toward controlling fuel accumulation. In some cases animal herds are actively used as means for controlling vegetation re-growth in areas of fuel treatment.

In general, efforts are concentrated mainly close to inhabited areas and focus on protecting humans and infrastructures. Firebreaks and fuelbreaks mainly aim to aid in limiting the spread of large fires but their density in areas where there is little population and low forest value is generally limited. Preventive silviculture, including prompt timber harvesting and development of mixed forests rather than monocultures are often solutions in seeking fire resistance in productive forests.

Acknowledgments

This paper was prepared following an invitation from the organizing committee of the Conference. It is mainly based on work performed in the context of the "EUFIRELAB" project that is funded by the European Commission, Directorate General for Research, 5th Framework Program (Contract EVR1-CT-2002-40028). Relevant information can be found on the project web-site (www.eufirelab.org). The support of the Protection Branch of the Ministry of Forests and Range of the Province of British Columbia, Canada, for making the trip and presentation to the Conference possible, is gratefully acknowledged.

Table 1—A summary of current fuel management practices in southern Europe.

Country	Firebreak construction	Fuelbreak construction	Manual clearance around roads	Mechanical clearance around roads	Grazing of cattle, sheep or goats	Prescribed burning for fuel reduction	Burning for grazing by shepherds	Silvicultural treatments	Clearance under powerlines
France	R	R	R	R	I	I	I	I	R
Greece	R	I	R	I	R	N	R	E	R
Italy	I	R	R	R	N	N – E	N	R - I	R
Portugal	R	I	I	R	R	E	R	I	R
Spain	R	R	R	R	R	I	R	I	R

Where: R : Regular operation
I : Applied but not on a regular basis
E : Applied in small scale or experimentally
N : Not applied

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Wildland Fire Use — Challenges Associated With Program Management Across Multiple Ownerships and Land Use Situations

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Abstract*—The application and use of wildland fire for a range of beneficial ecological objectives is rapidly expanding across landscapes supporting diverse vegetative complexes and subject to multiple societal uses. Wildland fire use originated in wilderness and has become a proven practice successful in meeting ecological needs. The use of wildland fire in non-wilderness is emerging as an important practice but its success is predicated on the acknowledgment of the fundamental inseparability and equal importance of ecological, social, and economic needs and requirements. The 2005 western fire season resulted in the single largest scale application of wildland fire use in non-wilderness to date and illustrated that managing wildland fire use in these areas is associated with a higher level of complexity driven by a number of elements including: spatial scale differences; presence of multiple ownerships and increased values to be protected; increased needs to plan and implement mitigation actions; temporal scale differences for implementing mitigation actions; greater social and economic concerns and needs; and increased public information needs. Continuing expansion of wildland fire use implementation across federal, state, and private land ownerships and all land use situations will encounter additional influences and new challenges, situations not previously experienced, and ancillary implementation questions which could potentially limit program growth and development.*

Introduction

Wildland Fire Use (WFU) is the application of the appropriate management response to naturally ignited wildland fires to accomplish specific resource management objectives in predefined designated areas outlined in Fire Management Plans (USDA/USDI 2005). What is currently wildland fire use has its origins in ground-breaking management decisions and actions in wildernesses, national parks, and other areas managed as de facto wildernesses over three and one-half decades ago. As this program expanded and evolved, planning processes, assessment procedures, and implementation techniques continued to progress. But, to successfully accomplish objectives as a land management practice in support of ecosystem maintenance, restoration, and community protection at the necessary scale, both temporal and spatial increases must be achieved and sustained. Consequently, wildland fire use applications must expand beyond wilderness into other suitable areas and broaden from a wilderness only application to one having potential applications across all land-use situations.

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Managing wildland fire in wilderness has prompted development of specific procedures and processes in response to risks and challenges and has become a proven and widely applied practice to meet ecological needs. Actual accomplishments by all agencies shows the average annual level of achievement from 2001 – 2005 to be about three times higher than the average annual output for the previous five years (figure 1). Managing WFU in non-wilderness, while having been applied since the late 1990's, has not achieved widespread use. However, the 2005 fire season exemplified the expanding nature of this program; the single largest scale application of WFU in non-wilderness in the United States occurred. The advent of WFU expanding into non-wilderness adds a substantial management component and accomplishments can be expected to increase over historic levels. Figure 1 illustrates WFU accomplishments since the implementation of the Federal Fire Policy in 1995 and the 2005 non-wilderness accomplishment.

Continued programmatic expansion of wildland fire use is presenting new challenges, previously unexplored situations, and additional implementation questions which could potentially limit implementation. To support sustained program expansion, these questions need addressed, management efficiency must be improved, potential barriers to success should be eliminated, and all prerequisites to continued implementation must be defined and in place.

Existing Challenges to Wildland Fire Use

Wildland fire use, regardless of the land use situation it is applied in, is affected by a large number of factors that are supportive or potentially limiting to this activity. These factors as experienced from a predominantly wilderness land use situation are shown in table 1.

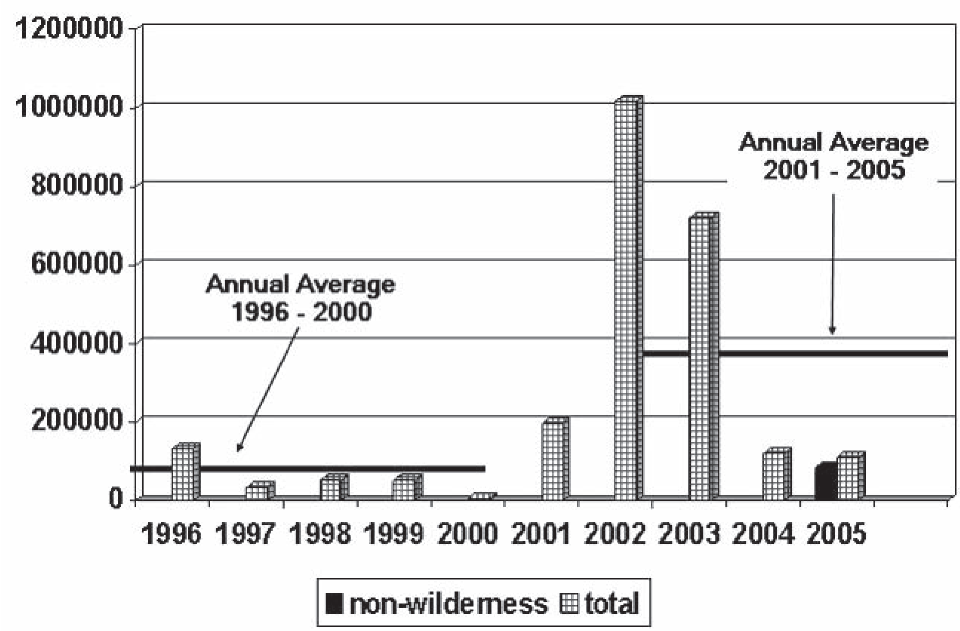

Figure 1—Wildland fire use accomplishments for all agencies, 1995-2005; comparison of annual total and non-wilderness for 2005 (source USFS, NPS data on file at National Interagency Fire Center, Boise, ID and National Fire Plan Annual Performance Reports, 2001- 2004. NOTE: NFP data is tabulated by fiscal year, not calendar year.)

Table 1—Current supportive and potentially limiting factors to wildland fire use (adapted from Zimmerman, in press).

Supportive Factors	Potentially Limiting Factors
▪ To date, the most supportive federal fire policy for using wildland fire as part of the full spectrum of appropriate management responses, ▪ To date, the highest level of advocacy for using wildland fire to accomplish resource benefits, ▪ To date, the highest level of scientific support for and technical capabilities to use fire, o Fire behavior prediction models, o Long-term risk assessment techniques, o Geographic information system capabilities, o Satellite imagery useful in assessing live fuel moisture, smoke production and dispersion, and fire locations, o Improved meteorological analysis and record keeping, o Fire effects prediction models, o Fuel measurements techniques, ▪ To date, the highest level of knowledge of fire effects and the natural role of fire, ▪ Higher levels of public awareness and understanding, ▪ Better definition and clarification in land management planning process in regard to the use of fire.	▪ More dominant temporal limitations in response to changing fuel complexes, ▪ More assertive social demands, needs, and tolerances which strongly sway public opinion, affect management opportunities, and in combination with continually expanding wildland-urban interfaces and associated protection concerns, dramatically affect the ability to apply fire across a wide spatial spectrum, ▪ Significant influence of threatened and endangered species and sensitive natural and cultural resource considerations, protection, and management in fire use decision-making, ▪ Changing fuel complexes and fire spread and intensity rates effects on increasing risk and complexity levels, ▪ Continuing needs for expanded public information, ▪ Smoke management concerns.

Emerging Challenges to Wildland Fire Use

The array of factors exerting influence on wildland fire use in non-wilderness encompasses the full set of factors listed in table 1. However, programmatic expansion into non-wilderness has encountered new situational elements presenting additional difficulty and complexity in wildland fire use management. It is apparent that prerequisite to full implementation in non-wilderness is the acknowledgement of the inseparability and equal importance of ecologic, social, and economic needs and requirements. During the past 35 years, wildland fire use has focused on ecologic needs and requirements as the most important objective. This focus is shifting as implementation moves out of wilderness and specific challenges are emerging during non-wilderness wildland fire use involving social and economic needs, planning considerations, and implementation procedures. Areas where concerns and questions associated with managing wildland fire use in non-wilderness have surfaced are shown in table 2.

Table 2—Emerging challenges supportive to, adding more management considerations, and potentially increasing complexity for wildland fire use, based on the 2005 fire season non-wilderness applications.

Supportive Factors	Concerns and Questions - Planning, Implementation, and General Understanding	Additional Complexity Influences
▪ Communication, education, and community relations opportunities ▪ Private landowner support for using wildland fire by on private lands in conjunction with federal activities, ▪ State agency support for using wildland fire for resource benefits by in cooperation with federal agencies, ▪ Support for State-led efforts to improve forest and watershed health and reduce potential wildfire effects ▪ Expansion of ecosystem restoration and maintenance and hazardous fuel strategy and accomplishments into all land use situations. ▪ Expanded implementation capability and greater accessibility.	▪ Number and kind of mitigation actions needed for successful management of the fire ▪ Size constraints/limitations on WFU in non-wilderness, specifically in regard to minimum size limits or thresholds (size thresholds) and a perceived similarity between non-wilderness wildland fire use management and prescribed fire ▪ Managing fire immediately adjacent to an MMA ▪ Equivalency to non-fire treatments ▪ Internal support for wildland fire use ▪ Communication, education, and community relations opportunities ▪ Cost containment	▪ Inclusion or exclusion of private lands within the MMA and wildland fire use affected areas ▪ Economic concerns – protection of necessary natural resources or establishment of alternatives ▪ Allotment fence protection – protection of necessary social-economic values ▪ Proximity to values – additional hazards ▪ Increased smoke management needs ▪ Fuels and fire behavior of lower elevational zones ▪ Susceptibility of non-wilderness to post-fire proliferation of invasive species

Supportive Factors

Communication, Education, and Community Relations—Perhaps one of the best opportunities to accomplish local communication and outreach is available during implementation of wildland fire use events in non-wilderness. The proximity of these fires to communities and increased public and media awareness due to the fire visibility, while likely adding difficulty to management actions, creates a virtual "classroom" where program and fire benefits can easily be explained and illustrated to increase public understanding and support. Such opportunities should be fully explored and utilized.

Increased Collaboration in the Use of Wildland Fire to Accomplish Beneficial Effects—

- Private Landowner Support for Using Wildland Fire on Private Lands—Much of the public and many but not all, private landowners are recognizing the value of restoring and maintaining fire-adapted ecosystems. This year, as wildland fire use expanded outside wilderness and proximate to private lands, significant interest in support of managing fires and numerous requests to include private lands in management areas were received. This unprecedented level of interest and request for collaborative involvement and management by private landowners illustrates a growing trend toward greater support for the use of wildland fire where feasible. Management agencies are actively responding to this interest in all possible ways and future wildland fire use applications in non-wilderness will be collaborative efforts, with federal, state, and private partners involved.

- State Agency Support for Using Wildland Fire for Resource Benefits—New initiatives aimed at the improvement of ecosystem health are providing an impetus to capitalize on all possible fuel treatment activities, biomass utilization opportunities, increased use of wildland fire, and the restoration of fire-adapted ecosystems throughout western states (State of New Mexico 2004, State of Arizona 2005). As implementation plans are developed, collaborative activities are receiving increasing attention. While some State agencies are limited in their authority to use fire, they recognize the role of fire in restoration and maintenance of forest and watershed health and are providing increasing support to Federal agencies in the use of wildland fire. In situations where authorities permit it, State agencies are becoming actively involved in planning and implementing wildland fire use. Increasing collaborative implementation of wildland fire use is occurring. This type of cooperative involvement includes federal agencies, state agencies, private organizations, and private landowners to some degree and will lessen barriers to implementation, potentially reduce costs, and advance the use of wildland fire for resource benefits.

Additional Support for State-Led Efforts to Improve Forest and Watershed Health and Reduce Potential Wildfire Effects—As State agencies seek to implement forest and watershed health initiatives and programs, they are incorporating all viable strategies. Since wildland fire has been such an important factor influencing the structure and composition of many ecosystems, fire risk reduction in many areas can be achieved by restoration of natural fire and community protection capability can be enhanced by WFU. Wildland fire use is a viable and increasingly important management option, especially as expanding experience demonstrates the mitigating role fire can perform. Expanding application of WFU directly supports state-led efforts and compliments new initiatives and programs.

Expanded Implementation Capability and Greater Accessibility— Managing wildland fire in non-wilderness presents a different capacity for implementation than in wilderness. Specifically, most areas have a well-defined road network and improved access. A wider range of tools and tactics to complete mitigation actions is available and improved access increases the ability to implement mitigation actions. However, fires are often closer to Wildland-Urban Interface (WUI) areas. This spatial situation can affect timing, duration, and kind of mitigation actions that can or must be applied.

Concerns and Questions – Planning, Implementation, and General Understanding

Wildland fire use implementation in non-wilderness will by necessity, frequently, but not always, be implemented on a smaller scale than in wilderness.

This requires closer attention to maximum manageable areas, potentially more in-depth operational planning, and a need for greater mitigation actions to successfully manage the fire within the desired area, respond to other societal concerns, influence fire behavior, and protect sensitive areas. A primary difference between this application and wilderness implementation is, commonly in wilderness, size and time are the primary mitigation measures used to ensure the fire will remain within the desired area and mitigate potential threats.

Number and Kinds of Mitigation Actions—Management of WFU does not have a strict requirement of no on-the-ground action; in fact, smaller area management actions must be commensurate with values to be protected, desired objectives, and are described in detail in Wildland Fire Implementation Plans (WFIP). The number of management actions identified in WFIPs will always be in response to the fire risk (based on values, hazards, and probability) (USDA/USDI 2005). Non-wilderness fires are proving in general, to present a slightly higher risk level. Consequently, more management actions are often necessary in these areas than for comparable size wilderness wildland fire use events.

In addition to the amount of mitigation actions, the kind of actions also can vary. While wilderness fire implementation can have a high focus on monitoring, mapping, and closures with some on-the-ground holding or checking actions, non-wilderness fires frequently require more intense containment actions including wider use of standardized firefighting operations. The scale of burn out operations can vary dramatically and range from small site-specific actions that carry fire along a road, fence line, or property boundary to larger applications of burning through sensitive resource areas or adjacent to private property with ground or even large-scale aerial ignition. These types of focused and more intense management actions, seemingly inconsistent with the original philosophy of restoring fire to wilderness, are not inconsistent with objectives of ecosystem restoration and maintenance in all land use situations. In fact, they may be a necessity on a specific piece of ground and are no more than the specific situational requirements of using wildland fire to accomplish resource benefits.

Size Thresholds and Similarity to Prescribed Fire—Questions have arisen regarding size thresholds of non-wilderness WFU applications; specifically, are more intense efforts to manage long-duration wildland fires justified for smaller areas or would prescribed fire more efficiently accomplish this? Wildland fire use is a viable tool for accomplishing landscape scale ecosystem restoration and maintenance. Prescribed fire has high applicability for site-specific applications conducted on small to mid-scale levels. As scale increases, prescribed fire becomes a longer duration proposition with less specificity in objectives. A key difference between prescribed fire and wildland fire use is the degree of precision necessary to accomplish objectives. For site-specific actions identifying specific measurable objectives, greater precision in application may be required. Small-scale prescribed fire affords the ability to obtain higher precision through more control over area burned, time of burning, direction of spread, rates of spread, intensity and severity, duration of burning, and potential fire effects. But, the larger the scale, the more difficult it becomes to exercise and maintain this level of specificity. Wildland fire use affords more influence over restoration of fire as a natural process but less influence over specific effects. When objectives relate to process restoration across a landscape with differential fire behavior, differential fire effects, and alteration of fuel complexes, stand structure, and stand composition as desired attributes; wildland fire use is an effective tool. In non-wilderness, size thresholds for WFU have limited value; there is no clearly definable lower size limit for WFU application. Wildland fire use in non-wilderness, while at times appearing operationally similar to prescribed fire, is appropriate to restore fire as a natural process and accomplish ecosystem maintenance and restoration objectives across landscapes, and in the majority of situations, will be as effective ecologically and economically. It should be considered/applied in all cases where it can accomplish landscape level effects (could occur in relatively small areas; the majority of all wildland fire use events are small size, short duration, inactive, and ecologically insignificant) and total application size will be influenced primarily by fuel types and continuity, just as wilderness fires are. But, a key difference will be the effect of land-use activities and land ownership patterns on implementation activities.

Managing Fire Adjacent to MMAs—Managing WFU in smaller landscapes creates numerous situations where the fire is immediately adjacent to a MMA. Past experience portrays this scenario as an undesirable situation. Textbook examples of MMAs nearly always show a fire well within an MMA in order to provide potential spread area for the fire and increased opportunities for management action points to mitigate or eliminate threats throughout the life of the fire. The smaller areas encountered in non-wilderness present situations where the fire can be immediately adjacent to the MMA from the onset or management actions burn out fuels between the fire and the MMA causing the fire to be adjacent to the MMA. These situations may be encountered during WFU implementation, will be more frequent in non-wilderness applications than in wilderness situations, and are not inappropriate or undesirable. Having fire against the MMA is only inappropriate when it taxes control capabilities, results from situations not described in the WFIP management actions, and/or is unanticipated. So long as management actions facilitate the accomplishment of objectives, having fire immediately adjacent to the MMA is acceptable.

Equivalency to Non-Fire Treatments—Managing WFU in non-wilderness in smaller areas or within the bounds of established road systems where additional mitigation actions are needed or where the fire is adjacent to the MMA introduces the question of whether objectives can be accomplished easier, quicker, and/or less expensively through the application of non-fire fuel treatments. Again, the precision of the objectives dictates what the most appropriate treatment technique should be. It is very difficult for non-fire treatments to simulate a natural fire and its effects. The timing of natural fire, its ability to present differential fire behavior and its indefinite duration across a range of weather conditions all contribute to the effects of fire. Non-fire treatments are more structured, lack the range of effects, and can be completed in finite timeframes that may be shorter than for a natural fire. In terms of expense, wildland fire use is proving to be less expensive than non-fire treatments, depending upon the final size. The long-term benefits of wildland fire use in terms of hazardous fuel removal, restoration of overall ecosystem health as reflected through changed fire regime condition class levels, restoration of fire as a natural process, and reduction of the threat of future wildfire spreading across landscapes and land ownerships outweigh short-term economic investments.

Internal Support for Wildland Fire Use—Some internal agency and interagency groups are resistant to accept wildland fire use as a legitimate fire management option. The individuals and groups are either "holding on" to old traditions or lack a complete understanding of the Federal Wildland Fire Management Policy. While the concentration of such attitudes vary among agencies and organizations, this current position must mature before WFU can be totally integrated into fire management strategies.

Communication, Education, and Community Relations Opportunities—Objectives of WFU, associated risks, planning procedures, implementation practices, and potential tradeoffs have not always been understood and were sometimes not well accepted. An understanding of the guiding principles and objectives of the WFU program by the public and media is essential for social and political acceptance and endorsement. Currently, this understanding is increasing and may be at an all time high, but there is still a continuing need to establish and maintain a proactive communication and education effort for both the program and individual fire level.

While general public awareness of the role of fire in western ecosystems is increasing, smoke on the horizon will remain unsettling to much of the public, particularly as more fires are managed in proximity to and visible from urban areas adjacent to wildlands. An understanding of the full range of appropriate management responses to wildland fire is needed as opposed to an oversimplified belief that all fires can and should be extinguished, preferably by fire retardant dramatically delivered by large air tankers.

Increasing programmatic accomplishments can provide a basis for improving long-term community relations in regard to the wildland fire use program. Fire restoration in highly visible areas can graphically demonstrate that wildland fire use operational actions are safe, well planned, adequately funded, and effectively executed. Strengthened awareness of the natural role of fire and fire effects, the role and value of ecosystem restoration needs in all land use situations, and removal or reversal of professional and public controversies surrounding fire management perspectives and philosophy can result from successful implementation. Landowners and community leaders may be stimulated to complete Community Wildfire Protection Plans and become much more proactive in hazard fuel reduction.

Cost Management—Cost management has become a significant topic of concern by agency administrators regarding both suppression fires and WFU events. High scrutiny and review of large fire suppression costs seem to be fostering a general feeling that equates low cost as a principle measure of success. Implementing an appropriate management response that is truly the best action for a given set of circumstances will have an associated cost. This cost should always be monitored and managed at an efficient level. But, it must be accepted as the price of implementing the proper action and not be the cause for reactive alteration of strategies and tactics.

Additional Complexity Influences

Inclusion of private lands—In many previous applications of the use of wildland fire to accomplish resource benefits, it was common to protect private lands and, in the process, exclude fire from burning outside federal lands. In 2005, there was considerable interest on the part of private landowners to be included in many wildland fire use applications if possible. Since this is converse to past planning and implementation practices, procedures to include private lands are not clear.

Wildland fire use is part of the full range of appropriate management response actions consistent with the Interagency Strategy for the Implementation of Federal Wildland Fire Management Policy (WFLC 2003). Some States support the implementation of WFU and are prepared to serve as cooperators in the management of the wildland fire including the development of systems and methods for the use of wildland fire on private lands. In addition, several states have developed statewide plans that address forest and watershed health. Other states are currently developing new policy to allow for the orderly proposal and designation of areas where alternative suppression strategies may be employed consistent with values at risk, fire ecology, and historic fire return intervals, and potential fire severity. This policy will provide a process to manage wildland fires under predetermined conditions, criteria, and prescriptions on federal, state, county, and private lands, as appropriate.

Specific authorities allow the Forest Service to enter into agreements with willing State governments and landowners for the protection, restoration, and enhancement of fish and wildlife habitat, and other resources on public or private land that benefit those resources within the watershed. The Wyden Amendment provides for benefits that include improving, maintaining, or protecting ecosystem conditions through collaborative administration and/or implementation of projects; improving collaborative efforts across all ownerships, not just limited solely to adjacent Forest Service lands; and increase operational effectiveness and efficiency through coordination of efforts, services, and products.

Collaboration to explore and utilize all opportunities to maximize ecological restoration activities and cross-jurisdictional, landscape efforts has yielded procedures for wildland fire use implementation adjacent to or potentially impacting private lands. Three scenarios have been developed to date: where State agencies can represent private landowners and collaboratively work with Federal agencies to implement WFU, where State agencies are limited in their capacity to implement WFU and agreements between Federal agencies and private landowners must be developed, and where agreements between Federal agencies and County governments must be developed. These scenarios are:

- State representation of private landowners and collaborative implementation—In some states, the state agency will be a cooperator in the management of the fire, including the development of systems and methods for the use of wildland fire on private lands. The State agency will provide the Federal agency with a Delegation of Authority to the Incident Commander or Fire Use Manager that directs them to manage the fire across private lands under State authority with the appropriate management response that could move across/around/remain outside of private lands.
- Individual Landowner Agreements—In some states, the State Forester may furnish advice to the people of the state on forestry matters and has the authority to prevent and suppress any wildfires on state and private lands located outside incorporated municipalities, and if subject to cooperative agreements, on other lands located in this state or in other states. The State Forester has the responsibility to prevent and suppress wildfires only on lands covered by cooperative agreements. However, no provision exists for the responsibility of wildland fire on private lands to rest with the State Forester. Therefore, he/she cannot re-delegate authority to the Forest Service to include private lands as part of WFU activities. So, procedures for WFU implementation adjacent to

or potentially impacting private lands in these states must either involve excluding private lands from the WFU area or developing individual landowner agreements between the Federal agencies and landowners.

- Pre-existing agreements with County Governments—During the period between 1999 and 2001, the Bureau of Land Management (BLM), in coordination with the USDI Solicitors Office, developed an agreement format to utilize when developing pre-existing agreements allowing for wildland fire use (on file, BLM Colorado State Office). The National Fire Plan emphasized that local and county governments should develop fire management plans for their jurisdictions that may or may not incorporate wildland fire use into their management schemes.

Economic Concerns – Protection of Necessary Natural Resources or Establishment of Alternatives—From an economic standpoint, wildland fires in non-wilderness potentially pose increased economic threats. A notable example is the impact to livestock operators. In some cases, these impacts can be mitigated by movement of livestock to alternative areas, delaying or checking the spread of fire through a specific area, or by maintaining a set of alternate grazing areas (vacant allotments, seasonal exceptions, etc.) that could constitute "grass banks." Whatever the specific action taken is, managers face additional concerns that must be planned for and effectively implemented. If not fully accounted for and addressed, these situations could severely limit wildland fire use applications.

Allotment Fence Protection – Protection of Necessary Social-Economic Values—Using wildland fire to accomplish resource benefits is almost universally accepted as producing only beneficial effects. But in fact, these are wildland fires, burning with differential fire behavior from random points of ignition and across widely ranging and partially mitigated areas. While fires have definite ecological benefits, they can also have some social and economic impacts. Allotment and pasture fences represent an additional concern, if not properly planned for, could limit or restrict wildland fire use applications. Many fences across federal lands are constructed of wood posts and stays. Even low intensity surface fires can remove most or all of these wood materials. There are also fences on private lands that can be impacted. If the allotment or pasture integrity is lost from fire damage, economic impacts to livestock operators can be incurred from movement of livestock or loss of grazing opportunities. Long-term impacts can result from inability to re-construct fences on both public and private lands; there is no avenue currently available to the federal land management agency to assist landowners in repairing or replacing damaged structures on private lands.

Threats to fences must be addressed as a social-economic concern during the planning process and mitigation actions must be developed that protect the fences or allow for movement of livestock to alternative sites. Such mitigation actions would need to be coupled with a strategy for either protection or reconstruction to eliminate longer-term impacts.

Proximity to Values – Additional Hazard—Many wildland fires in non-wilderness will be situated in closer proximity to private lands and even to communities and developed areas. Decreased distance from values to be protected can result in higher probabilities of rare fire spread events, greater spread potential depending on fuel types, and a likelihood of more area covered by finer fuel types. Overall, non-wilderness land use situations will present a higher hazard and correspondingly, increasing risk.

Proximity to Values – Increased Need for Communication, Education, and Community Relations—While an aggressive and efficient communication and education effort for wildland fire use programs and for each wildland fire that is managed is important, it is imperative for this to occur when fires are closer to developed areas or are visible daily. Without this, inaccurate perceptions, assumptions, or beliefs could strongly sway public opinion, affect management opportunities, and have fast-acting impacts on our ability to use fire across diverse landscapes.

Increased Smoke Management Need—Having fires closer to urban areas increases concerns over smoke management. Since WFU events may be of longer durations, smoke production will ebb and flow according to weather and fire behavior and present an increased element of complexity. Some weather combinations will result in undesirable smoke conditions. Additional planning will be required to ensure fires can be managed while meeting air quality and smoke management needs.

Fuels and Fire Behavior of Lower Elevation Zones—Public lands are managed with significant industrial, commercial, agricultural and recreational use on-going almost on a year-round basis. Fuel types typically found on lower elevation areas tend to support fire behavior characterized by rapid spread rates and high intensity. Using wildland fires to accomplish resource benefits in such areas can be difficult and require a much more aggressive timetable to complete planning requirements as well as constant awareness and attentiveness to the escalating fire situation in order to maintain the ability to implement timely mitigation actions. Various levels of pre-planning can help but generally, all planning and implementation activities after ignition occurs must take place in a more accelerated timeframe than in areas supporting less flammable fuel types.

Susceptibility of Non-Wilderness to Post-Fire Proliferation of Invasive Species—A concern in much of the arid western United States is the invasion of burned areas by non-native and noxious species. Though managed fire is beneficial in the long term, short-term protection against invasive species until native plants are established may be needed. If invasive species invade an area, fire hazard can become considerably more severe. There are no simple methods available to mitigate the potential for invasive species entering a burned area once the fire has passed. Current policies do not permit the use of emergency stabilization funds on WFU events. This has created the need for fire and land managers to pursue a variety of means to implement short-term mitigation actions that reduce or minimize the risk of invasive species spread and intensification and soil erosion on burned areas. In some instances, a lack of mitigation options has caused agency administrators to choose a suppression strategy so that emergency rehabilitation and stabilization funds can be accessed.

Summary

The long history of fire suppression and protection of natural resources has fostered definitive and well-established attitudes regarding “good” and “bad” aspects of wildland fire. As wildland fire became increasingly important to accomplish beneficial effects, general understanding and acceptance did not keep pace. A "let burn" perspective that evolved over the years pervaded the general thinking about fire management. Confusion associated with seemingly conflicting objectives of fire suppression and fire management resulted and general program endorsement suffered. Appreciation and understanding of the natural role of fire and fire effects are now reaching an all time high and attitudes are changing accordingly, although slowly.

Wildland fire use has proven to be an effective management practice in wilderness and is now expanding into non-wilderness situations with highly successful results. The use of wildland fire in non-wilderness must be applied under certain circumstances and within specific bounds. Even though success has been achieved, this practice is not suitable in all non-wilderness situations, and may not even be feasible in others. As this program expands across multiple ownerships and land use situations, new challenges, higher complexity, and needs to address additional management concerns, on-the-ground mitigation actions, and public concerns are surfacing. Specific challenges facing managers in these areas include: private lands, protection of economic concerns, values to be protected and their proximity, increased smoke management concerns, and numerous planning, implementation, and interpretation questions.

Expansion of wildland fire use outside wilderness has the potential to increase vegetation mosaics, decrease long-term wildfire potential, and increase community protection capability. Expanding wildland fire use beyond wilderness and across all land-use situations will broaden fire management accomplishments, strengthen ecosystem maintenance and restoration and community protection strategies, and advance land management practices. But, successful management must be predicated upon continued and proactive collaboration among federal and state agencies, private organizations, and private landowners.

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U.S. Policy Response to the Fuels Management Problem: An Analysis of the Public Debate About the Healthy Forests Initiative and the Healthy Forests Restoration Act

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Abstract—*The Healthy Forests Initiative (HFI) and Healthy Forests Restoration Act (HFRA) represent major policy and legislative responses to the fuels management problem in the United States. This study examined the nature and evolution of the public discussion and debate about these policy responses. Computer content analysis was used to analyze favorable and unfavorable beliefs about HFI / HFRA expressed in about 2,800 news stories published from August 1, 2002 through December 31, 2004. The most frequently mentioned favorable beliefs that emerged included the view that HFI / HFRA will (1) reduce the risk of catastrophic wildfire, (2) protect people, communities, and property, and (3) cut red tape and speed up decision making processes. The most commonly expressed unfavorable beliefs included the view that HFI / HFRA (1) is an excuse to increase logging, (2) will weaken environmental protections, and (3) will reduce public input. Some evidence was found of a growing consensus on the problem of fuel buildup and the need to reduce the risk of wildfire. But mistrust was found to be an ongoing issue as the HFRA is implemented. Building public trust will be a key to continuing to gain support.*

Introduction

The Healthy Forests Initiative (HFI) and Healthy Forests Restoration Act (HFRA) represent major policy and legislative responses to the fuels management problem in the United States. This study examined the nature and evolution of the public discussion and debate about these policy responses, as expressed in the news media.

Research by communications and public opinion researchers has found that the news media both shape and reflect public attitudes and beliefs about a wide range of social issues (Burgess 1990; Fan 1988; McCombs 2004). For example, Elliott and others (1995) found a significant impact of changes in media coverage on the level of public support for environmental protection. The news media also strongly influence agenda-setting for public policy issues (Dearing and others 1996; McCombs 2004). In other words, there is a relationship between the relative emphasis given by the media to issues and the degree of salience these topics have for the general public. Therefore, analysis of the public debate about social issues contained in the news media is not mere “media analysis,” it is a window into the broader social debate and a means to gauge, indirectly, public attitudes.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Part of the explanation for the influence of the news media on public attitudes is the importance of the media as the primary information source for public policy issues, including forestry and other environmental issues. For example, a survey in Oregon found that "The most important sources of information about forestry issues tend to be newspaper and television, followed by radio, other printed materials, friends and relatives, and interest groups. Only 16 percent overall considered natural resource agencies to be important sources" (Shindler and others, 1996: 7).

The news media have also been found to be important information sources with respect to wildfire. In a study of public support for fuel reduction strategies in forest-based communities, Shindler and Toman (2003) asked respondents to rate the usefulness of information sources. Newspapers and magazines were rated as most useful, and the percent of respondents who rated the USDA Forest Service as a useful source dropped from 60 percent in 1996 to 48 percent in 2000.

Given the strong influence of the news media on public attitudes and the importance of the news media as an information source about wildfire, fire managers and policy makers need a better understanding of the way in which fire and fire policy is discussed in the media. Lichtman (1998: 4) argued that building support for fire policy will require paying close attention to the ways in which fire is portrayed in the public discourse. This paper contributes to this understanding by analyzing the news media discussion of the Healthy Forests Initiative (White House 2002) and the Healthy Forests Restoration Act of 2003. The following section describes the data and methodology used in this study, followed by a discussion of the main findings. A final section discusses the conclusions and implications for wildfire policy in the United States.

Methodology and Data

This analysis involved five main steps: (1) identifying news media stories dealing with HFI / HFRA and downloading them from an on-line commercial database, (2) "filtering" the text to eliminate irrelevant news stories, (3) identifying favorable and unfavorable beliefs about HFI / HFRA contained in the stories, (4) developing computer instructions to score the paragraphs for the identified beliefs, and (5) assessing the accuracy of the analysis. These steps are briefly described in the following paragraphs.

Data for this study consisted of the text of articles from over 200 U.S. news media sources downloaded from the LexisNexis® online database. A Boolean search term was developed to identify articles about HFI / HFRA. The time frame for the analysis covered August 1, 2002 (the month in which the Healthy Forests Initiative was first proposed) through December 31, 2004. The downloaded text was then "filtered" using the InfoTrend™ method (described briefly below) to remove news stories that were not about the HFI or HFRA.

Favorable and unfavorable beliefs about HFI / HFRA were identified by reviewing a random sample of news stories. Eight main favorable beliefs and seven unfavorable beliefs were identified. The specific favorable and unfavorable beliefs are discussed in the following section.

Scoring the text for expressions of the favorable and unfavorable beliefs was done using the InfoTrend computer content analysis method and software. An algorithm was developed to score the text, that is, to count the number of expressions of each of the beliefs. Briefly, this involves development of a *dictionary* (composed of a list of ideas related to the favorable and unfavorable beliefs, and groups of words and phrases associated with each idea) and a series of *idea transition rules* (computer instructions specifying how pairs of ideas in the dictionary are combined to give new meanings).

For example, one favorable belief that was expressed in the news stories and scored in this analysis is that HFI and HFRA will reduce the risk of wildfire. For this belief, a set of dictionary terms such as "avert," "control," "curb," "eliminate," "decrease," "risk of," etc., was developed and used to identify expressions of the concept of *reduce risk*. Another set of terms such as "blaze," "burn," "fire," etc., was used to identify expressions of the concept *wildfire*. An *idea transition rule* was then developed specifying that when a "reduce risk" term and a "wildfire" term are in close proximity of each other within a paragraph that mentions HFI or HFRA, then one expression of the belief that HFI / HFRA will reduce wildfire risk is counted. For example, the statement "With 190 million acres at high *risk of* catastrophic *fire* across the country, this is the kind of partnership we need if we are going to conserve forests…" (Norton 2003: B7) connects the ideas "wildfire" and "reduce risk" in the context of a paragraph discussing HFI / HFRA, and was counted as one expression of the belief that HFI / HFRA will reduce the risk of wildfire.

To identify expressions of the belief that HFI or HFRA do *not* reduce the risk of fire, the same process was used but with the addition of a set of *negation* terms (for example, "not," "won't," "can't," "fail") in close proximity to a statement that HFI or HFRA reduces wildfire risk via another idea transition rule.

Finally, an assessment of the accuracy of the scoring was done by reviewing a random sample of paragraphs to check the accuracy of computer-coded results. After final refinements in the dictionary and idea transition rules, accuracy rates for the scoring of beliefs about HFI / HFRA were all in excess of 80 percent, which is used as an acceptable accuracy level in content analysis (Krippendorff 1980).

Findings and Discussion

We found approximately 2,800 news stories about HFI / HFRA for the analysis time period August 1, 2002 through December 31, 2004. To put the number of stories in perspective, for the same time period and for the same news sources, there were more than 45,000 stories about wildfire, so news media discussion of HFI / HFRA was only about 5 percent of the volume of all wildfire discussion. The most commonly expressed favorable beliefs that we found about HFI / HFRA, in order of prevalence, included the beliefs that HFI / HFRA: (1) will reduce the buildup of fuels in forests and reduce the risk of catastrophic wildfire, (2) will cut red tape, streamline bureaucracy, and speed up decision making processes, (3) will protect people, communities and property, (4) will restore "forest health," (5) will help deal with insect infestation and disease, (6) will create economic benefits, such as job creation and sustaining the local economy in forest-based communities, and (7) involves a collaborative approach with community involvement and partnerships.

In addition to these seven specific favorable beliefs about HFI / HFRA, we found many non-specific favorable expressions, such as the belief that HFI was "a step in the right direction" or HFRA was a "common sense" approach.

A "general favorable" category was created to count all of these non-specific expressions of support for HFI / HFRA. There were also a number of infrequently expressed favorable beliefs, such as the view that HFI / HFRA will help protect wildlife and wildlife habitat, or that it will pay for itself. These beliefs were not tracked in this analysis because they were rarely expressed.

Figure 1 shows the share of each favorable belief as a percent of all expressions of favorable beliefs about HFI / HFRA in our database. The most frequently expressed favorable belief was "reduces fire risk," the view that HFI / HFRA will reduce fuel buildup and reduce the risk of catastrophic wildfire. This belief accounted for 38 percent of all expressions of favorable beliefs. An example of an expression of this belief scored by our computer content analysis instructions is: "If signed, the bill will give foresters the funds and tools they need to prevent catastrophic wildfires from threatening homes and watersheds, supporters say," (deYoanna 2003: B1). This text was also scored as an expression of the belief that HFI / HFRA will "protect people, communities, and property."

"General favorable" expressions about HFI / HFRA was the second most frequently expressed favorable belief, accounting for 26 percent of all favorable beliefs. "Cuts red tape" was the third most frequently expressed, followed by "protects people, communities and property," and "restores health." The other three favorable beliefs were not often expressed and were not a significant part of the public discussion.

The most commonly expressed unfavorable beliefs that emerged in the news media debate included the beliefs that HFI / HFRA will: (1) be an excuse to increase logging and is really a subsidy to the timber industry, often referred to in the news media discussion as "stealth logging," (2) reduce or weaken important, long-standing environmental protections, (3) reduce public input and threaten citizens' rights to be involved in decision-making on U.S. National Forests, (4) fail to reduce the risk of catastrophic wildfire, (5) fail to protect people, communities, and property, and (6) fail to restore forest health.

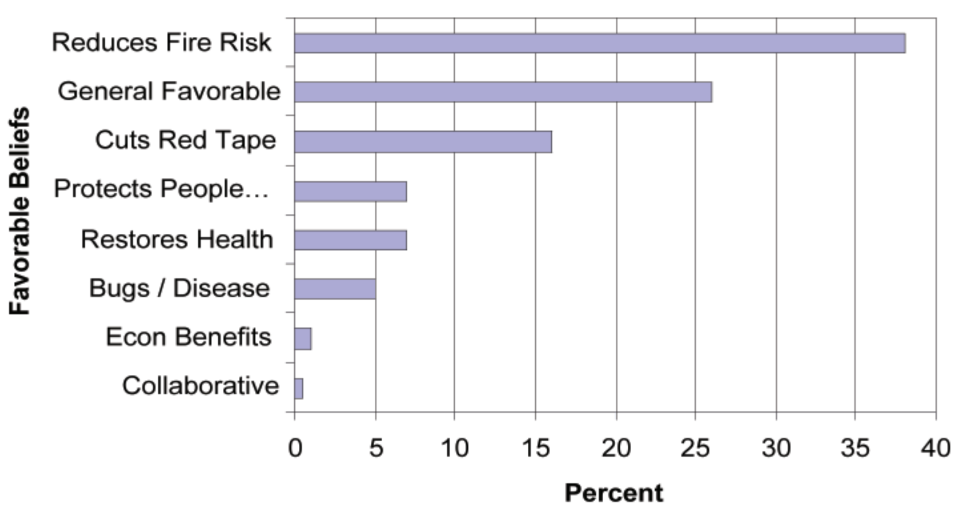

Figure 1—Share of favorable beliefs about the Healthy Forests Initiative and Healthy Forests Restoration Act, August, 2002 through December, 2004.

There were also many general, non-specific unfavorable expressions related to HFI / HFRA. These included unfavorable characterizations of HFI / HFRA such as "deceptive," "double-speak," "smoke and mirrors," and so on. In addition, there were also a number of infrequently expressed unfavorable beliefs, such as the view that HFI / HFRA will be too costly, will result in more roads in National Forests, or will harm wildlife habitat due to increased logging. These infrequently expressed unfavorable beliefs were not tracked in this analysis.

Figure 2 shows the share of each unfavorable belief as a percent of all expressions of unfavorable beliefs. The most frequently expressed unfavorable belief was "stealth logging," the view that HFI / HFRA is primarily about logging and subsidizing the timber industry. This belief accounted for 32 percent of all expressions of unfavorable beliefs. An example of an expression of this belief is: "The "Healthy Forests Restoration Act" passed by the U.S. House this week has nothing to do with healthy forests and everything to do with a return to environmentally reckless, taxpayer-subsidized timber cutting," (The Columbian 2003: C8).

"General unfavorable" expressions also accounted for 32 percent of all unfavorable beliefs (fig. 2). "Reduces environmental protection" was the third most frequently expressed unfavorable belief, followed by the belief that HFI / HFRA "limits input." The other three unfavorable beliefs were not often expressed and were not a significant part of the public discussion as reflected in the news media.

Figure 3 shows an aggregation of all favorable and all unfavorable beliefs about HFI / HFRA expressed in the news media over time. Peaks in the volume of discussion are associated with major events. The biggest spike in discussion occurred in August, 2003 and coincided with President Bush using wildfires in the western U.S. as a backdrop for promoting the Healthy Forests Initiative. Other spikes in coverage are associated with the introduction of HFI by President Bush in August, 2002, the passage of HFRA by the U.S. House of Representatives in May, 2003, Senate passage of HFRA in October, 2003, and the signing of HFRA by President Bush in December, 2003. Since that time, there has been a dramatic drop in the volume of news media discussion of HFI / HFRA.

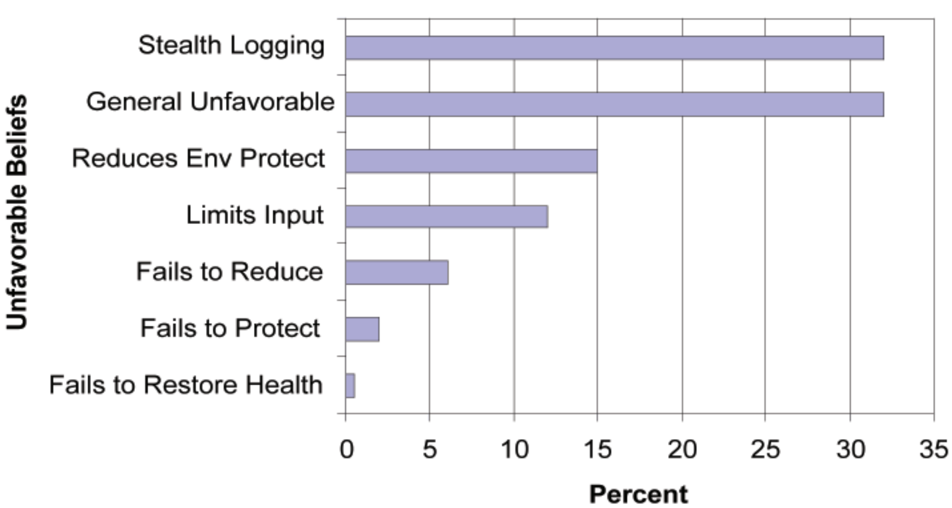

Figure 2—Share of unfavorable beliefs about the Healthy Forests Initiative and Healthy Forests Restoration Act, August, 2002 through December, 2004.

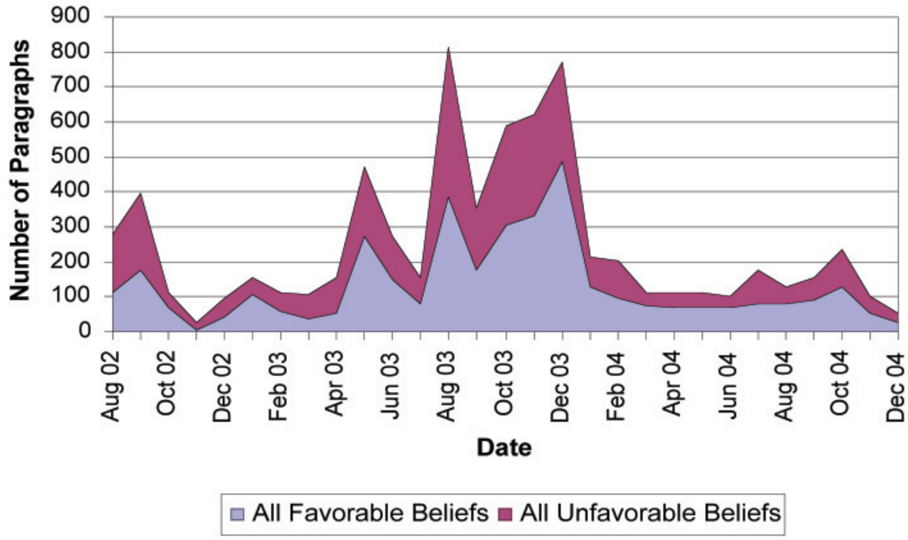

Figure 3—All favorable and all unfavorable beliefs about the Healthy Forests Initiative and Healthy Forests Restoration Act, August, 2002 through December, 2004.

We also found evidence in our database of HFI / HFRA news stories of a growing consensus about the fuel buildup problem and the need to deal with it. Although we did not develop computer instructions to explicitly identify expressions of this idea, this growing consensus was evident in the news stories we analyzed. For example:

"There's strong consensus that the forests, particularly the federal forests, are in fuel conditions that are unnatural because of fire suppression and past management choices. There's probably strong consensus on what can be done" (Cruz 2002: B1).

"We have serious reservations about some details of the President's Healthy Forests Plan. But we have no lingering doubts about the need for Congress to approve fire legislation" (Oregonian 2003: B1)

"It doesn't matter your race, religion or political beliefs—you have to make sure you don't have a forest fire in your backyard" (Ratt 2004).

Other researchers have argued that there is a growing consensus among many stakeholders that fuel buildup and the risk of catastrophic wildfire is of great concern, especially in the wildland urban interface (Vaughn and Cortner 2005).

Concluding Comments

This study examined the national debate about the Healthy Forests Initiative and Healthy Forests Restoration Act as reflected in the news media. A primary conclusion is that the Bush administration has been successful in connecting the Healthy Forests Initiative and the Healthy Forests Restoration Act with the need to reduce the risk of catastrophic wildfire and excess fuel buildup. The most frequently expressed belief in the news media discussion and debate, either favorable or unfavorable, was that HFI / HFRA will reduce the risk of wildfire. Reducing wildfire risk has been the main selling point of HFI / HFRA and it has resonated loudly in the public discourse.

It is notable given the term "healthy forests" in the titles of the HFI and the HFRA that there was very little discussion of the favorable belief "restores health" in the news media discussion. Even if the "bugs and disease" category were combined with "restores health" in a broader forest health category, this would still only rank fourth in frequency of expression among the favorable beliefs.

The most frequently expressed unfavorable belief, "stealth logging," indicates a strong lack of trust in the legislation, the Administration's motives, and in the Forest Service's implementation of HFRA. In addition, the terms used to identify "general unfavorable" expressions about HFI / HFRA also conveyed deep distrust. Examples of these terms include "cynically named," "deceptive," "dishonest," double-speak," "duplicitous," "insidious," "misleading," "Orwellian," "pernicious," "smoke and mirrors," "untruthful," and so on. Others have noted the vital role of building and maintaining trust in fuels management (Winter and others, 2004). Building trust will be a key concern for the Forest Service as it implements HFRA. The public and other stakeholders will be watching closely to see how the Healthy Forests Restoration Act is implemented.

Acknowledgment

Funding was provided as part of a North Central Research Station National Fire Plan research project coordinated by Sarah McCaffrey. The authors thank Cindy Chojnacky of the USDA Forest Service Policy Analysis Staff in Washington, D.C. for guidance and input during the early stages of this research, and they thank Sarah McCaffrey and Bernie Lewis for helpful comments on an earlier version of this paper.

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Influences on USFS District Rangers' Decision to Authorize Wildland Fire Use

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***Abstract**—United States wildland fire policy and program reviews in 1995 and 2000 required reduction of hazardous fuel and recognition of fire as a natural process. Although an existing policy, Wildland Fire Use (WFU), permitted managing natural ignitions to meet resource benefits, most fuel reduction is still achieved through mechanical treatments and prescribed burning. However resource constraints suggest that successful fuel and ecosystem management hinges on expanding WFU. The decision to authorize WFU in the U.S. Forest Service rests with line officers, and the 'go/no go' decision constitutes a time-critical risk assessment. Factors influencing this decision clearly impact the viability of WFU.*

This study examined influences on line officers' go/no go decision. A telephone survey was conducted of all U.S. Forest Service district rangers with WFU authority in the Northern, Intermountain, and Southwestern Regions. The census was completed during February 2005 and obtained an 85 percent response rate. Data were analyzed using classification and regression tree (CART) analysis.

Personal commitment to WFU provided the primary classifier for 91 percent of the district rangers who authorized WFU. External factors, negative public perception, resource availability, and a perceived lack of support from the Agency were the main disincentives to authorizing WFU.

Introduction

Fuel buildup resulting from a century of fire exclusion has left millions of acres prone to higher severity wildland fires than those that historically visited the landscape. Active fire seasons in 1994 and 2000 drew attention to this unanticipated consequence of fire suppression. As a result, national fire policy has shifted towards hazardous fuel reduction and recognition of fire as an essential ecological process. In an attempt to reduce the immediate likelihood of 'catastrophic' wildfire while providing performance measures, agency direction has focused on mechanical treatments and prescribed burning.

Despite this effort to address fuel accumulation, fuels still accumulate at two to three times the current treatment rate (USDA-FS 2004). The most accessible, and therefore least expensive, treatments may already have been done (Calkin, personal communication 2005; GAO 2005), and in the current climate of budget rescissions, it seems doubtful that all the acres that need treatment to remedy 100 years of fuel buildup will receive it. Furthermore, treatments focus mostly on the 0-to-35 year return interval fire regimes, and one-time treatments will not resolve the problem of fuel accumulation. These areas will need maintenance treatments on regular intervals to truly resolve the forest structure problems resulting from fire exclusion (Black 2004).

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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While mechanical treatments and piecemeal prescribed-burns do alter the forest structure responsible for the higher severity fire events, they do not remedy the underlying problem of almost systematic fire exclusion. In contrast to these two treatments, wildland fire use (WFU) provides another option to the suppression policy.

Wildland fire use is the fire management strategy that allows natural ignitions to burn in predetermined locations under scripted conditions. This strategy allows fire to assume its role as a vital ecosystem process, as encouraged by changes to national fire policy since 1995. This new direction, in conjunction with the ability of WFU to restore both structure and process, suggests that WFU should assume a more prominent role as a fuel management tool. However, in 2004 U.S. land management agencies managed a mere 2.7 percent of all lightning ignitions as WFU (NICC 2005).

Policy Framework

The decision to allow WFU (called 'go/no go') can only come after meeting three planning requirements (NWCG 1995a). The Land/Resource Management Plan (L/RMP) provides general direction for the wildland fire management direction. In the USFS, the L/RMP corresponds to the Forest Plans that must go through a public comment period (36 CFR 219). Fire Management Plans (FMP) tier to this document. These plans identify the fire management strategies available for every burnable acre. For areas determined as eligible for wildland fire use by the FMP, managers must create guidelines that specify the burning conditions acceptable for wildland fire use (NWCG 2003).

Finally, the Wildland Fire Implementation Plan Stage 1 (WFIP1) must be done to further scrutinize any ignition that meets the criteria outlined in the FMP. This time-critical process, with an 8-hour deadline[1], first evaluates the candidate fire's physical elements against the prescriptions established in the FMP and in the WFU guidebook. Criteria considered in this step include: threat to life, property, or public and firefighter safety that cannot be mitigated; potential effects on cultural and natural resources outside the range of desired effects; relative risk indicators and/or risk assessment results unacceptable to the appropriate agency administrator; other proximate fire activity that limits or precludes successful management of the fire; other agency administrator issues that preclude wildland fire use. Existence of any one criterion results in the decision to suppress. Foremost, public and firefighter safety take precedence over any other concern (USDA-FS 2000), and only trained and qualified personnel may implement a WFU project (USDA-FS 2000). Beyond this stipulation, only natural ignitions may be managed for resource benefits (NWCG 2005). In addition, each wildland fire may have only one objective, and suppression overrides resource benefit in case two fires merge (NWCG 2005).

The decision to authorize WFU ultimately rests with agency administrators (NWCG 2005). The need for managerial accountability has created a decision process that places all of the authority (and consequent liability) on these administrators. Specifically in the U.S. Forest Service (USFS), District

[1] Until January of 2005, including the fire season preceding this study, agency administrators operated under a 2-hour time constraint.

Rangers are the administrators, or line officers, most frequently presented with the 'go/no go' decision on whether to allow WFU.

All federal land management agencies must follow national policy direction that mandates allowing fire to function in its natural role (NWCG 1995*a*). Assessing the feasibility of this policy and facilitating WFU implementation demands understanding the drivers of the so-called 'go/no go' decision.

Drivers of the Go/No Go Decision

Several authors have touched on factors potentially affecting the decision to authorize wildland fire use. The considerations either discourage or bolster a 'go' decision.

The principal factors acting against authorizing WFU include risk, liability, lack of public support, air quality, and inadequate staffing. Most frequently, authors cited the risk of a WFU event escaping as a barrier to authorizing WFU (Arno and Brown 1991; Daniels 1991). This risk assumes greater importance when calculated with potential damage to private property, natural resources, and professional consequences (Czech 1996; Miller and Landres 2004; Arno and Fiedler 2005). Negligence could indicate liability for ensuing damages (White 1991), further raising the stakes. In the case of employee injury, decision-makers could be held liable without evidence of negligence (Stanton 1995).

Lack of public support (Daniels 1991), coupled with the documented need for public buy-in for successful fire and fuels management (Cortner and others 1990; Shindler and Toman 2003; Weible and others 2005) could also factor into the agency administrator's decision. Further, air quality concerns from both regulatory and public opinion perspectives could also (NWCG 1995b; Cleaves and others 2000).

Staffing concerns affect the decision to authorize WFU in two ways. The managerial endurance required to commit to managing a WFU event for an extended and indeterminate period enters into the go/no go decision (Bonney 1998; Daniels 1991; Tomascak 1991). Sufficient availability of highly qualified personnel also weighs heavily in the decision to use WFU (Cortner and others 1990; Daniels 1991; Cleaves and others 2000; Miller and Landres 2004).

While these authors predominantly suggest factors that tip the decision towards "no go," others indicate influences in favor of authorizing WFU. Anecdotal evidence of cost savings through wildland fire use suggests this as a possible motivator (Daniels 1991; Czech 1996; Bonney 1998; Calkin and others forthcoming). In addition to reducing costs, the desire to minimize firefighter exposure to the dangers of wildland fires could also influence the go/no go decision (Bonney 1998). Finally, a dedication to stewardship that dictates a commitment to restoring fire could inspire a 'go' decision (Pyne 1995; Miller and Landres 2004; Arno and Fiedler 2005).

Although the agency administrator ultimately makes the decision to authorize wildland fire use, no study has sought their input as to the relative importance, if any, of the elements found in the literature. Understanding the drivers of the 'go' decision requires identifying the factors affecting the people who must assume authority for the consequences.

This study aims to determine the factors influencing the line officers' go/no go decision.

Methods

The question addressed in this study narrowed the potential population to those agency administrators able to authorize wildland fire use in their areas. As an agency with a mandate to manage for multiple-use, the USFS presented an ideal candidate for examining the complex decision-making behind wildland fire use. Meteorological and ethical factors indicated that USFS district rangers with wildland fire use authority on their districts in USFS Regions 1, 3, and 4 provided an appropriate population to investigate. These regions represent a swath through the Intermountain west, and include forests with WFU authority in Montana, Idaho, Nevada, Wyoming, Utah, Arizona, and New Mexico. This study did not include district rangers in USFS Regions 2 and 6 because too few rangers in these regions have WFU authority on their districts to guarantee confidentiality in their responses.

The USFS employee directory, available on the internet, provided names, email addresses, and phone numbers of district rangers. Unpublished data, provided by the USFS Rocky Mountain Research Station Aldo Leopold Wilderness Research Institute, identified forests with WFU approved in their forest plans.

This identification process led to a potential population of 81 district rangers with WFU authority both in and out of designated wilderness across Regions 1, 3, and 4. Twenty-nine rangers with WFU authority work in Region 1, 27 in Region 3, and 25 in Region 4. Given the small population size, this study conducted a census rather than a sample of the identified district rangers.

This study relied on a telephone questionnaire due to the associated improvements in response rate and efficiency over a mailed one (Dillman 1978; Groves and others 2004). Questionnaire construction followed widely accepted guidelines (Sudman and Bradburn 1982; Groves and others 2004).

Previously-identified, potential drivers of the go/no go decision provided guidance in developing appropriate questions to include in the survey instrument. A subset of line officers, not included in the population, verified the survey instrument's content, organization, and clarity. Question formulation for followed guidelines outlined by Groves and others (2004). The questionnaire included 50 multiple-choice questions, and six open-ended ones. Respondents were invited to expand on their answers, although these discussions did not contribute to statistical analysis.

The questions included in the final questionnaire covered eight subject groups: respondent eligibility, external factors (including resource availability), past experience with fire, concern for public perception, confidence in staff, perception of internal support, perception of agency protocol, and demographics. The data reduction conducted to facilitate analysis reflected these question groups.

I conducted the telephone interviews between February 9, 2005 and March 21, 2005.

Classification and regression tree analysis (CART) offered the most appropriate analysis tool for this data set. The go/no go decision amounts to a detailed risk assessment that weighs potential costs against potential resource benefits. The Decision Criteria Checklist in the WFIP Stage 1, described previously, specifies five tiers to this process. If, at any of these levels, cost exceeds benefit then the decision tips to 'no go' and the risk assessment stops. Other factors entering into the go/no go decision that this study explored could follow a similar tiered pattern. CART provides a 'road map' to navigate such a hierarchical decision process. The classification marks each intersection and determines whether a case progresses towards 'go' or if the risk assessment halts.

The model used a binary target variable, WFU. The binary variable resulted from collapsing the number of lightning strikes in the WFU-approved area managed as WFU in the last three seasons. A score of 0 was attributed to answers of 'none' or 'few.' 'About half,' 'most' or 'all' were attributed a score of 1. Model runs used Salford Systems CART 5.0 software (Steinberg and Colla 1997) and kept the default settings of the Gini splitting criterion, 10-fold cross-validation, minimum parent node N=10, and minimum child node N=1. The best tree was selected based on minimum probability of misclassification estimated through cross-validation. Cross-validation (test) prediction success provides the most accurate estimate of model performance (Steinberg and Colla 1997).

The model used a reduced group of factors to classify the district rangers as having authorized WFU on their unit. These factors reflect the question groups explored in the questionnaire. These independent variables include confidence in staff, external factors, experience with fire, agency support, protocol, perceived program value, staffing level and concern for public perception. For all variables, larger scores indicate higher levels of the variable in question.

Results

Contact with 22 district rangers revealed that they did not have WFU authority on their districts and reduced the actual population to 59. The American Association of Public Opinion Research (AAPOR 2004) defines six methods of obtaining response rate, ranging from conservative to expansive. Using the most conservative computation yields a response rate of 84.75 percent. Twenty-one (of 25) district rangers from Region 1, 12 (of 16) from Region 3, and 17 (of 18) from Region 4 participated.

As a census with an 84.75 percent response rate, errors of non-observation cause minimal concern. Conducting a census eliminates concerns of sampling errors. Although not eradicated, errors associated with coverage and non-response were minimized.

Of nine non-respondents, four corresponded to either vacant positions or positions that had been filled since the 2004 fire season. The remaining five non-respondents face contexts (terrain, weather, fuel, and political) similar to their neighbors who participated. This similarity in geographical and political situations suggests that their responses would resemble their neighbors' and would therefore not alter the study's results.

A combination of residual instrument errors and respondent errors may have contributed the most significant source of error in the data collected. Several of the questions either reflected areas of Agency direction or inquired after professional motivations. Despite confidentiality guarantees, the respondents could have opted to 'toe the Agency line' and not provide completely candid answers.

Analysis

Model 1 from the CART analysis used eight variables to classify the dependent variable. This classification resulted in a tree with five decision nodes and six terminal nodes (Figure 1). Program value, concern for public perception, staff trust, external factors, and agency support successfully identified 63.6% of respondents who authorized wildland fire use. Table 1, below, summarizes Model 1 performance.

Figure 1, on the following page, depicts Model 1. Each intersection, or node, provides a make-or-break rule for whether or not the respondent will continue down the tree. Respondents whose answers meet the splitting rule move down the path to the left. The tree shunts respondents who fail the splitting rule to the right.

The first intersection, at program value (PROGVAL <= 3.8), diverts 11 respondents and classifies them as not authorizing WFU (terminal node 1). This indicates that program value is the most important factor, and progression to the next decision rules hinges on the score for this variable.

Respondents who make it through the intersection at program value move to the next one, at concern for public perception (PUBPERC <=−0.2). Here, though counter-intuitive, respondents who reported less concern for public support are classified as not authorizing WFU (terminal node 6). Survey participants who reported higher concern for public support (lower negative score) continue to the next intersection, which occurs at staff trust.

This more intuitive split (STFTRST<= 2.4) indicates that staff trust plays the next most important role in determining whether or not respondents have authorized WFU. Respondents who reported a level of confidence in their staff below 2.4 are classified as not authorizing WFU (terminal node 2) and do not continue down the tree.

The next criterion involves external factors. Respondents who scored at the upper end of external considerations (EXT>6.5) do not authorize WFU (terminal node 5). Those who meet the splitting rule of EXT <= 6.5 move on to the final intersection, at agency support.

This final tier separates those respondents who perceive that the Agency facilitates the decision to use WFU. Again counter-intuitively, respondents who scored above the threshold value of 2.5 did not authorize WFU (terminal node 4). Conversely, respondents who met the decision rule AGSPRT<=2.5 did authorize WFU (terminal node 3).

Ninety-one percent (20 of 22) of respondents who authorized WFU follow the tree all the way through to the final intersection at agency support.

Table 1—Model 1 test prediction success.

	Actual Class	Total Cases	Percent Correct	Predicted Class 0 N=19	Predicted Class 1 N=27
Test	0	28	67.9	19	9
data	1	22	63.6	8	14

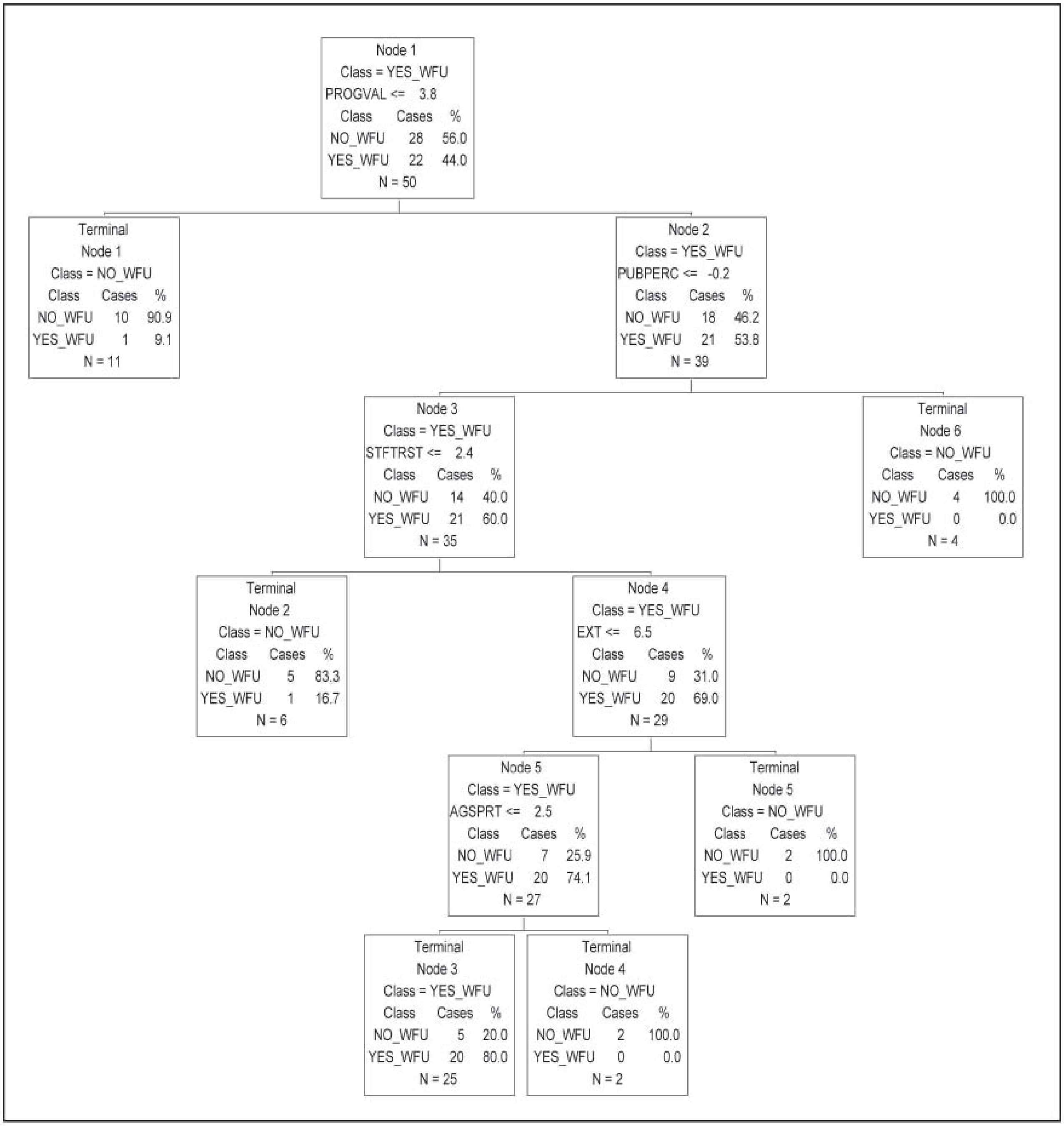

Figure 1—CART Model 1.

Discussion

Interpretation of CART-analysis results indicates that the go/no go decision rests on personal commitment to returning fire to the landscape. This overarching theme helps explain the somewhat counter-intuitive modeling results. The decision structure presented by Model 1 highlights potential deterrents to WFU, and responses to individual survey questions expand on them.

"You are acting outside the scope of your employment if you do not do what is best for the land"

The CART model suggests that the value placed on the WFU program provides the most important determinant of whether a respondent authorized wildland fire use.

From Model 1 emerges a group of decision-makers that stands behind returning fire to the landscape, and is strongly motivated by 'doing the right thing' for the land. Beyond this belief, these district rangers have confidence in their staff, but worry about public perception and do not feel supported by their employer. As one respondent said, "the nexus of temporal, spatial, and political factors doesn't always align" and yet individuals driven by their desire to do right by the land will proceed with WFU.

The results of Model 1 suggest that "the laudable, noble goal of ecosystem restoration" motivates a cohort of district rangers, convinced that WFU will accomplish this goal. According to the CART model, this cohort will predictably see potential benefits to the resource outweighing potential risks, and decide to 'go.' The model suggests the idealistic nature of those who reliably authorize WFU, but also highlights the obstacles that prevent district rangers from authorizing WFU across the board.

"There is more value to the resources at risk than value to allowing fire back on the landscape"

Responses to the open-ended questions in this study flesh out the backbone suggested by the CART model and draw attention to the risks that make implementing a stewardship ethic a costly gamble. External factors, public perception, resource availability, and agency support all surfaced as top considerations that inhibited the 'go' decision.

External Factors: "WFU is Risky Business"

Environmental factors came up as the main consideration influencing the go/no go decision, and a key to managing non-suppression fires to meet objectives. Specifically, fire danger indices were mentioned seven times in the context of managing a non-suppression fire and 21 times as the top consideration in the go/no go decision. Location and time of year surfaced 17 and 16 times, respectively, as the most important factors influencing the go/no go decision. Beyond these repeated concerns, weather, ignitions, smoke, and threatened and endangered species habitat all came up as considerations that weighed in the go/no go decision. These factors reflect concern for "risk of the unknown" that 8 respondents mentioned as a disincentive to use WFU.

Deciding to authorize a WFU event can engage a district's management capacity for an extended period. The time commitment involved depends on unpredictable events such as weather and lightning ignitions. In the midst of this uncertainty, air quality and endangered species regulations, in addition to private property considerations impose definite restrictions on management activity. Even for those supportive of fire restoration, the daunting requirements to ensure in this uncertain environment often prove prohibitive.

Public Perception: "Dick Cheney is not too hip on smoke"

Public support and public perception surfaced six times as a requirement for managing non-suppression fires to meet objectives and seven times as a disincentive to using WFU. Respondents evoked concerns for the political fallout of the external considerations described previously. Smoke, perceived or real threats to threatened and endangered species habitat, and resource damage perceived as unacceptable by the public or by others within the agency, all came up as specific areas of public concern. These concerns stem to some extent from a partially misinformed public that still views all wildland fires as a threat.

Resource Availability: "We need trained people with the right qualifications"

Resource availability surfaced 20 times as the top factor entering into the go/no go decision, 14 times as what was needed to manage a non-suppression fire to meet objectives, and in 18 of 43 unprompted discussions that arose during the interviews. Respondents mentioned that the level of qualifications required for fire use managers constrained WFU authorization. In addition, several respondents indicated that they lacked skilled personnel in sufficient numbers to manage WFU.

Respondents also indicated that candidate lightning ignitions frequently occurred when other fire activity was high. In these situations, the line officers did not have the staff on hand to manage the ignitions as WFU. Potential staff shortages cause concern given the indeterminate duration of WFU events.

Respondents mentioned the need for aerial resources in addition to personnel. Two respondents specifically indicated that the availability of helicopters had allowed them to manage WFU events to meet their objectives. In both cases, water-bucket drops by the helicopters cooled down flanks that would have otherwise hit management action-points and triggered a shift to suppression.

Agency support: "Signing 'go' is a lonely feeling"

The need for agency support surfaced as a requirement for managing non-suppression fires to meet objectives. Respondents also cited a perceived lack of agency support as a disincentive to authorizing WFU. This perceived lack of agency support takes two forms. First, respondents expressed a doubt that the agency would stand behind their decision if a WFU event went awry. Second, respondents indicated that the current focus on meeting hazardous fuel reduction targets impeded their use of WFU.

Potential career impacts surfaced seven times as a disincentive, and 14 times in unprompted discussions. Three respondents mentioned specific concerns about the potential for criminal charges as a result of recent after-action reviews of suppression fires that led to fatalities. Weighing resource benefits against potential damage to the decision-maker's family makes 'no go' more attractive.

Pressure to meet targets and lack of credit for WFU came up as disincentives to using WFU and surfaced in 14 unprompted discussions. These respondents indicated that they could not credit acres restored through WFU towards fuels targets. At the same time, they suggested that prescribed burn targets conflicted with using WFU. Further, two respondents reported that they would suppress lightning fires within areas prepared for prescribed burns because the WFU fire would not count towards the prescribed fire targets.

Conclusion

The position of line officer in the U.S. Forest Service draws people with a strong commitment to working for the good of the land. As with many public sector careers, there are few benefits other than satisfying a personal land stewardship ethic—a characteristic that holds true in the context of using lightning ignitions to restore fire to the landscape. This study suggests that authorization of WFU by district rangers primarily stems from their personal commitment to restoring fire for the good of the land, despite multiple disincentives. If national policy mandates restoring fire as a natural process, then implementation should not rely uniquely on those willing to take risks for their personal ethic.

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Modeling, Risk Assessment and Decision Support

Considerations in the Use of Models Available for Fuel Treatment Analysis

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***Abstract**—Fire managers are required to evaluate and justify the effectiveness of planned fuel treatments in modifying fire growth, behavior and effects on resources and assets. With the number of models currently available, today's fire manager can become overwhelmed when deciding which model to use. Each model has a required level of expertise in order to develop the necessary data, run the model(s), and analyze and interpret their associated outputs. In addition, each model has an appropriate temporal and spatial scale for its use, e.g., stand level versus landscape level. Traditional fuel treatment analyses have focused on stand level changes in fire behavior and effects. This approach does not to account for the topological effects of treatments in modifying fire growth, fire behavior and fire effects. To fully investigate fuel treatment effectiveness requires the examination of the spatial interaction of fuel treatments. This requires the use of spatial models to analyze and display these effects.*

Introduction

The fire behavior triangle consists of fuels, weather, and topography. The only element managers have direct control over is fuels. Management strategies of the 20th century, and the unintended consequences of fire suppression have contributed to the increase in large fires across the western U.S. (Agee and Skinner 2005). During the time period 1970-2002, 97-99% of all fires reported on U.S. Forest Service lands were still less than 121 ha (300 acres) (Calkin and others 2005) suggesting that suppression is still effective on small fires. However, 1.1% of all fires (greater-than 121 ha) during this time period accounted for 97.5% of the burned area and current data trends suggest that the number of large fires and their average size is increasing (Calkin and others 2005). It is the 1% of fires that are of greatest concern because of their effect across large portions of forested landscapes. This is the great irony of successful fire suppression; past success has contributed to failure today (Brown and Arno 1991; Agee and Skinner 2005).

The success of fire suppression, especially in dry forest types of the western United States has lead to drastic changes in the horizontal and vertical continuity of fuels as well as a buildup of surface fuels (Agee and Skinner 2005). This success has changed the fire regime from frequent low-intensity surface fires to more intense fires capable of becoming crown fires in these forest types (Arno and Brown 1991; Agee and Skinner 2005). The accumulation of fuels contributing to larger fires in the future has long been identified (Weaver 1943; Dodge 1972; Brackebusch 1973). Individual large fires as well as large scale fire events since 1988 have garnered much political attention and resulted

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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in numerous reports by federal land management agencies (for example, 10-Year Cohesive Strategy; National Fire Plan). The focus of these reports on fuels treatments and fuels management aimed at reducing "catastrophic" and large wildfires resulted in increased funding for these activities.

In the last decade the annual area burned by wildfire has continued to rise despite an increase in funding for fire suppression resources and fuel hazard reduction projects (Stephens and Ruth 2005). This should not be a surprise for several reasons. There is an inherent delay from the initial identification and funding to implementation of projects. It takes time to work through the NEPA process and then implement the plans. Additional delay or failure to implement a planned project can occur due to funding availability, personnel availability, weather conditions and administrative appeals or litigation (GAO 2003a). Also, the amount of area treated nationally has been focused around high-risk high priority areas, primarily Wildland Urban Interface (WUI) where from 2001-2004 greater than 65% of available fuel treatment monies have been spent and more than 50% of the treated acres have occurred (USDI-USDA 2006). As such, the opportunity for wildfires to test fuel reduction treatment areas at a landscape scale and their potential effect on reducing fire size and changing fire movement has likely been low. Lastly, most projects fail to adequately analyze treatments from a spatial perspective. While treatments are often recognized as having a positive localized effect on fire behavior and fire effects (Graham and others 1999; Graham and others 2004) the topological effect of strategically placed treatments designed to interact with one another at changing fire movement and size across a landscape are not (Finney 2001, 2003; Agee and Skinner 2005; Finney and others 2005). Thus, large fires still generally have free reign to move across the landscape essentially unimpeded.

This has lead to a number of reports and reviews of Federal agencies' fuels management practices, primarily by the General Accounting Office (GAO). Most, if not all are critical of federal agencies in this area. Criticisms include a need for improved planning to identify and prioritize those areas needing treatment (GAO 2003b) and that a systematic and defendable approach was not being used to assess risks and environmental consequences of fuels treatments as well as taking no-action, e.g., no fuel treatment (GAO 2004). No treatment is still an action and not always with the desired outcome (Agee 2002).

The General Accounting Office (GAO 2004) identified that neither the Forest Service nor Bureau of Land Management (BLM) have an institutionalized systematic way to analyze fuel treatment effectiveness at the landscape level. Furthermore, it concludes that fire management planning guidance is not specifically provided by the National Environmental Policy Act (NEPA) on how fuel management projects are to be accomplished (GAO 2004). Franklin and Agee (2003) also identified a need for a comprehensive national fire policy dealing with all aspects of wildfire management including, fire suppression, fuels management and issues surrounding when, how, and why fuels projects are conducted, as well as salvage and restoration treatments following wildfire events.

However, localized grassroots efforts have been undertaken to look at fuels treatments at the landscape level and the topological interaction of fuel treatments. The Fireshed Assessment Process as developed in the Pacific Southwest Region (R-5) of the USDA, Forest Service is one such program. Fireshed assessments offer a methodology to assess the strategic placement of treatments across large landscapes that are meant to interact with each other in reducing adverse fire behavior and ecological effects (Bahro and others, in press).

In the past fire managers were left to their own devices when it came to analyzing fuel treatments and navigating through the often confusing and contradictory list of models to choose from. Currently an abundance of tools exists with a dearth of data, especially for spatial fire models, and the local manager is often uncertain as to which model to select and how to go about the process. Recent publications (Graham and others 1999, 2004; Agee and Skinner 2005; Peterson and others 2005) have provided the principles, concepts, effects, and scientific basis for changing stand structure through the use of thinning, prescribed fire or a combination of these on altering fire behavior and fire effects. However, rarely is there an in-depth discussion of various fire decision support systems for analyzing pre- and post-treatment effects. The goals of this paper are to leave the manager with information on models and modeling concepts, a general discussion of fuel treatment analysis, and the models currently available for conducting these types of analyses.

Models in General

Models are used for a variety of reasons such as making inferences concerning processes and parameters of interest, determining potential effects of management actions or changes in environmental conditions on the subject of interest, evaluation of management alternatives by displaying the modeled effects, to display or communicate the effects of changes to concerned parties or in public meetings, and to test theories and assumptions one may have about conditions that can not easily be accomplished with formal experiments, for example, crown fire experiments.

Modeling itself is both an art and a science (Burnham and Anderson 1998). Modeling is an art because one must understand the inner workings of the model and the data and how adjustments must be made to achieve realistic, defendable, and quantifiable results. It is a science, because the user must have a fundamental understanding of the biological, mathematical and statistical relationships contained and used within the model as well as the assumptions and limitations inherent to the model. The user must be cognizant of the limitations and assumptions of the respective model, realize that all models need to be validated and calibrated to some past or current documented and observed condition, and that all results need to be tempered based on the user's experience, knowledge and observations.

It is incumbent on the end user to understand and comprehend these issues. After all, good models used poorly are no better than guessing. One must remember that all models are simplifications of reality (Burnham and Anderson 1998). If the model developer adheres to the concept of parsimony then the model itself cannot hope to account for all the complexities and interactions encountered in the modeling of natural or biological phenomena. A statement that rings very true is "All models are wrong but some are useful" (Box 1976; Burnham and Anderson 1998). Therefore the end user must accept and realize that some level of error and uncertainty exists, even if the "best" available model is used.

The advantage of using models is they have often undergone some type of peer review process, either through academia, evaluation through the formal publication process or by use and acceptance by experts in the field. Models generally incorporate previously published relationships, interactions or equations often bundling them as sub-models into a decision support system (Finney 1998; Andrews and Queen 2001). By using widely accepted, formally published and peer reviewed models one can state they are using the best available science for the time in their analysis. Models also provide an instrument to quickly evaluate multiple sets of conditions, alternatives, and theories or assumptions the end user may have.

However, models have a downside. Models that operate at the landscape scale are data intensive and require a certain level of expertise by the end user. Because computers are capable of making very fast and very accurate mistakes, the modeled solution may become generally accepted as fact. That is, it does not matter about the quality of the data, the expertise of the user, the applicability of the model to appropriately assess the situation or the interactions of all these in contributing to the solution. A common mantra is "Garbage In Garbage Out (GIGO)" perhaps a more appropriate revision would be the warning "Garbage In Gospel Out."

Models do not replace your knowledge and experience; beware of falling into the "Black Box Syndrome." The nirvana of modeling expertise and understanding tempered with an adequate knowledge and expertise in fire behavior is difficult to achieve and not often found. Harry T. Gisborne (1948), one of the founding fathers of fire research coined the term, experienced judgment, and defined it as: Opinion based on knowledge acquired by experience. However, Harry also points out the following (Gisborne 1948, page 23):

> "If you have fought forest fires in every different fuel type, under all possible different kinds of weather, and if you have remembered exactly what happened in each of these combinations your experienced judgment is probably pretty good. But if you have *not* fought all sizes of fires in all kinds of fuel types under all kinds of weather then your experience does not include knowledge of all the conditions."

Sage advice and something to consider, especially when model outputs are contrary to *your* experienced judgment. When this occurs it is easy to disregard the model output as spurious and thus unworthy of consideration. However, are the results flawed due to the data, the model or the user, or are there other plausible explanations? Are the results within your acquired knowledge base? Are the model parameters outside those you have experienced first-hand? Perhaps the model has shown you some possible outcome that you have not considered or previously experienced. While all model output should be evaluated with an appropriate level of skepticism, do not disregard it off-hand without due consideration.

Error Sources

General sources of error in the modeling process can be attributed to the data, the user, the model or the complex intersection and unions of these respective areas (Personal Communication, Dave Sapsis) (Figure 1). From personal experience, data and associated issues can account for up to 75% of encountered modeling difficulties. For example, Jones and others (2004) found that errors in the fuels map resulted in greater changes to model outputs than errors in terrain while erroneous weather information resulted in highly unstable outputs for a wildfire threat model for Australia. The remaining general sources of modeling error can be attributed to the user, model and interactions of error components (data, user, model).

Spatial modeling requires a seamless landscape of data attributes regardless of ownership or jurisdictional boundaries. Rarely, do the necessary data exist wall-to-wall thus necessitating some larger modeling exercise be undertaken

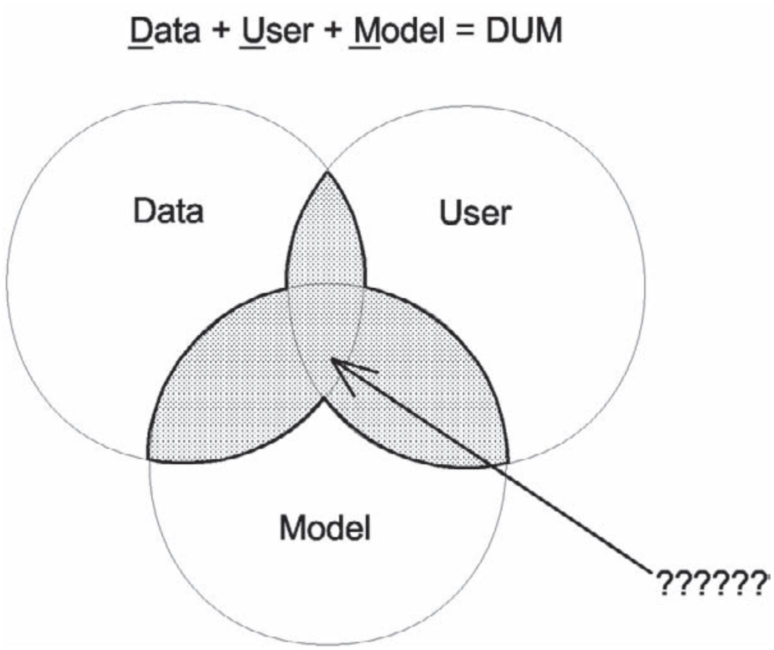

Figure 1—Components of modeling errors and their respective interactions.

to populate the landscape. This is typically accomplished using biophysical attributes, remote sensing, and statistical techniques such as Most Similar Neighbor (MSN; Crookston and others 2002) or Gradient Nearest Neighbor (GNN; Ohmann and Gregory 2002). Issues related to data such as inappropriately collected field data, limitations of the data in modeling natural or biological phenomena, inappropriate construction of data sets, assignment of the wrong units associated with the data, extrapolation of existing data to areas without data based on some other modeling exercise, and inappropriate rule sets used to develop data sets given the respective ecology and biological processes for the area. Additionally, data are often developed over large areas and assumed to represent some homogeneous condition within an artificially assigned boundary, such as a timber-stand. Because of this assumption critical data attributes may often represent the "average condition" for data values. This can have adverse consequences for some fire behaviors such as crown fire. In these instances the "average" crown base height likely does not reflect the minimum values that permit crown fire to initiate. Rarely, does the average condition account for problem fire behavior (Fulé and others 2001; Scott and Reinhardt 2001).

The end user can introduce error into the process by using an inappropriate model or user-defined model settings, simulating scenarios outside the limitations and assumptions of the model, from errors introduced during input of data, and in output interpretation. All models have assumptions and limitations associated with them. Error associated with the limitations of the data used to develop the model, using the model for phenomena outside that which the model was intended for and the models themselves have an associated error factor.

Finally, the area where all three components interact through the process of compensating errors can introduce uncertainty into the modeling process as well. Results may be correct or incorrect and the complexity of these interactions can make it difficult to discern which component is contributing to the modeled outcome.

Modeling Process

Fire modeling should not be thought of as a linear process, but rather as an open system of feedback loops whereby each idea can interact with the other causing a completely open system (Figure 2). While the following is offered in a linear fashion it is only to facilitate discussion and not intended to imply a linear, step-by-step operation.

- Define the modeling objective or question
- Model selection based on modeling objective or question
- Spatial and temporal data development required by selected model
- Gather supporting spatial and temporal data
- Data critique and analysis of developed data
- Calibration of the model to a past event(s)
- Simulations, evaluation and critique of results, and documentation
- Gaming-out, and what-if scenarios of fuel treatment location and prescription
- Evaluation, write-ups, and presentation of results

The framing of any project and defining the question or objective in a very specific nature is critical to selection of an appropriate model. For example, fuel treatments should be designed for a specific prescription of wind, weather and fuel moistures, should identify and target those fuel properties able to impact the targeted fire behaviors, e.g., surface fire versus crown fire, and take into account the short lived nature of treatments (Finney 2001; Finney and Cohen 2003; Agee and Skinner 2005; Finney and others 2005). Objectives and treatment prescriptions must be specific if the analysis is to adequately address the identified problem. Finally, after the questions and objectives have been defined this will assist in guiding one to a likely list of models to select from.

However, choosing the appropriate model is also data dependent. If a model relies on spatial data, these data must be available. If not, what data do you have and how long will it take to collect and develop the missing data sets? Can you develop the required data and still meet project deadlines? Are the data you have appropriate for the question you want to answer? For example, to examine the occurrence of crown fire do you have the additional required information (crown base height, crown bulk density, and stand height)? Do monitoring data exist from past fuel treatment or timber sale projects that could provide information on fuel models, fuel loadings and stand structure pre- and post-treatment? Additionally, does monitoring data from previous prescribed burn projects within treated areas exist that could provide insight into fire behavior and intensity following treatment? Monitoring data from previous projects, informal feedback, and an adaptive management approach is useful in developing and refining data and modeling scenarios as well as in the evaluation and validation of simulation results.

Temporal information on weather, wind, and fuel moisture parameters for the model will also be needed. This requires the user acquires, critiques,

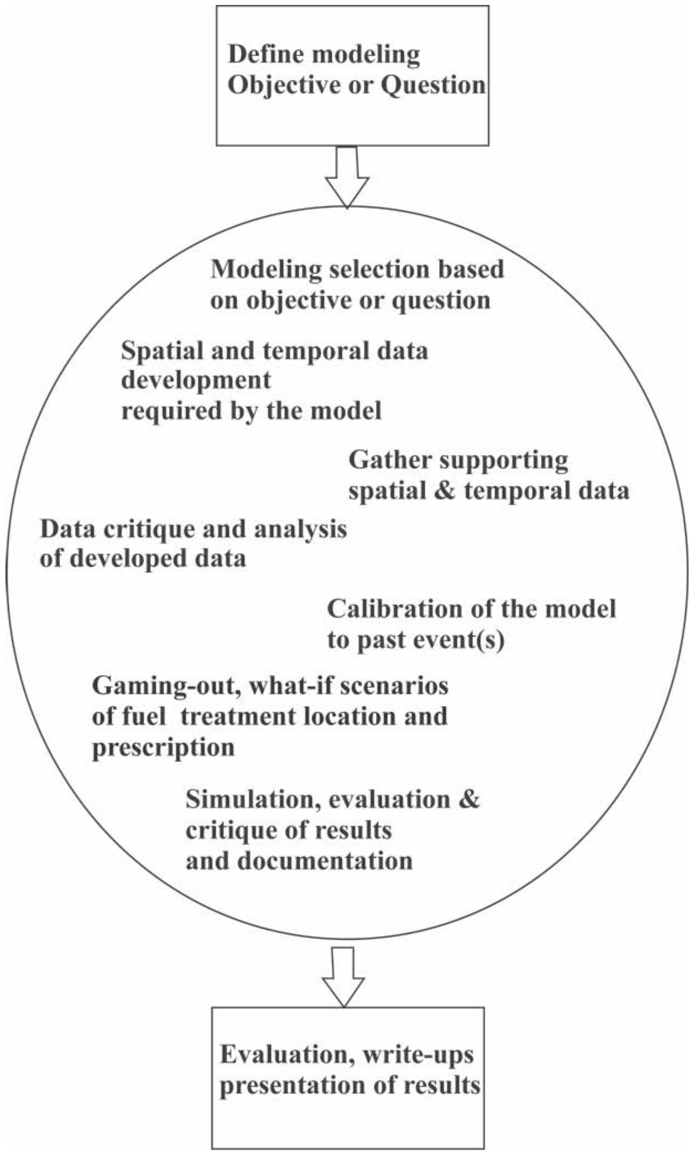

Figure 2—Conceptual representation of the modeling process. The process should not be considered linear in nature but rather as an open series of feedback loops within the circle.

analyzes historical climatological data or base all modeling scenarios on well known critical fire weather and fuel moistures for the respective area. Other potential sources of this information include fire behavior summaries from past fire events or monitoring reports from previous prescribed burn projects. Either can be very useful in the calibration of simulations and in developing critical fire weather and fuel moisture information for modeling scenarios.

Critique and analysis of weather data can be performed using FireFamily Plus (Bradshaw and Brittain 1999; Bradshaw and McCormick 2000). FireFamily Plus allows the user to interrogate historical climatological information for erroneous data as well as summarize fuel moistures and analyze critical weather and wind variables. Prior to any analysis the user should evaluate the values recorded for windspeed and direction, temperature, relative humidity, and precipitation amount and duration for erroneous values.

The modeler should also be cognizant that windspeed values based on the reported observation time from the selected Remote Automated Weather Station (RAWS) will likely be too low for most extreme fire weather modeling scenarios. Crosby and Chandler (1966, 2004) provide some guidance on interpolating average wind speeds to maximum wind speeds and the probable momentary gust speed. Another option is to access the Western Regional Climate Center's RAWS climate archive (http://www.raws.dri.edu/index.html). From this location one can access the hourly wind information for 10-minute average as well as the peak gust speed and direction, conduct a wind probability analysis and develop a Wind Rose for an individual RAWS station.

The gathering of ancillary spatial data can be very useful in providing spatial context to simulations and greatly assist in the critique and analysis of data and model outputs. At a minimum the following data should be considered; fire history (point, polygon, and progression), roads, hydrology, ownership, and vegetation.

Data critique and review should be considered an ongoing and never ending practice throughout the modeling exercise. During this process it is important to document your modeling assumptions, weather/wind and fuel moisture development used in simulations, limitations in the data, and data/model interactions. Data critique and review should take place during the initial spatial and temporal data development, immediately following the completion of data development, during the calibration of datasets to past fire events, during actual simulations, and again while analyzing model outputs. Critique of data during simulations and post-simulation is critical. Often, erroneous results due to model and data interactions will not manifest themselves until model simulations are run. Error examples may include but are not limited to the fire moving in the wrong direction, due to bad wind direction information, or too little crown fire activity due to the interaction of crown base height and fire behavior model.

Calibration can be defined as a procedure by which the factors controlling fire growth are verified and adjusted to make the predicted fire behavior match the observed or past event as closely as possible (Personal Communication, Robert C. Seli). Calibration of modeling scenarios to past events is critical. Calibration provides a mechanism for testing interactions of the data and model, allows one to evaluate model and data performance in predicting or matching to past documented fire events, provides insight into the respective fire models and how the interactions of data and user-defined model settings can affect modeled outputs. Additionally, and most importantly, it provides a means to evaluate the relevancy and accuracy of the data and instill confidence in future modeling projections.

Simulations allow the user to test silvicultural and fuel treatment prescriptions, treatment location and size and their effectiveness in altering fire behavior and growth under specified wind/weather and fuel moisture conditions for a specific project. However, simulations can also be used to game-out different scenarios which is critical in evaluating treatment locations, treatment prescriptions, and their effectiveness. The modeler can efficiently evaluate changes in treatment location, prescription intensity, treatment effectiveness, and treatment longevity based on temporal changes to fuels, stand structure, and user defined model settings. With the gaming-out of each new scenario an alternative pattern of treatment locations and prescription can be evaluated providing insight into fire spread and behavior across a landscape under various ignition locations, model duration, and wind/weather, and fuel moisture scenarios (Bahro and others, in press).

Evaluation and critique of results not only occurs during calibration but during modeling scenarios. This provides another opportunity to evaluate predicted fire behavior and fire growth, the review of spatial and temporal data quality and model-data interactions. It is important the user consider the predicted fire behavior and growth for the fuels and weather conditions, the effects of user-defined model settings and whether the selected model is appropriate for the simulated fire type. At this stage, documentation of results, user-defined model settings, wind/weather and fuel moisture values and assumptions concerning changes to landscape data pre- and post-treatment, fuel model assignment logic, treatment time span and time since treatment, and an organized filing structure is encouraged. Having a succinct and organized record of what was done can prove to be very beneficial in the future.

Evaluation and presentation of results following fuels treatments is the last 5% of the process and perhaps the most critical. Analyzing the results appropriately and presenting them in a concise and meaningful manner can be difficult. The modeling results should demonstrate reduced fire damage from an ecological standpoint, and show improved controllability, e.g., increased line production rates, reduced rates of spread, reduced spotting, changes in the proportion of crown fire type, thus allowing for flexibility in employed tactical and strategic options. This section should also address short and long-term risks, fire effects, fire behavior, and compare and contrast the consequences of no fuel treatment to conducting fuel treatments.

Fuel Treatment Analysis

In the dry forest types of the western United States the effect of fuel treatments on fire behavior at the localized or stand level is well documented (Graham and others 1999, 2004; Graham 2003; Finney and others 2005; Peterson and others 2005; Raymond and Peterson 2005; Cram and others 2006). Documentation has consisted of anecdotal and observational, literature reviews, theoretical analyses, and more recently empirical evidence. Published papers on this topic have done an adequate job of identifying and reviewing past work in these areas (Graham and others 1999, 2004; Raymond and Peterson 2005; Stephens and Moghaddas 2005b; Cram and others 2006). Due to the opportunistic nature of wildfire impact studies, empirical evidence of fuel treatment efficacy has been severely lacking. However, empirical evidence on the efficacy of fuel treatments is becoming more evident and for a larger portion of the western United States (Pollet and Omi 2002; Agee and Skinner 2005; Finney and others 2005; Raymond and Peterson 2005; Cram and others 2006). In some instances, the effects of fuel treatments have been captured by Landsat-7 satellite imagery (Figure 3), the most demonstrative to date has been the Rodeo-Chediski fire in northern Arizona (Finney and others 2005).

Fuel Treatment Principles

Fuels treatments can be effective when they are targeted at specific components of the fuel complex; specifically surface, ladder and canopy fuels (Agee 1996; Scott and Reinhardt 2001; Finney 2004; Graham and others 2004; Agee and Skinner 2005; Peterson and others 2005). Treatment of these fuels components should occur in a hierarchal manner from the bottom up (Figure 4) with the following order of precedence: 1) Surface fuels, 2) ladder

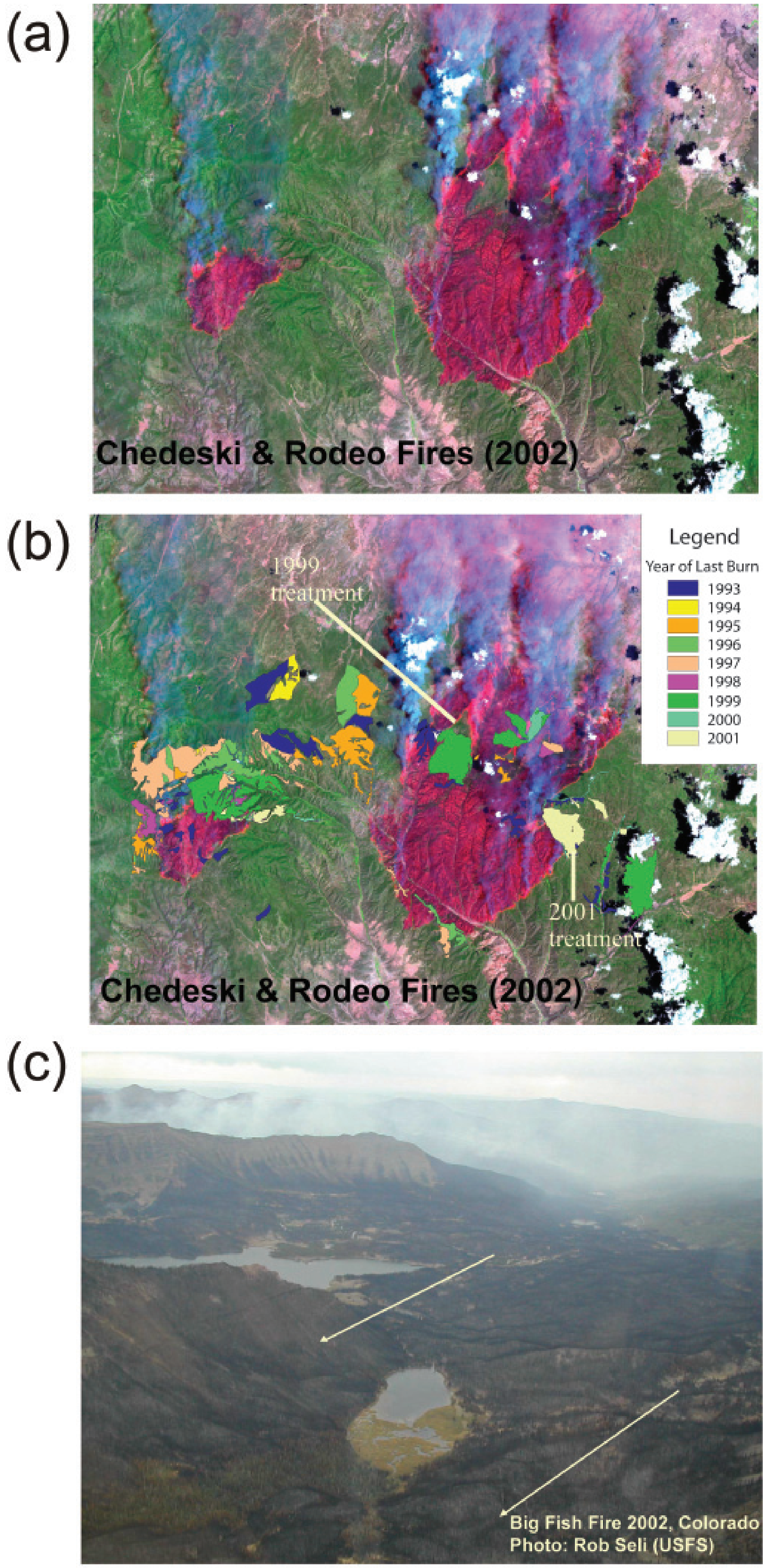

Figure 3—Landsat-7 ETM Plus satellite image of the Rodeo-Chediski fire on June 21, 2002 (a); Chevron shaped areas within the fire front (a) correspond to recent fuel treatment activities 1999 and 1993 (b); (c) Natural barriers such as lakes can cause fires to exhibit the same behaviors as fuel treatments. Note area on the leeside of the lake in the foreground. Example from the Big Fish Fire 2002, arrows show path of fire movement.

fuels, and lastly 3) canopy fuels (Agee 2002; Hessburg and Agee 2003; Finney 2004; Graham and others 2004; Agee and Skinner 2005). Fuels treatments must be of appropriate intensity to significantly change those fuel components at the stand or local scale critical to identified fire behaviors of concern in the context of their spatial location and size, anticipated treatment effectiveness, temporal changes to fuel and stand structure (treatment longevity) under the targeted wind/weather and fuel moisture conditions.

Surface fuel treatments consist mainly of broadcast prescribed burning which has proven effective at changing fire behavior, fire severity, and even in limiting the extent of future fires (Weaver 1943, 1957; Wagle and Eakle 1979; van Wagtendonk 1996; Pollet and Omi 2002; Fernandes and Bothello 2003). Removal of surface fuels limits the spread rate and intensity of surface wildfire, which reduces the ability for fire to heat and ignite tree canopies (Van Wagner 1973, 1977).

Ladder fuels consist of small trees and limbs that facilitate the vertical movement of a surface fire into the tree canopy (Van Wagner 1973; Scott and Reinhardt 2001). Mechanical methods can be used to remove small trees or even prune lower limbs, which increases the vertical gap between the surface and canopy fuel stratum (Graham and others 1999, 2004; Scott and Reinhardt 2001). When followed by prescribed burning, such low thinning hinders the initiation of crown fire (Graham and others 2004). Cram and others (2006) and Raymond and Peterson (2005) reported that a combination of mechanical treatments followed by prescribed burning had the greatest effect on reducing fire severity in the Rodeo-Chedeski and Biscuit fires respectively.

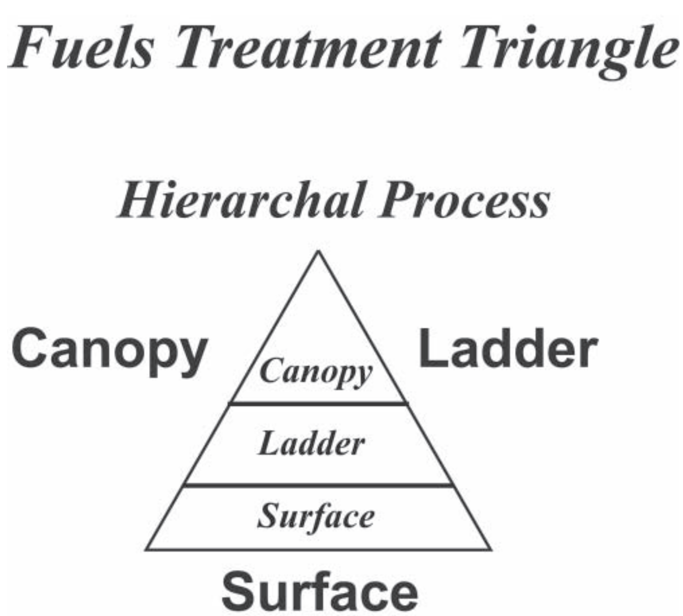

Figure 4—Fuel treatment triangle. Treatment of fuel components should be considered a hierarchal process starting with the surface fuels moving upward into the canopy fuels.

Finally, canopy fuels might be thinned to limit the potential for active crown fire spread presuming fire has been initiated into the crowns (Finney 2004; Graham and others 2004; Agee and Skinner 2005). Large trees with foliage held high above the ground surface and their thicker bark are more resistant to fire damage (Peterson and Ryan 1986). Dominant canopy trees offer the least available fuel source and are generally more fire resistant and thus should be the last stratum considered purely for fuel treatment prescriptions. However, balancing the financial feasibility of fuel treatment prescriptions may require removal of some large trees to offset costs of the treatments themselves (Larson and Mirth 2001; Lynch 2001; Franklin and Agee 2003). Over time, the costs of treatments will be much less-than the costs associated with fire suppression, post-fire rehabilitation, and long-term ecological damage to watersheds (Lynch 2004).

Fuel Management Scale

Fuel treatments affect fire behavior at two spatial scales: the stand or local scale, and at the landscape scale (Finney 2001, 2003). A *stand* is considered a reasonably homogeneous unit that can be clearly differentiated from surrounding stands by its age, composition, structure, site quality, or geography (Daniel and others 1979). While there is no precise size attached to a stand, their smallest unit of size is defined by the land management agency based on a minimum mapping unit, typically around 2-4 ha (5-10 acres). *Landscapes* represent larger areas and typically are aggregations of individual stands that can be burned by a wildland fire. This is a functional definition related specifically to fire and fuel treatment analysis. While there is no set number of stands or area limitation to define a landscape it should be large enough to allow treatments the ability to disrupt large fire growth that has occurred in the past. While watershed boundaries are the most common, ecological management units, range allotments, fireshed assessment area or some other arbitrarily defined extent may be used to define an individual landscape.

McKenzie and others (1996) found in previous fire ecology studies, generally the area represented by a stand to vary from 10 to 1,000 ha (24.7 to 2,417 acres) while landscapes ranged from 1,000 to 1,000,000 ha (2,471 to 2,471,044 acres). Recently, Finney and others (In Review (a)) analyzed landscapes ranging in size 40,500 to 54,600 ha (100,077 to 134,919 acres) with stand sizes ranging from 4 to 515 ha (10 to 1,273 acres) to simulate the spatial-temporal effects of landscape level fuel treatments and their affect on large wildfires. Both studies report sizes similar to those proposed by Simard (1991) for analogous classifications.

Fuel Treatments and Topology

Fire whether at the stand or landscape scale is a *contagion* process, meaning the fire behavior at one site or point in space is directly influenced by the characteristics of the adjacent site or point in space (McKenzie 1991). *Topology* is the spatial relationship of one feature to another (ESRI 2004). Because of fire's contagion process the topological relationship of treatments and their interaction become important when locating fuel treatments at the landscape scale (Finney 2001). However, rarely is placement of treatment units based on topological considerations and this effect on altering fire growth and behavior across a landscape (Finney 2001, 2003). Treatment placement is typically based on other management considerations and thus unlikely to have little impact on changing the overall growth and size of fires until significant portions of any one landscape are treated (Finney 2001). Topologically placed treatments collectively interact at changing fire growth and fire behavior across the landscape and can require fewer acres treated than when treatments are located without this consideration (Finney 2001, 2003; Finney and others, in review (a)). It is important to remember the importance of treatment topology, treatment intensity, and the proportion of the landscape treated when designing landscape level fuel treatments (Figure 5). Based on these findings and the impracticality of treating every acre, the strategic placement of treatments, treatment intensity, and the proportion of treated landscape and their resultant effect in changing fire behavior and growth should be considered when designing and implementing fuel treatments (Finney 2001, Finney and others, in review (a)).

Analyses of fuel treatment effectiveness typically display, describe and summarize fire behavior at the stand or local level. While this is important in displaying stand level treatment effects in changing fire behavior, it does not model the topological effects of treated stands in altering fire movement between treated stands at the landscape scale. This is the problem of stand or local-scale fire behavior analyses. This methodology can indicate a change in fire behavior at the stand scale as well as an overall change in fire behavior and fire effects summarized across the defined landscape. However, stand-level analyses offer no means to analyze, display, or show the topological effect of these treatments in changing fire growth and movement nor the off-site leeward protection (leverage) afforded by fuel treatments (Finney 2001; Loehle 2004; Agee and Skinner 2005; Finney and others 2005). Thus, aggregation of localized effects is not an appropriate method to analyze at the landscape scale, the effects of treatments in changing fire behavior, fire growth and movement.

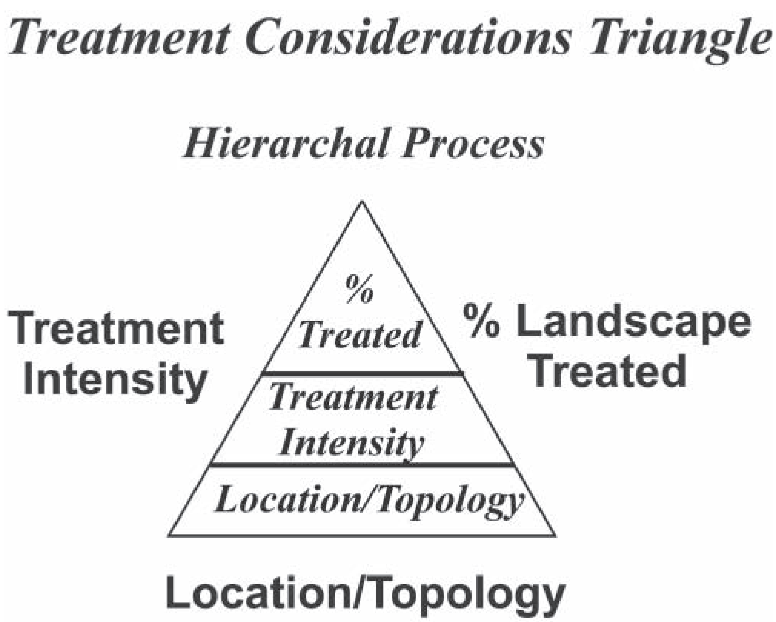

Figure 5—Theoretical illustration of the relative importance (starting from the base up) of treatment topology, fuel treatment prescription intensity, and proportion of landscape treated.

Fire Modeling Tools

With increased emphasis on fuel management, fire managers are continually asked to offer analytical support related to fuel management decisions. There are numerous tools available to the fire manager to model fire behavior which can provide critical insight in assessing current situations, forecasting future fire scenarios, and evaluating fuel treatment alternatives (Andrews and Queen 2001). However, the availability of these tools and supporting data (or lack of data) from the internet can often lead to confusion on which tool is appropriate and at what spatial scale (stand or landscape). Additionally, users are commonly guilty of the misapplication of the respective model, the data and interpretation of outputs (Andrews and Queen 2001).

Terminology

The terminology proposed by Andrews and Queen (2001) is used when referring to the tools discussed here. They define a *fire model* as a mathematical relationship that describes an aspect of fire while a *decision support system* incorporates multiple individual fire models under a unifying architecture to provide various outputs related to fire behavior and fire growth (Andrews and Queen 2001). *Fuel models* are lists of numbers that describe the fuels as required by the respective fire model (Andrews and Queen 2001). All of the decision support systems here use fuel models as described by Anderson (1982) and initially formulated by Rothermel (1972) and Albini (1976) and those recently developed by Scott and Burgan (2005). For the purposes of this discussion I presume all the tools discussed here are decision support systems (DSS) (table 1).

Table 1 outlines each of the individual DSS applicable scale (stand, point or landscape), their required inputs and associated outputs. Tools designated as a point or stand can only be used to analyze or display fire behavior for an individual stand or location. Decision support systems with a landscape designation are also capable of analyzing the topological effects of treatments as

Table 1—Decision support systems available for fuel treatment analysis.

Model	Applicable Scale	Inputs		Outputs		
		Spatial	Temporal	Spatial	Tabular	Graphical
Behave/BehavePlus Andrews (1986) Andrews and others (2005)	Point/Stand	NO	NO	NO	YES	YES
FARSITE Finney (1998)	Stand/Landscape	YES	YES	Vector & Raster	YES	YES
FlamMap Finney (this proceedings)	Stand/Landscape	YES	NO	Vector & Raster	NO	NO
FMA Plus Carlton (2005)	Point/Stand	NO	NO	NO	YES	YES
Fire Fuels Extension (FFE) Reinhardt and Crookston (2003)	Point/Stand	NO	YES	NO	YES	NO
NEXUS Scott (1999)	Point/Stand	NO	NO	NO	YES	YES

fire moves across a landscape. Those DSS with *Spatial inputs* require data for fuel model, topography, stand structure and canopy fuels generated within a GIS and provided to the model in the form of Grid-ASCII raster data. Decision support systems with *temporal inputs* allow for modeling fire behavior and growth over time thus requiring information on duration and intervals of the modeling scenario as well as time dependant wind and weather streams. *Spatial outputs* indicate the DSS is capable of generating simulation results as shapefiles or GRID-ASCII raster data that can be directly ingested into a GIS system for display and further analysis.

Decision Support Systems

The DSS listed in table 1 comprise the more common tools used to analyze fuel treatments from either a stand or landscape level. While some are more appropriate for certain scales of analysis than others, all essentially incorporate the same mathematical fire models for surface fire spread rate, crown fire initiation and crown fire spread rate models (Scott 2006). Furthermore, all the DSS discussed here use the previously discussed fire behavior fuel models.

The most common approach to analyzing fuel treatment effects have been on a stand or point basis. BEHAVE (Andrews 1986), BehavePlus (Andrews and others 2005), Fuels Management Analyst Plus (FMAPlus; Carlton 2005), Fire Fuels Extension (FFE; Reinhardt and Crookston 2003), and NEXUS (Scott 1991; Scott and Reinhardt 2001) have all been used to conduct these types of analysis (table 2). All these systems can generate information on fire behavior, crown fire, and fire type. However, they are only valid for the point or stand information provided. None of the DSS are capable of simulating

Table 2—Publications using fire decision support systems in fuel treatment analysis. NO: Study tested treatments based on Non-site specific locations.

Author	Modeling System(s)	Location
Kalabokidas and Omi (1998)	BEHAVE	Colorado
Brose and Wade (2002)	BEHAVE	Florida
Keyes and O'Hara (2002)	BEHAVE	NO
Hummel and Agee (2003)	BEHAVE	Washington
Van Wagtendonk (1996)	*FARSITE*	NO
Rice and Miller (1998)	*FARSITE*	California
Stephens (1998)	*FARSITE*	California
Finney and others (2002)	*FARSITE*	California
Stratton (2004)	*FARSITE*/FlamMap	Utah
Stephens and Moghaddas (2005a,b)	FMAPlus	California
Scott (1998a)	NEXUS	Montana
Fulé and others (2001a)	NEXUS	Arizona
Fulé and others (2001b)	NEXUS	Arizona
Fulé and others (2002)	NEXUS	Arizona
Scott (2003)	NEXUS	NO
Fulé and others (2004)	FVS-NEXUS	Arizona
Raymond and Peterson (2005)	NEXUS	Oregon
Scott (1998b)	FFE-FVS	Montana
Fiedler and Keegan (2003)	FFE-FVS	New Mexico
Fiedler and others (2004)	FFE-FVS	Montana

fire spread between points or stands. However, using GIS, simulation outputs from these models such as, flame length or crown fire can be linked back to a stand boundary data layer and displayed spatially across a landscape. However, this still provides no information on the topological effects of the treatments in altering fire behavior and growth at the landscape scale.

Analyzing topological effects of fuels treatment must also be done to examine their effectiveness in altering fire movement and behavior at the landscape scale (Finney 2001, 2003). To accomplish this a DSS capable of modeling fire behavior at the stand level and incorporating the topological effect of treatments in altering fire movement across the landscape is needed. Only *FARSITE* (Finney 1998) and the Minimum Travel Time (MTT; Finney 2002) or Treatment Optimization Model (TOM) component within FlamMap (Finney, this proceedings) are widely available for this analysis. Simulation outputs of fire growth and behavior from these models are spatial and easily brought into a GIS for display and further analysis.

Available Tools

BEHAVE/BehavePlus—BEHAVE (Andrews 1986) and BehavePlus (Andrews and others 2005) are decision support systems that are only capable of determining fire behavior at the point or stand level, do not require spatial information or model fire behavior temporally and can only provide limited outputs in the form of tables, graphs or diagrams (table 1). Previous efforts using this system were completed using BEHAVE (Andrews 1986) and examined the effectiveness of fuel treatments in changing fire behavior as well as changes in fire behavior associated with changes in stand structure following a spruce budworm outbreak (table 2). While BEHAVE and BehavePlus can be used for evaluating fuel treatment effectiveness, its primary uses have been in projecting the behavior of ongoing fires and in planning prescribed fires. BehavePlus (Andrews and others 2005) is the successor to BEHAVE and should be used for future modeling exercises. BehavePlus can model surface fire spread and intensity, crown fire spread and intensity, safety zone size, size of point source fire, fire containment, spotting distance, crown scorch height, tree mortality, wind adjustment factors, and probability of ignition (Andrews and others 2005).

NEXUS—NEXUS links existing models of surface and crown fire behavior that can be used to assess crown fire potential at the point or plot scale (Scott and Reinhardt 2001). NEXUS does not require spatial or temporal data inputs and the outputs from NEXUS include tables, graphs, and text files (table 1). While NEXUS can provide an index of crown fire hazard, fire type, and potential fire behavior it cannot determine or simulate fire spread or the spread of fire between stands or points. NEXUS has been used to analyze changes in crown fire hazard following fuel treatments with crowning index and torching index used to reflect these changes (table 2). NEXUS version 2.0 has the ability to run in batch mode, which can process up to 32,000 records at one time.

FVS-FFE—The Fire and Fuels Extension (FFE; Reinhardt and Crookston 2003) contained within the Forest Vegetation Simulator (FVS; Wykoff and others 1982) allows one to model stand dynamics and changes to fuels over successional time and the associated behavior and impacts of fire as stands grown and change (Reinhardt and Crookston 2003) or associated with specific treatments (table 2). Because of this ability FFE can add a temporal effect to the analysis and display the changes in stand structure and potential fire hazard as a time-series over periods of a year to decades. While FFE can determine potential fire behavior it cannot determine fire probability or simulate fire spread or the spread of fire between stands (Reinhardt and Crookston 2003). The data used to determine potential fire behavior and effects is based on the stand averages which leads to some homogenization of the data and can influence the simulated outputs. Results can be displayed visually using the Stand Visualization System (SVS) (McGaughey 1997) or in tabular format. Exporting the data out in a spreadsheet format allows the user to construct graphs of the simulation. Since data sets used in the modeling are typically tied to a spatial representation of stand boundaries, simulation results can be displayed spatially in GIS. With the spatial relationship of the stand data, and the ability of FVS-FFE to model stand dynamics and fuel accumulations over time one could use the model to develop spatial-temporal data (fuel models, stand structure, canopy fuels) that can be imported into spatial models such as *FARSITE* or FlamMap. A recent study used FVS-FFE in just this way (Finney and others, In Review (a)).

FMAPlus—FMAPlus incorporates previously established methodologies and fire models to produce fuel inputs, outputs of fire behavior, crown fire potential, crown scorch and mortality based on field collected data (Carlton 2005). It is appropriate for point or stand level analyses. FMAPlus requires no temporal or spatial inputs, and only produces tabular or graphical outputs (table 1). Because it can incorporate field-collected data and import tree list data from FVS (Wykoff and others 1982), temporal analysis over time (year or decades) could be accomplished. Within FMAPlus fuel treatment analysis is accomplished by altering the tree list data to reflect post-treatment stand conditions. Only recently has the use of this model to display fuel treatment effects been published (table 2).

FARSITE—With the development of the Fire Area Simulator *FARSITE* (Finney 1998) the ability to analyze fire growth at the landscape scale in a spatially dependent environment became available. *FARSITE* uses spatial information on elevation, slope, aspect, canopy cover, fire behavior fuel model, stand height, crown base height, and crown bulk density as well as temporal information concerning weather, wind, and fuel moisture to run fire growth simulations and generate fire behavior outputs (table 1). Outputs consist of spatial (shapefiles and GRID ASCII) for fire growth and behavior as well as tabular and graphical information on area burned, fire perimeters, and fire numbers. Examples of the use of *FARSITE* in evaluating the efficacy of fuel treatments in changing fire behavior and the effectiveness of fire suppression following fuel treatments in changing fire size and economic damage have been published (table 2). Its reliance on spatial data and the common lack of availability of these data have been a major impediment to its use. However, the LANDFIRE (http://landfire.gov/) project is tasked with the development of spatial data for use in *FARSITE* for the lower 48 States, which should alleviate this data barrier over time.

FlamMap—FlamMap (Finney, this proceedings) is a simplified version of *FARSITE* requiring the same data inputs while generating similar fire behavior outputs. One of the benefits of FlamMap over *FARSITE* is many scenarios can be run very quickly and many of the assumptions required by *FARSITE* are simplified or eliminated. However, there is no temporal component in FlamMap, as such it uses spatial information on topography and fuels to calculate potential fire behavior characteristics at a specific instant for the landscape under a specified set of conditions for every raster cell on the landscape with without contagion between data cells. FlamMap does not simulate temporal variations in fire behavior caused by weather and diurnal fluctuations, nor will it display spatial variations caused by backing or flanking fire behavior. Because of this, FlamMap is an ideal tool to compare relative fire behavior changes resulting from fuel modifications. Using just the fire behavior option, FlamMap is much like a point/stand fire model, however, the ability to analyze many stands in their georeferenced position does offer some degree of landscape perspective, albeit without topological influences. To get around this issue Stratton (2004) incorporated both FlamMap and *FARSITE* to analyze fuel treatment effectiveness in southern Utah. However, Version 3 of FlamMap can also evaluate the topological effects of fuel treatments by using the Treatment Optimization Model (TOM; Finney, In Review (b)) and evaluate the spatial movement of fire across a landscape based on Minimum Travel Time (MTT; Finney 2002; Finney, this proceedings; Finny In Review (b)).

Model Selection

Given this list of potential models, which model is the best or appropriate model? As mentioned previously the objective and questions that need to be answered are of paramount importance, however, one should select the model based on the intricacy of the question(s) or objectives. Associated with this decision process one should also consider the following.

First, what are the intended uses of the model? Is the objective to assess changes to crown fire hazard following fuel treatments? Then perhaps NEXUS is the appropriate model. If one wishes to examine the effects of fuel treatments on changes to fire behavior then, BehavePlus or FlamMap may be more appropriate.

Secondly, what are the required inputs of the model? If one decides to use a spatial model such as *FARSITE* or FlamMap do you have the required spatial data? If not, do you have the time to acquire any needed ancillary data, develop the data, critically analyze and assess the accuracy of the data, and develop the required data layers needed for the questions of interest?

Thirdly, what are the outputs generated by the model and will they allow the user to fully answer and analyze the questions or objectives of the modeling exercise? Do you need only tabular or graphical outputs of fire behavior characteristics or do you need these outputs to be spatially represented across the landscape. All of the previously mentioned fire behavior tools generate tabular and graphical outputs of data, but only *FARSITE*, FlamMap, FVS-FFE generates outputs that can easily be applied spatially within GIS.

Lastly, what is the complexity and time frames associated with the current project? Complexity is directly related to the type of analysis being performed, e.g., Categorical Exclusion (CATEX), Environmental Analysis (EA), or Environmental Impact Statement (EIS). All of these processes require a certain level of analysis and time commitments to meet their respective legislative intents. As such, it can have a direct impact on the required decision support system. For a CATEX the use of BehavePlus may be the appropriate tool to use to assess changes in fire behavior associated with fuel treatments, especially if one needs to develop many of the required spatial layers to use *FARSITE* or FlamMap. The project timelines associated with each of these also controls whether the fire manager has the time to develop the required data layers taking into account those items mentioned in previously.

Summary

Large wildfires have impacts well outside the localized effect of individually treated stands. Treatment placement that does not consider treatment topology is unlikely to have any impact on changing the overall growth and size of fires until significant portions of any one landscape is treated (Finney 2001, 2003). Based on this and the fact it is impractical to treat every acre the strategic placement of treatments and their collective effect in changing fire behavior and growth needs to be considered (Finney 2003). An effective landscape fuel management scheme should do the following:

- Treatments burn at a reduced severity
- Treatments are located to collectively reduce fire sizes and severity
- Change probability of fire movement
- Facilitate a change in suppression tactics and strategy
- Reduced fire sizes and fire severity under target environmental conditions
- Reduced large-fire suppression costs

When using any decision support system to analyze fuel treatment effectiveness or ongoing fire events, there are three potential sources of error: data, user, and model (DUM). The end user needs to be cognizant of these errors at all times during data development and the modeling process.

Fuel treatment prescriptions should focus on defined elements of wildland fuel structure following a hierarchal order of treatment (surface, ladder and canopy fuels). Treatment design should also consider treatment topology, treatment prescription intensity, treatment size and planned longevity, and the amount of landscape treated.

While treatments are focused on altering fire behavior at the stand level, it is the topological placement of treatments that is important in changing fire growth and behavior at a larger landscape scale. Treatment locations that are strategically placed and based topologically may actually require fewer acres be treated to achieve an equivalent reduction in affected acres when this is not considered (Finney 2001, 2003; Finney, in review (a)). Because topology of treatments is important we can no longer rely on the number of acres treated as a metric for treatment success. Developing a more appropriate metric to measure fuel treatment effectiveness and success is an area requiring further investigation and should be included in any future national fire policy (Franklin and Agee 2003; Stephens and Ruth 2005).

Modeling fuel treatment effectiveness is one of the more difficult applications of fire decision support systems. It requires the modeler to make assumptions about the future conditions of fuels and vegetation structure, which is difficult at best. This analysis however is critical to assist in management decisions. When modeling fuel treatment effectiveness, it is best to remember the advice of Yogi Berra: "Prediction is very hard, especially when it's about the future."

Acknowledgments

The author thanks Mark Finney, Dave Sapsis, Bernie Bahro, Rob Seli, and Rick Stratton for their helpful comments on an earlier version of the manuscript.

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A Computational Method for Optimizing Fuel Treatment Locations

Mark A. Finney[1]

Abstract—*Modeling and experiments have suggested that spatial fuel treatment patterns can influence the movement of large fires. On simple theoretical landscapes consisting of two fuel types (treated and untreated) optimal patterns can be analytically derived that disrupt fire growth efficiently (i.e. with less area treated than random patterns). Although conceptually simple, the application of these theories to actual landscapes is made difficult by heterogeneity (fuels, weather, and topography) compared to the assumptions required for analytical solutions. Here I describe a computational method for heterogeneous landscapes that identifies efficient fuel treatment units and patterns for a selected fire weather scenario. The method requires input of two sets of spatial input data: 1) the current fuel conditions and 2) the potential fuel conditions after a treatment (if it were possible). The contrast in fire spread rate between the two landscapes under the weather scenario conditions indicates where treatments are effective at delaying the growth of fires. Fire growth from the upwind edge of the landscape is then computed using a minimum travel time algorithm. This identifies major fire travel routes (areas needing treatment) and their intersections with the areas where treatments occurred and reduced the spread rate (opportunity for treatment). These zones of treatment "need and opportunity" are iteratively delineated by contiguous patches of raster cells up to a user-supplied constraint on percentage of land area to be treated. This algorithm is demonstrated for simple and for complex landscapes.*

Introduction

Fuel treatment effects on wildland fire behavior have long been documented at the stand level (Biswell et al. 1973, Wagle and Eakle 1979, Helms 1979, Pollet and Omi 2002, Fernandes and Botelho 2003, Graham 2003). Prescribed burns and thinning operations change fuel structure and have together been successful in modifying fire behavior and consequent effects in the areas treated (Weaver 1943, Kallender et al. 1955, Cooper 1961, Martin et al. 1989, Graham et al. 1999, Schoennagle et al. 2004, Graham et al. 2004, Agee and Skinner 2005, Cram et al. 2006). The landscape level, however, is composed of many stands and mixtures of fuel conditions through which large fires burn, and there has been little work on strategies for treatment at this broad scale. Prescribed burning and general fuel management will be a necessary part of mitigating and even reversing effects of fire suppression (Arno et al. 1991). Evidence shows that even widespread treatments that change fire behavior at the stand-level can be circumvented by larger fires (Salazar et al. 1987, Dunn 1989, Finney et al. 2005). This paper reports on an algorithm that optimizes the placement of treatment units to limit this circumvention and thereby interrupt the movement of large fires.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Precedence for landscape-level fuel modifications is found in the patchwork or mosaic formed by free burning fires in large wilderness areas in the western United States. Here, patterns of old burns delay and detour later fires (van Wagtendonk 1995, Parsons and van Wagtendonk, Rollins et al. 2001). These interactive effects are possible when fire frequency is high enough to maintain some unknown fraction of the landscape in a modified condition. By comparison, intensive fuel treatment methods are expensive and wholesale treatment of large landscapes is impossible for practical reasons including land ownership, conflicting management objectives, and funding. Typically, the amount of land area and the locations of treatments are constraining, thus, the question of where to place treatments becomes a problem suitable for optimization.

Theoretical work for artificial landscapes has shown optimum efficiency from a pattern of rectangular treatment units that reduces fire growth rates with a minimum of area treated (Finney 2001a). Rectangular units that partially overlap in the predominant fire spread direction (determined from historic climatology) allow the fire to move through and around them at the same rate. Fire growth is slowed by the pattern because fire progress is dominated by lateral movement. When small fractions of land are treated, these patterns are efficient compared to random arrangements (Finney 2003, Loehle 2005). Random patterns may require several times as much treatment to reduce fire growth rates to comparable levels (Gill and Bradstock 1998, Bevers et al. 2004). Although conceptually simple, the application of these theories to actual landscapes is only just beginning (Hirsch et al. 2001) and is made difficult by the heterogeneity of real landscapes (fuels, weather, and topography) compared to the assumptions required for analytical solutions (Finney 2001b).

The computational method reported here uses spatial GIS data to represent the heterogeneity of actual landscapes and produces a map of treatment areas that collectively disrupt fire growth at scales coarser than the individual treatment units. The algorithm is applied to simple and complex landscape conditions showing that the treatment pattern is one of many that achieve effective results comparable to those suggested by the analytical theory.

Assumptions And Methods

Fire Sizes and Severity

The objective explicitly assumed by this analysis for landscape fuel management is to delay the growth of large or "problem" fires. Information on such fires is readily obtained for most wildland areas from local or regional fire history or fire atlases (Figure 1). The reasoning for this assumption follows from the conditions that foster the growth of such fires in areas dominated by suppression-oriented management in western North America. Here, fires become large by escaping initial attack and then spreading far from where they start. Large fires are resistant to suppression efforts because of the dry and windy weather that contributes to their rapid growth, the sheer size and length of perimeter they present to control, and the fire behaviors produced under the extreme weather conditions originating their escape (crown fire, spotting). Suppression success typically occurs only when durable changes in the weather abate rapid fire growth. During periods of active spread, such fires are responsible for the greatest damages to watersheds, ecosystems, and

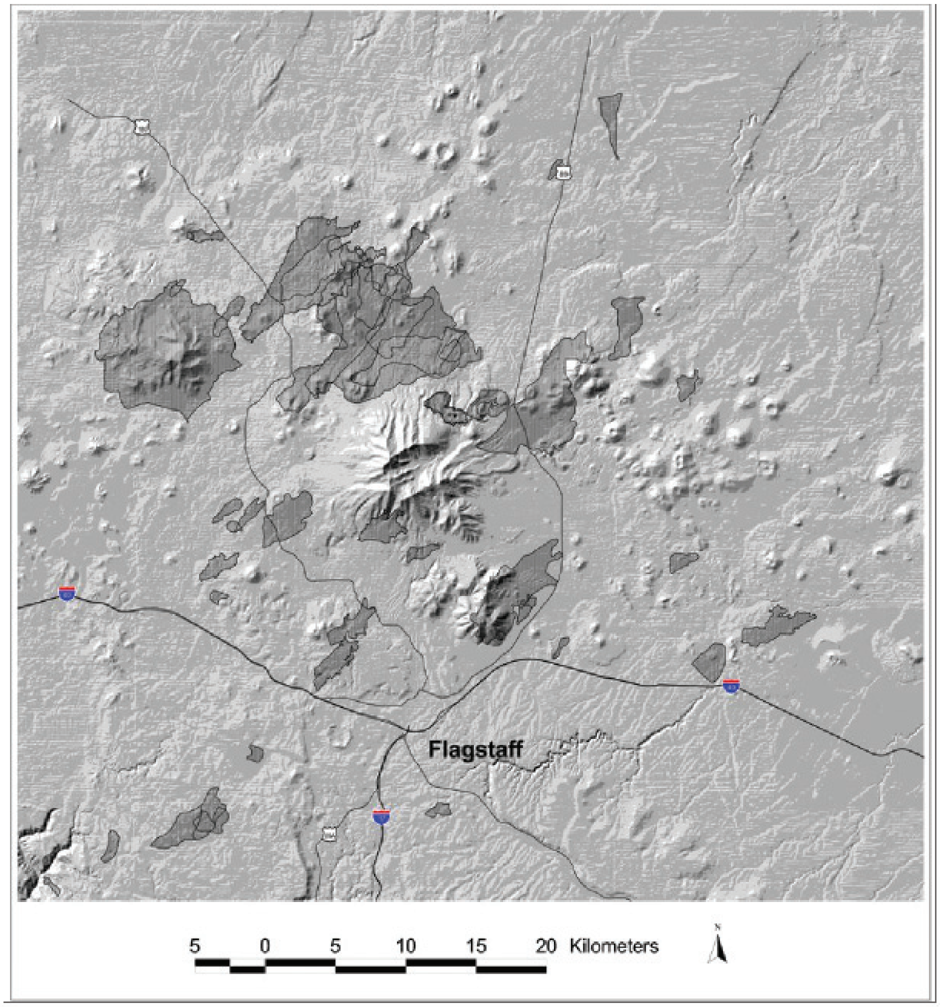

Figure 1—Fire history atlas around Flagstaff, Arizona shows large fires are mostly oriented along a southwest-northeast axis. Wind conditions associated with these fires are about 35 mph (56 kph) with fuel moistures from 3 to 5 percent.

present the greatest threats to human developments beyond the borders of the wildlands *per se*. Managing the condition of the landscape and the spatial fuel structure, therefore, offers the only possible means to resist the growth of fires under such conditions, reducing the spread rate and ultimate size of the fires (Gill and Bradstock 1998, Brackebusch 1973). This contrasts with the use of fuel breaks (Green 1977, Weatherspoon and Skinner 1995, Agee et al. 2000) which require active fire suppression for benefits to be realized. Fuel is the only element of fire behavior that is manageable, since weather and topography are beyond human control.

Weather Conditions

By targeting large fires for treatment efforts, the analysis of fire behavior can be restricted to a small subset of weather conditions contributing to the growth of those kinds of fires. Large fires typically occur under the most extreme weather conditions that originate their escape from initial attack. The weather during historic large fires is well known to local fire management officials and can be synthesized from climatological records (Rothermel 1998, Mutch 1998). These weather conditions provide critical data on general fire spread directions and spread rates for all fuel types on the landscape and narrows the focus of fuel management efforts to specific ranges of humidity, fuel moisture, and winds (Figure 1). By assuming a single set of specific weather conditions for large fires (fuel moistures across a landscape, wind speed and direction) fire behavior can be calculated for all areas of each landscape.

Sizes of Fires Greater than Fuel Treatment Units

The large size of these fires relative to the size of treatment units also suggests that the starting locations of fires can be ignored. This assumption allows the analysis to focus on the directions of fire movement. Large fires moving across landscapes encounter smaller treatment units with relatively wide fronts that have become largely independent of the exact ignition location. The major direction of fire movement is, however, critical because the rapid spread rates of the heading fire (moving with wind and slope) burn the most acreage with the highest intensities (Catchpole et al. 1982). Heading fire is more important to modify than flanking and backing portions of the fire which have lower intensities and cause less severe fire impacts.

Fuel Treatments

The fuel treatment optimization procedure described below depends on fire behavior contrasts between the two fuel profiles burning under the target weather conditions: one represents the starting conditions or current state of fuels and forest structure, and the second represents the fuel conditions following treatment (Figure 2). The assumption here is that desired fuel conditions can be identified on a stand-by-stand basis across the landscape for all stands where treatment is possible. These fuel conditions are represented across a large landscape as a rectangular grid at a fixed resolution. The cells of the grid are assumed uniform at scales finer than the resolution in terms of fuels, topography, and weather. The treated landscape describes the potential areas for treatment that must total more than the constraint imposed on total area treatable within the planning horizon. Treatment prescriptions within each stand or cell on a landscape, such as prescribed burning or various stand-level thinning guidelines can vary to reflect local objectives or restrictions on activities. Although any prescription can be applied, field evidence consistently suggests that fuel treatment prescriptions achieve reductions in wildfire spread rate and intensity by removing surface fuels through prescribed burning and decreasing the continuity between surface and canopy fuel strata through "low-thinning" (van Wagtendonk 1996, Pollet and Omi 2002, Agee and Skinner 2005). Mechanical treatments that leave slash or don't remove pre-existing surface fuels may not change fire behavior sufficiently (Graham 2003, Raymond and Peterson 2005, Cram et al. 2006) or even exacerbate fuel hazards (Alexander and Yancik 1977). Lands excluded from treatment consideration retain the identical fuel descriptions in both landscapes or involve prescriptions that increase the fire spread rate. Thus, the optimization will choose from the lands where treatments change fire behavior to achieve the greatest collective reduction in landscape fire spread rate.

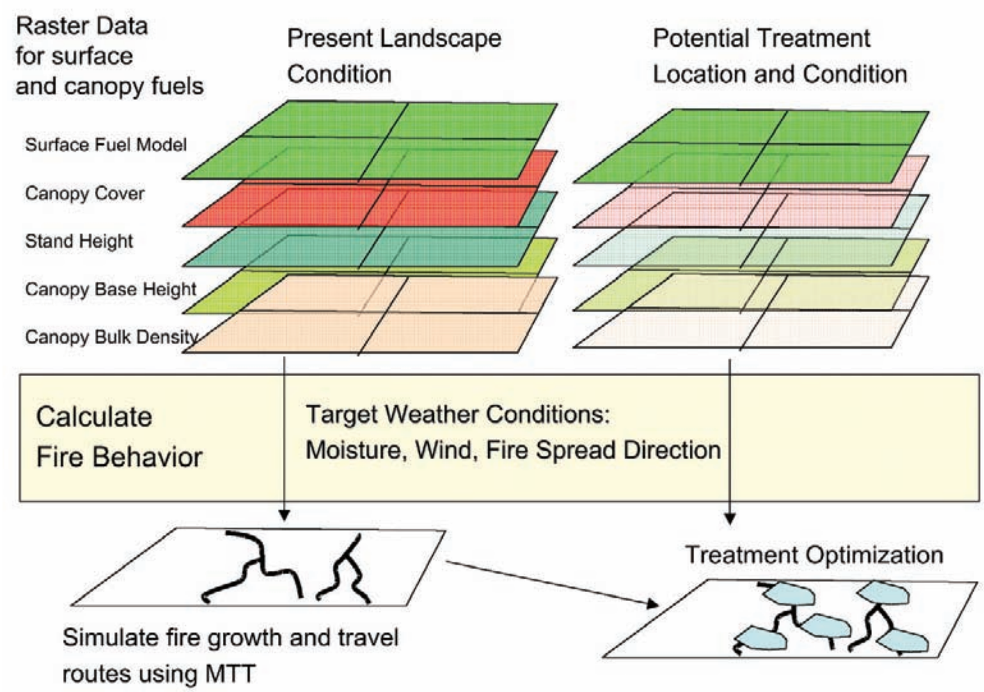

Figure 2—Two landscape fuel conditions area required for the optimization algorithm. The first landscape represents the pre-treatment or current fuel conditions whereas the second landscape represents the potential treatment conditions (i.e. modifications of fuel strata) everywhere treatments can potentially be located. Both landscapes are processed for fire behavior under the "target" weather conditions (i.e. those weather conditions that the treatments are designed for).

Algorithm

The objective of the fuel treatment optimization is to find the specific treatment areas that reduce fire growth for the target weather conditions by the greatest amount. In other words, it is attempting to maximize the minimum travel time for fire moving across the landscape. With the emphasis on fire travel time, a critical component of this optimization is a method for calculating fire growth under the target weather conditions. Fire growth simulation using a minimum-travel-time algorithm (Finney 2002b) is well suited to this task because it rapidly produces a fire arrival time field for a given ignition (which can be contoured to visualize fire growth at constant time intervals) and records the travel routes of fire movement from one node to the next (Figure 3). Both fire growth contours and travel routes are used by the fuel treatment optimization.

The optimization algorithm begins by dividing the landscape into a series of parallel strips oriented perpendicular to the main fire spread direction (Figure 3). The width of these strips is determined as a user input that

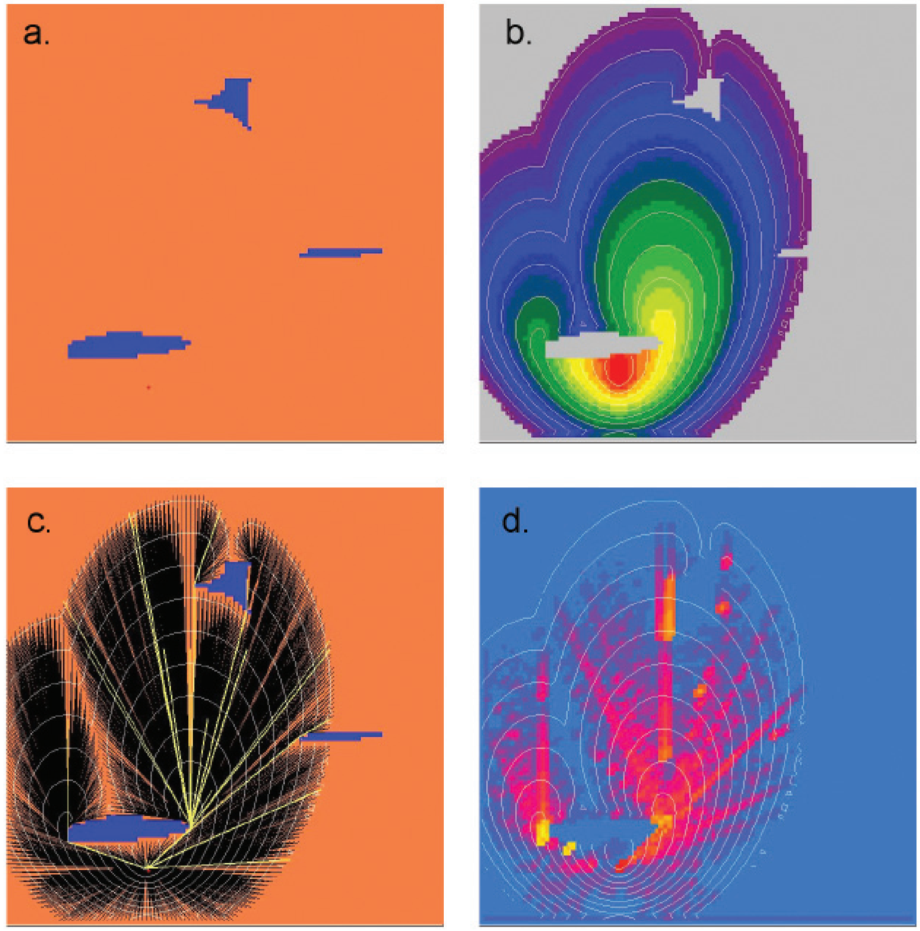

Figure 3—The fire behavior simulation uses a minimum travel-time (MTT) algorithm that (a) for a given landscape (b) produces an arrival time map which can be contoured to indicate fire progression and (c) displayed along with fire travel routes which correspond to calculations of "fire influence" (i.e. the area burned as a result of burning through that grid cell). All travel paths are shown in (c) as fine black lines and the "major" travel paths chosen at specified distance intervals and are indicated by bold yellow lines.

regulates the maximum dimension of treatment units allowed. This is similar to the method described by Finney 2002b, but this algorithm produces a deterministic solution:

1. Beginning with the upwind strip, fire growth and minimum travel routes are computed (Figure 4a). Concave segments along the fire arrival time contour are identified. These segments are concave in terms of the fire arrival time at a particular row of the landscape, which means that they start and end with a local maximum arrival time (Figure 4b).
2. Within the strip, the minimum travel time path for each segment is identified and followed backwards in time and space to record intersections with areas where fire behavior differences exist between the two landscapes (Figure 4c).
3. A choice is made for the best place to start the fuel treatments for each segment. The choice was based on criteria of having the earliest time where fuel treatments are possible. Arrival times are reset to infinity for all nodes (on the entire landscape) having an arrival time <u>later</u> than the time at the starting location.

4. The minimum travel-time algorithm is re-run for the strip using the post-treatment landscape data (Figure 4d). This is done for the entire strip separately for each segment identified in #1 above since the time contour used as starting point for fuel treatments identified in step 3 is typically different for each segment. The new arrival time map is stored for each segment and represents the rate of fire growth assuming all fuel treatments have occurred.
5. An iterative procedure identifies and delineates treatment units within the strip that have sizes and shape for efficiently retarding fire growth. A treatment unit is identified as a contiguous group of cells marked as treated using a contagion algorithm (Figure 4e). For each travel path the process marks treatable contiguous cells with arrival times greater than the starting point up to a time limit that is iteratively increased until the specified fraction of the landscape (strip) is treated. For each treatment unit, the contiguous block of marked cells is expanded laterally until the forward time difference is also reached. This creates a treatment unit that approximates the balance between time required for spreading through the unit and spreading around the unit (Finney 2001a).

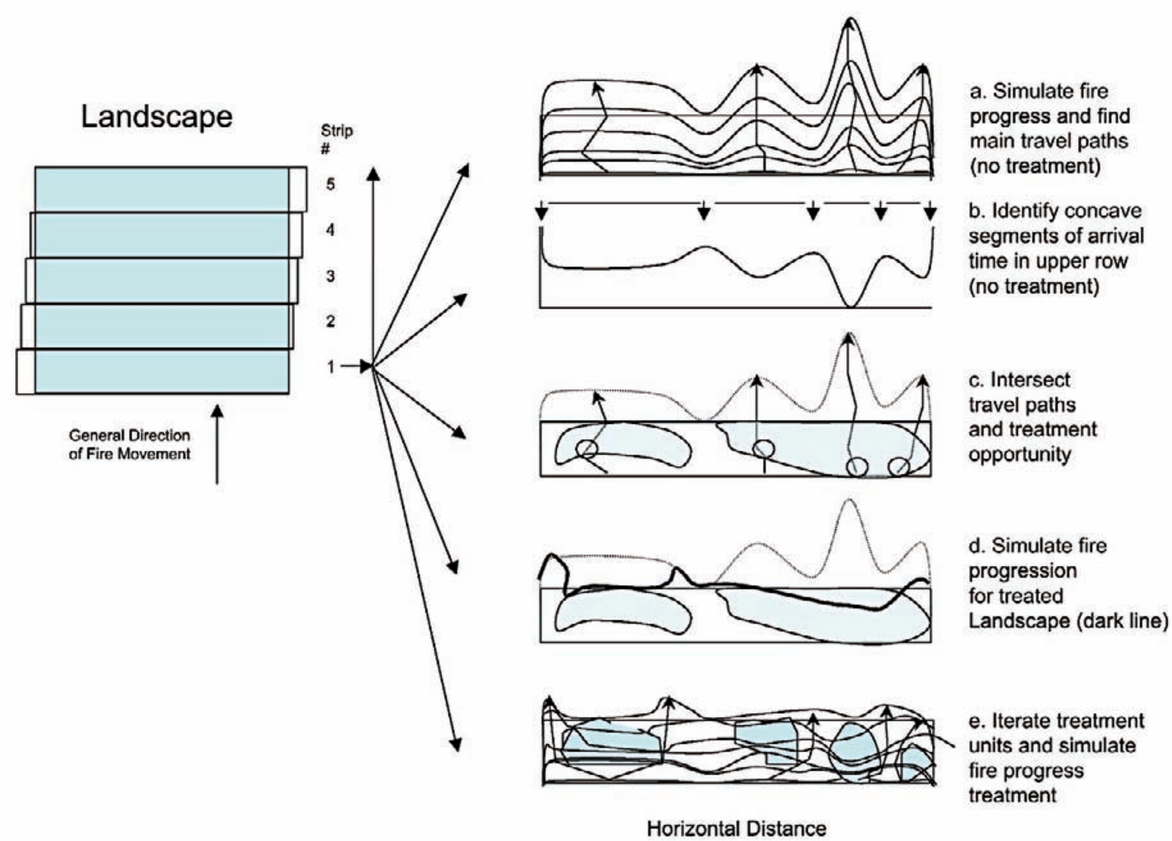

Figure 4—Optimization process begins by dividing the landscape into rows. For each row beginning with the row farthest upwind (a) fire growth for the pre-treatment landscape is calculated using the MTT calculation to identify travel routes and produce an arrival time map (b) the concave segments of arrival time are identified at the ending row, (c) intersections of the major fire travel paths and the treatment opportunity are identified (areas where treatments reduce the fires spread rate) and the point with the earliest arrival time of this intersection is recorded, (d) fire growth for the potential landscape is calculated from the starting time identified in (c), and (e) iteration of treatment unit size and shape is performed.

The algorithm assumes that the fire front will have a rippled time contour or "fingers" at the forward edge produced by varying spread rates that result from fuels, topography, or wind patterns. The algorithm targets fuel treatments to block these fingers since they are local zones of faster spread. For relatively uniform conditions, where little or no variation exists, the algorithm must be modified to place fuel treatments by some other rule. The rule used here within a given strip was a systematic and regular spacing, which produces the ripples at later time periods.

In optimal regular patterns (Finney 2001a) the most efficient treatment unit size depends on overlap and separation of neighboring treatment units. These dimensions are constant among units, and as such, are difficult to transfer directly to actual landscapes that contain complex variation in fuels, topography, and perhaps weather (wind direction, fuel moisture). The regular patterns don't apply here because the size and orientation of a given treatment unit is only efficient in the context of other possible units encountered immediately before and after by fire moving across the landscape. Yet, each unit modifies the path of fire into succeeding units. Thus, a compromise was undertaken for the algorithm that assumes that the delay of fire spread through the unit must be twice the delay in circumventing it. This will not be strictly valid if the fuel conditions downwind of the treatment unit are substantially different from those upwind.

Evaluation of the Algorithm

Two kinds of landscapes were used to evaluate the performance of the algorithm. First, an artificial simple landscape with several slow-burning fuel patches was used to test the ability of the algorithm to produce treatment patterns similar to the theoretical patterns described by Finney (2001) and illustrate the sensitivity to localized non-uniformities in the landscape. Here fuel treatments were implemented to reduce spread rate to 1/20th of the untreated rate. The second landscape was located near Flagstaff Arizona. The historic fires were plotted and the predominant SW to NE orientation of the large wildfires was used to orient the treatment units against this major spread direction. Weather for the fire simulations were chosen at 99th percentile of the historic National Fire Danger Rating System (NFDRS) index Energy Release Component for fuel model "g" (ERC(g)) which provides the fuel moisture content of the fuel components required for fire behavior modeling. Wind speed and wind directions were chosen to reflect the period of major fire growth associated with the historic large fires (Figure 1) that have burned in this area. Treatment prescriptions were only applied to ponderosa pine and mixed conifer forest areas in public ownership and consisted of changing surface fuels to fuel model 9 (Anderson 1982) increasing the crown base height and decreasing crown bulk density (both making crown fire more difficult). No treatment was permitted in meadows, on privately owned lands, or in a designated USFS Wilderness area in the north part of the area.

The response of the fire behavior to the various treatment options was measured in terms of average spread rate, relative change in wildfire size, and conditional burn probability. The conditional burn probability was determined by random fires simulated under the target weather conditions (Finney 2002a) for varying amounts of time (resulting in various fire sizes after 360, 720, and 1080 minutes of spread). This probability is "conditional" because is represents the probability of burning once a fire becomes large (>100 ha) or escapes initial attack, which typically occurs at a rate of less than 2% per year (NIFC 2002, Neuenschwander et al. 2000). Mean spread rate was obtained by dividing the average arrival time for the last row in the landscape by the linear travel distance.

Results

Treatment optimization for the simple landscape produced partially overlapping patterns similar to those of the analytical model (Finney 2001a) with the exception of the downwind edge of the few slow-burning patches (Figure 5). Patterns were similar when the optimization was directed to vary the sizes of treatment units. The average spread rate of the fire across the entire landscape showed the same response to increasing amounts of treatment as average fire sizes and average burn probability (Figure 6) for a given size of simulated fire. Burn probabilities were higher when larger fires were simulated but responded the same across the range of treatment percentages (Figure 6b,c). In addition, the increased efficiency of the optimal pattern compared to random treatment patterns was similar to the same comparisons for theoretical patterns (e.g. Finney 2003).

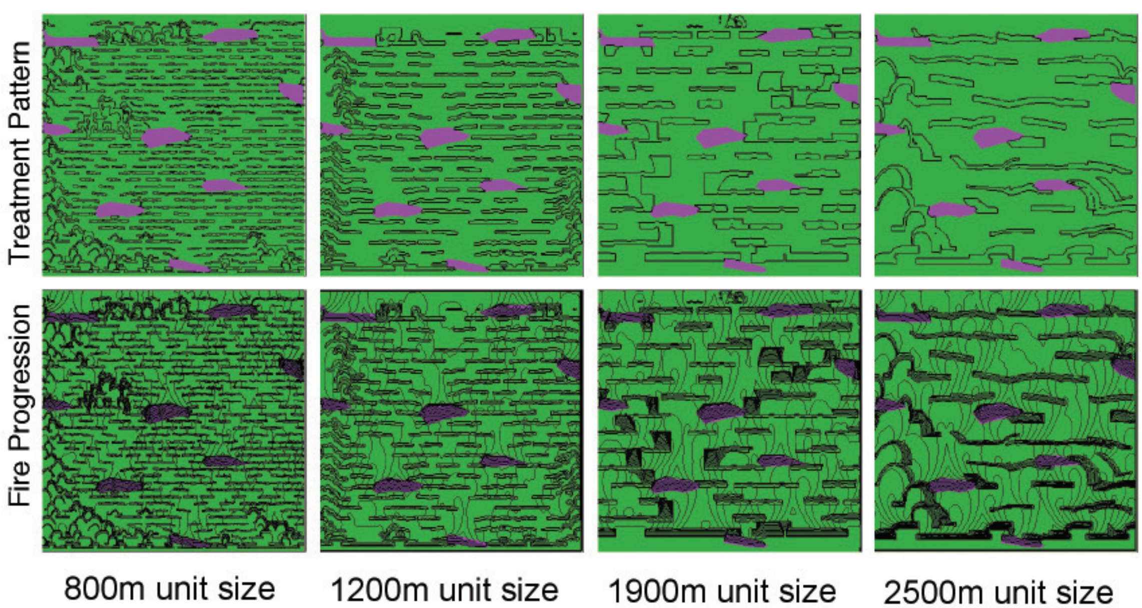

Figure 5—Treatment optimization runs for a simple flat landscape that contains eight small patches of slow-burning fuel (purple). From left to right the maximum treatment dimension is increased from 800 m to 2,500 m. Treatment units are shown independently along with the fire progression which reveals that treatment units cause repeated disruptions of fire movements.

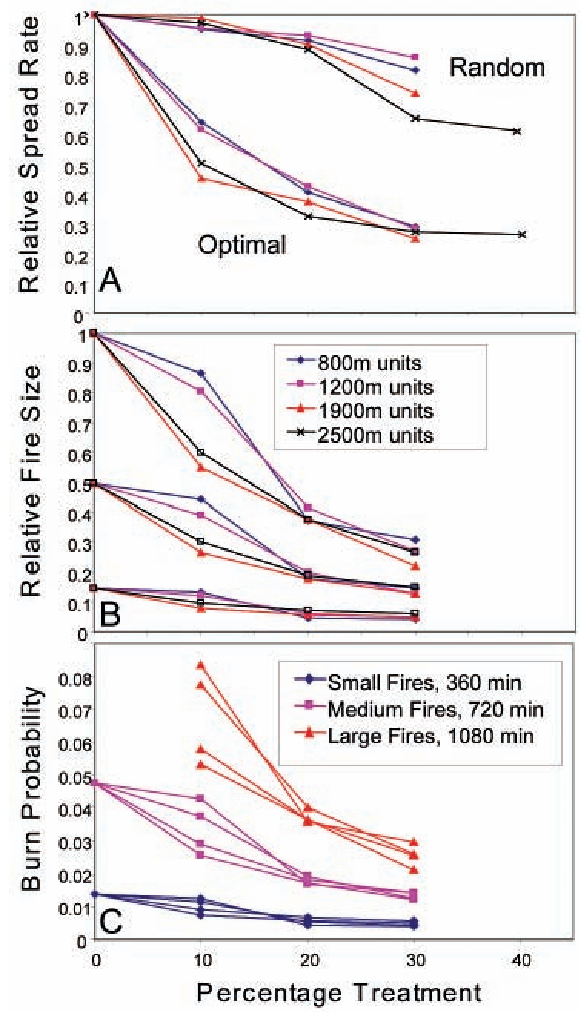

Figure 6—Summary of optimization results for simple landscapes over ranges of treatment amount were measured in terms of (a) average spread rate across the landscape, (b) average fire sizes for 1,000 simulated randomly ignited fires of different durations, and (c) average burn probability for the landscape determined from 1,000 random ignitions.

The optimal patterns for the Flagstaff landscape were less systematic than the patterns on the real landscape (Figure 7) and were strongly influenced by areas where treatment was precluded by ownership (private and designated wilderness) or vegetation type (i.e. meadows represented by grass fuels (Fuel Model 1)). The optimal pattern was more efficient at all levels of treatment than the random pattern (Figure 8a). However, the presence of untreatable area interspersed among the forests provided conduits for rapid fire spread and decreased the efficiency of the optimal pattern in retarding overall fire growth compared to random patterns as seen in the simple landscape and theoretical comparisons (Figure 8a). As with the simple landscapes, the relative fire sizes and conditional burn probability decreased with amount of treatment (Figure 8b,c).

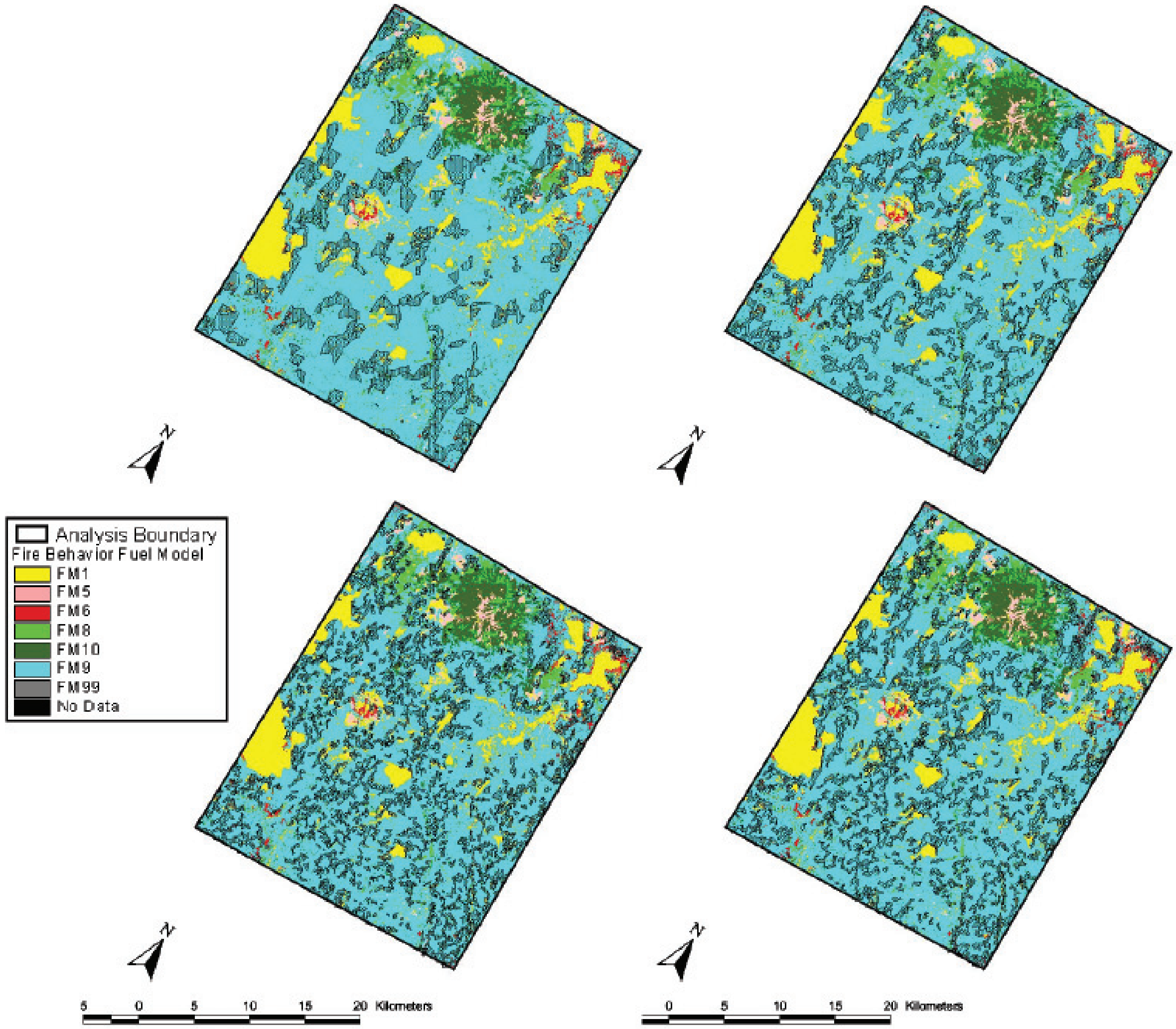

Figure 7—Optimal treatment patterns for the Forest Ecosystem Restoration Analysis project (FERA) for an area surrounding Flagstaff, Arizona. Each pattern represents 20% of the analysis area in treatments with only the treatment size varying by alternative. 2,500 m (a), 1,200 m (b), 800 m (c), and 600 m (d). The analysis area is 2,906 km^2 and 168,853 ha within the Kaibab and Coconino National Forests and is a portion of a larger landscapes (809,375 ha).

Discussion

This study showed that an optimization algorithm produced treatment patterns on simple landscapes with impacts on spread rate similar to the analytical solutions for similar landscapes (Finney 2001a). This is encouraging because performance on complex landscapes cannot be directly assessed relative to theoretical results. Relative performance of optimal patterns on both simple and complex landscapes could be assessed in relation to random patterns. This comparison suggested that optimization efficiently reduced spread in both landscapes but that the presence of untreatable areas within the landscape compromises the efficiency of the overall pattern. The poor efficiency of the random patterns is also similar to theoretical results (Finney 2003).

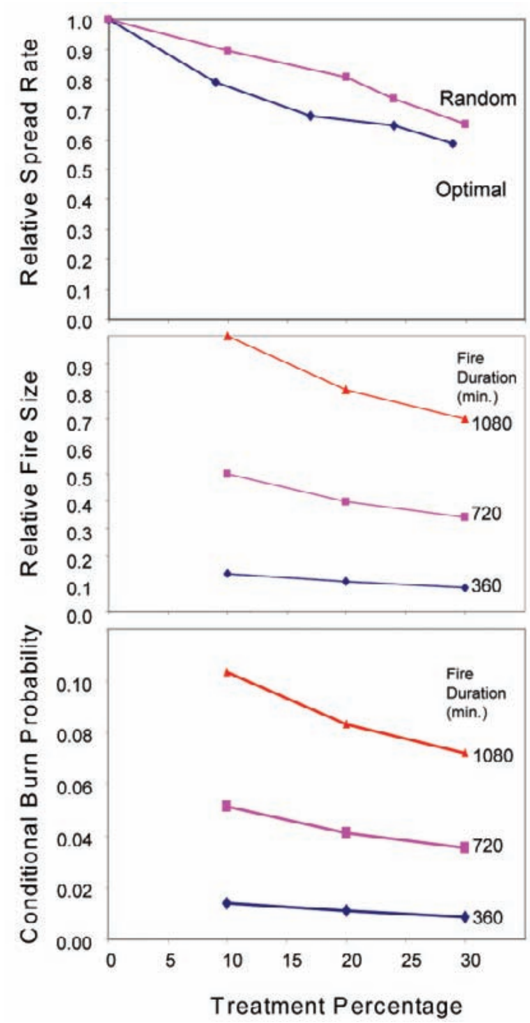

Figure 8—Optimal and random treatment patterns for 1,500 m units on the Flagstaff landscape reduced fire spread rate (a), mean fire sizes (b), and conditional burn probability (c) efficiently compared to random treatments. Although fuel treatments individually reduced fire spread rate by about 90%, the collective benefit of even the optimal pattern was compromised by the presence of large grass meadows that could not be treated. Grass fuels with full wind exposure had spread rates more than four times faster than the forest fuel types and served as conduits for fire growth which reduced effectiveness of treatment pattern in minimizing overall fire growth.

The intent of the optimization was to target treatment locations in areas where fire flow is greatest, meaning that these areas have greater influence on the area burned downwind. The position of the treatment units relative to the slow-burning patches that existed before treatment illustrated how treatment units were positioned to avoid the lee-side wake on the back-side of each of these patches. The major flow paths are located laterally around the left and right flanks of the slow-patches and directed the location of the treatment units.

Maximum treatment unit dimension was varied from 800 to 2,500 m (~0.5 to 1.5 mile diameter, or up to 160 to 960 acres if the units were square) in the optimization but made little difference to the aggregated spread rate, burn probabilities, or the average fire sizes. The flexibility of treatment size would be important to application of treatment units to different landscapes, ecology, topography, and constraints on treatment as illustrated by the Flagstaff example where meadows could not be treated (Figure 7). Treatment unit sizes also affect the optimal spacing between units and appropriateness for wildfires in different fire regimes. Large fire patterns may permit large treatment units and wide spacing, but smaller fires are theoretically little affected by widely spaced treatment units. The possible enhancement of treatment longevity associated with larger units (Finney et al. 2005) may be an additional consideration in selecting treatment sizes for the optimization.

The algorithm developed here was intentionally designed to produce "greedy" solutions for individual treatment units by blocking flow-paths that are identified as "major" only within the current strip. An alternative would be to identify and block fire flow-paths that become important farther downwind than the immediate strip. These two approaches will probably diverge for more complex landscapes because remote downwind landscape conditions (e.g. fuels and topography) may obviate a local pathway. The emphasis on a greedy solution has two advantages. First, it is faster computationally because fire growth does not have to be simulated far downwind from the current strip. Second, and perhaps more importantly for fire management applications, the greedy solution situates a treatment unit on a locally major pathway which increases the proximity of a well-placed treatment unit to a randomly located ignition source.

Amount of treatment tested was limited to 40 percent because theoretical differences between the optimal and random treatment patterns diminish with treatment cover above some level around this point (Finney 2003, 2004). This means that if financial or operational resources permit landscape treatment at a rate sufficient to maintain a landscape at about 30 or 40% treatment annually, then the spatial pattern becomes less important and optimization is not as useful. In natural fire regimes, observed interference by fire history patterns on subsequent wildfire growth (van Wagetndonk 1995, Parsons and van Wagtendonk 1996) is derived from largely random ignition patterns only because the frequency of fire is sufficient to maintain a large fraction of the landscape in a fuel-modified condition.

The spatial optimization assumes that the spatial pattern is extant at a given instant in time. In reality, however, treatments are accomplished on an annual basis and treatment effects to reduced fire behavior diminish with time. To achieve an effective spatial pattern means that the annual rate of treatment or maintenance must be high enough to achieve the cumulative spatial pattern while treatment effectiveness decreases. Little is known about treatment longevity but a few studies suggest that benefits to fire effects are limited to about 10 to 15 years (Biswell et al. 1973, Fernandes et al. 2004, Finney et al. 2005). Consequently, this suggests that the minimum annual treatment rate can be estimated to be about $1/10^{th}$ of the total treatment cover desired. For example, if treatment of 20% of the landscape is a desired state, then the annual rate of treatment must be no lower than approximately 2%.

Spatial constraints are accommodated in the treatment optimization automatically where fire behavior is identical between pre-treatment and potential treatment landscapes. Areas where fuel treatment changes fire spread rate will be considered available for treatment and perhaps selected if intersected by major fire travel paths. Those areas where treatments are not possible contain the same fuel conditions in both landscapes, thereby offering no contrast in fire behavior and no reason for selecting them for treatment even if major flow paths intersect these areas. Such effects can be seen in the large areas with no treatment in the Flagstaff example because of the location of grass meadows and designated wilderness areas that are not available for treatment even though the fire may spread very rapidly (Figure 7).

The current algorithms neglect effects of spotting on fire progression and fuel treatment locations. Spotting is a fire behavior that includes the lofting and transport of burning embers downwind which start new fires and permit fire to breach barriers and discontinuities of fuels. Models for ember production and transport (Albini 1979) are included in other fire behavior systems (Finney 1998) and can be included here in future. The exact effect of spotting on treatment performance is not clear because fuel treatments often limit the source of new embers as well as retard the growth of eventual spot fires. Spotting effects may be minimized by manually increasing the size of treatment units to mitigate overflight possibilities. But longer separation distances between larger treatments permit wider headfires to develop in between treatment units which may increase spot fire generation. Even if spot fires breach the treatment units, an extensive landscape pattern of treatments would impose repeated interruption of any new fires.

Conclusions

The optimization procedure was developed with the intent of obstructing the movement of large wildfires rather than containing them. The algorithm was capable of reducing the average fire growth rate efficiently for complex and simple landscapes. This procedure can be useful for inclusion in fire management planning activities because it offers a means of measuring the performance of fuel treatments at both a stand- and landscape-level.

Acknowledgments

This study was funded by the U.S. Joint Fire Sciences Program, the Bureau of Land Management (BLM), and the USDA Forest Service, Missoula Fire Sciences Laboratory. The author is grateful to Charles McHugh, Rob Seli, and Rick Stratton for their efforts in testing the optimization model and helping prepare data and graphics for this paper. Howard Roose provided critical funding from the BLM for software development.

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Simulation of Long-Term Landscape-Level Fuel Treatment Effects on Large Wildfires

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***Abstract**—A simulation system was developed to explore how fuel treatments placed in random and optimal spatial patterns affect the growth and behavior of large fires when implemented at different rates over the course of five decades. The system consists of a forest/fuel dynamics simulation module (FVS), logic for deriving fuel model dynamics from FVS output, a spatial fuel treatment optimization program, and spatial fire growth and behavior model to evaluate the performance of the treatments in modifying large fires. Simulations were performed for three study areas: Sanders County in western Montana, the Stanislaus National Forest in California, and the Blue Mountains in eastern Oregon. Response variables reported here include: (1) fire size distributions, (2) large fire spread rates, and (3) burn probabilities, and all revealed the same trends. For different spatial treatment strategies, our results illustrate how the rate of fuel treatment (percentage of land area treated per decade) competes against the rates of fuel recovery to determine how fuel treatments accrue multi-decade cumulative impacts on the response variables. Using fuel treatment prescriptions that involve thinning and prescribed burning, even optimal treatment arrangements (designed to disrupt the growth of large fires) require at least 10% to 20% of the landscape to be treated each decade. Randomly arranged units with the same treatment prescriptions require about twice that rate to produce the same effectiveness. The results also show that the fuel treatment optimization tends to balance maintenance of previous units with treatment of new units. For example, with 20% landscape treatment, fewer than 5% of the units received 3 or more treatments in 5 decades with most being treated only once or twice and about 35% remaining untreated the entire planning period.*

Introduction

Benefits of fuel treatments for mitigating the severity of wildfires have been documented at the stand level for much of the 20th century (Weaver 1943, Cooper 1961, Biswell et al. 1973), particularly in ponderosa pine and dry mixed conifer forests in the western United States (ponderosa pine and Douglas-fir). Recent large wildfires have stimulated renewed interest in fuel treatments and prompted new studies that have confirmed these findings (Pollet and Omi 2002, Graham 2003, Graham et al. 2004, Raymond and Peterson 2005, Agee and Skinner 2005, Cram et al. 2006). Beyond the immediate stand level (i.e. fuel changes over time and large spatial scales) treatment effects are poorly understood. Only a few studies of treatment longevity exist (Biswell et al. 1973, van Wagtendonk and Sydoriak 1987, Finney et al. 2005) and indicate diminishing benefits beyond about a decade. Landscape-level effects from various treatment patterns are still largely theoretical (Finney 2001a, 2003, Hirsch et al. 2001) with few observations of

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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treatment performance in altering fire movement (Finney 2005). Given the difficulty with implementing large-scale and long-term experiments in fuel treatment, this study sought to use computer simulation to explore complex interactions of landscape treatment pattern and temporal vegetation/fuel changes in addressing the following questions:

1. What effect does spatial treatment pattern have on fire growth on complex landscapes?
2. At what rate must fuel treatments be implemented across a landscape to produce aggregated or cumulative effects on wildfire growth?
3. For purposes of disrupting fire growth, should existing fuel treatment units be maintained or should effort be made to implement new treatment units?
4. How do restrictions or constraints on fuel treatment location (because of conflicting land management objectives) affect treatment benefits?
5. How do landscape-level fuel treatment patterns perform under weather scenarios more moderate than the extreme conditions specified in their design?

Methods

Our objectives were to produce a simulation system that implements fuel treatments over large landscapes in order to evaluate the impact on potential fire behavior over multiple decades. The system (Figure 1) consisted of:

1. The Forest Vegetation Simulator (FVS) for simulating the changes over time in forest vegetation (Crookston and Stage 1991) and fuels (Reinhardt and Crookston 2003). The FVS models were used for multiple stands comprising a landscape and for implementing the treatment prescriptions.

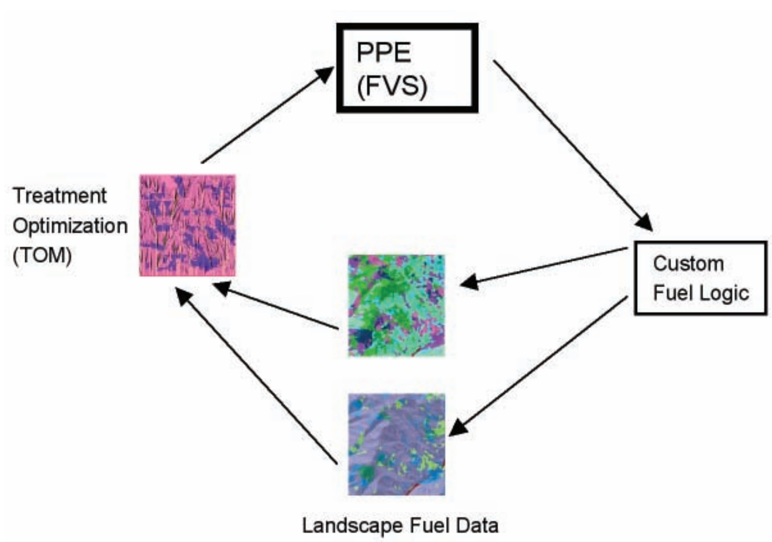

Figure 1—The simulation system was run for each decade. This system consisted of the Parallel Processing version of the Forest Vegetation Simulator (PPE-FVS) that simulated forest development with and without treatment, derivation of surface fuel models from the biomass categories and production of spatial landscapes for each scenario, spatial optimization of fuel treatment locations for disrupting fire growth, and implementation of treatments as feedback for the next simulation cycle in PPE-FVS.

2. A spatial model for choosing the location of treatment units using optimal or random selection logic (Finney 2002a, 2004, Finney in prep.).
3. A fire growth simulation model used to evaluate the impact of treatments in terms of fire growth rate, fire sizes, and relative burn probability (Finney 2002b).

Simulating Forest and Fuel Conditions and Treatment Prescriptions using FVS

The Forest Vegetation Simulator (FVS) is widely used in the U.S. for forest growth and yield modeling (Wykoff et al. 1982) and has recently been modified to record information on fuels and woody debris (Reinhardt and Crookston 2003). FVS has multiple "variants" that correspond to species, growth rates, and fuel types of forests in numerous regions throughout the U.S. Our system relied on a custom verson of the Parallel Processing Extension (PPE) of FVS (Crookston and Stage 1991) which processes the stand list cycle-by-cycle (rather than one at a time for all cycles as in the normal version of FVS) and implements specific silvicultural and fuel treatment prescriptions (i.e. modifies forest and fuel structures). This custom version of PPE controls the simulation loop that calls separate routines outside of PPE that identify specific stands to treat. The PPE module then implements the prescriptions and processes the growth and fuel deposition for the next simulation cycle.

The stand-level prescriptions representing fuel treatments in FVS were specifically developed for treating fuels rather than to extract forest products (e.g. timber volume) or meet long-term ecological objectives. Treatments that include removal of surface fuels by prescribed burning have shown the greatest effectiveness in reducing fire intensity and severity (Helms 1979, Martin et al. 1989, Fernandes 2003, Raymond and Peterson 2005, Agee and Skinner 2005), either alone or in combination with silvicultural activities that reduce vertical and horizontal continuity of canopy fuels (Hirsch and Pengelly 1999, van Wagtendonk 1996, Stephens 1998, Graham et al. 1999, Agee et al. 2000, Cram et. al. 2006). Canopy fuel parameters that influence crown fire include crown base height and canopy bulk density (Agee 1996, Scott and Reinhardt 2001, Agee and Skinner 2005). Treatments that only involve cutting or canopy manipulation without surface fuel mitigation were not implemented here because these activities often increase fuel availability (Alexander and Yancik 1977, van Wagtendonk 1996, Brown et al. 2004, Stephens and Moghaddas 2005, Raymond and Peterson 2005). Based on the precedence of modifying surface fuels whenever canopy fuels are manipulated, prescriptions were developed for each stand on the entire landscape based on the forest species composition, structural stage, and general understory fuel type (e.g. shrubs, grass, litter).

- Prescribed burning only. This prescription was used for maintenance of the surface fuels when there was no need to reduce aerial fuels. This prescription reduces surface fuels only and may kill small understory trees and regeneration using the mortality functions in FVS (Table 1).
- Prescribed burning after various harvest prescriptions (typically low-thinning). This treatment removes slash from the mechanical activities as well as the pre-existing surface fuels (Table 1).

FVS requires a "tree-list" to be supplied for each stand. A tree list contains the number of trees by species and stem-diameter class. FVS also requires initialization of dead and downed "fuel pools" which represent the current loading states of various fuel components and are critical to consequent fuel

Table 1—FVS treatment prescriptions were developed to work inside of FVS/PPE which provided a variety of general fuel treatments based on stand and fuel conditions at the beginning of each decade.

Seedling/Sapling size class
Thin from below to 1580 trees/ha (640 trees/acre)
If 0 to 7.62cm diameter fuel loading (0-3 inch) >= 5.6Mg/ha (2.5 tons/acre)
Pile and burn fuel treatment
Poletimber size class
For fire tolerant forest types (PP & DF)
Thin from below to 30 m^2/ha (130 ft^2/ac) of basal area
Prescribe burn
For fire intolerant forest types (all others)
Thin from below to 34 m^2/ha (150 ft^2/ac) of basal area
Pile and burn fuel treatment
Sawtimber size class
For lodgepole pine forest type
Clearcut with reserves
Prescribe burn
For fire tolerant forest types (PP, DF, WP, & WL)
Thin from below to 32 m^2/ha (140 ft^2/ac) of basal area
Prescribe burn
For fire intolerant forest types (all others)
Thin from below to 34 m^2/ha (150 ft^2/ac). of basal area
Pile and burn fuel treatment

dynamics. Since a landscape is composed of polygons that delineate individual stands, all stand polygons must be assigned a tree list. We used a process called Most Similar Neighbor (MSN, Crookston et al. 2002) that uses a representative sample of tree lists from areas throughout the landscape to imput tree lists to polygons with no local measurements. The MSN process uses canonical correlation analysis, a multivariate technique, to select the tree list that corresponds to the polygon with minimum weighted distance of predictor variables. Tree lists for measured stands were obtained from existing data collected by a) local forest stand exams, and b) Forest Inventory and Analysis plots (FIA) (Van Deusen et al. 1999, McRoberts et al. 2000, Reams et al. 2001). The size of stand polygons was approximately the same for each study site, varying from 5 ha to 10 ha.

The output from the PPE version of FVS is contained in a table of stand conditions each year in the planning period (we used a period of 10 years). This table contains the fuel conditions that would have occurred with no treatment along with those that resulted from application of the treatment prescription that is critical for assessing the impact of the treatment on potential fire behavior. The fuel conditions specified are those required of the fire behavior models used to evaluate wildfire impacts (Finney 1998). The FVS polygon fuels data specifically includes canopy cover, stand height, crown base height, canopy bulk density, as well fuel pools, treatment history, and stand species information for assigning a fuel model (Anderson 1982, Scott and Burgan 2005). Because FVS currently does not utilize the Scott and Burgan surface fuel models, the fuel model assignment for each stand was accomplished outside of FVS-PPE. When the stand conditions are mapped spatially to the polygon locations, a forest landscape can be constructed to contrast the effects of treatment for all stands in terms of fire behavior variables. Non-forested polygon fuel conditions (e.g. grass, rock) were held constant through the simulation.

Spatial Locations of Fuel Treatments

Having two sets of landscape fuel conditions each decade (depicting conditions with and without treatment) makes it possible to spatially delineate areas where fuel treatments are effective at changing stand-level fire behavior. Treatments were only considered possible for areas where fire behavior would be modified by implementing that prescription (e.g. thinning and prescribed burning of a particular stand could not be conducted in sequential decades if the second treatment did not reduce fire spread rate). Thus, the landscape configuration of areas suitable or available for fuel treatment would vary from decade to decade.

To move from the stand-level to the landscape-level, the spatial treatment optimization attempts to locate a specified percentage of these stands to treat, which optimally disrupt the growth or movement of large fires across that landscape (Finney 2002a, 2004, Finney in prep.). This optimization numerically implements the concepts described by Finney (2001a) for an optimal spatial arrangement of discrete units on a simple landscape that can be solved analytically. For complex real landscapes, a numerical technique is required, and makes use of a fire growth technique (Finney 2002b) to identify major travel paths produced by fires growing under a set of specified weather conditions. These weather conditions are obtained from historic local climatology associated with large and extreme fires.

The algorithm finds intersections between the fire travel paths and stands where the treatments slow the fire under the specified “target” weather conditions. Target weather conditions are synthesized for a particular study area from weather associated with historic large fires for which suppression is ineffective (Finney 2001a). Weather parameters include fuel moisture, wind speed and wind direction for the afternoon burning period (when the majority of fire area is burned). Typically, most large fires in a particular region have a similar orientation produced by the wind flow of a synoptic weather system that repeatedly contributes to the escape and rapid growth of fires. Thus, selecting these conditions ensures that treatment prescriptions modify fuels to sufficiently change fire behavior when fire suppression is impossible. Stands that slow the fire are identified by the contrast in fire behavior between treated and untreated stands. Fire behavior is calculated for each grid cell of each landscape using an implementation of fire behavior models described by (Finney 1998). Thus, a comparison of spread rate between two locations indicates where treatments reduce spread and can thereby contribute to retarding fire movement.

The spatial optimization technique begins by dividing the landscape into rectangular strips oriented normal to the predominant wind direction (Finney 2002a, 2004, Finney in prep.). Beginning with the strip farthest upwind, fire growth is simulated to identify major fire travel routes and their intersection with potential treatment areas (areas where the fire is slowed by the treatment). The process then iterates to delineate separate treatment units (one for each travel route) as constrained by unit size total treatment area. The orientation of the treatment units will typically be perpendicular to the major fire spread direction because this intercepts the main direction of fire movement. This procedure is followed for each strip moving successively in the direction of the wind because treatments imposed on the landscape affect the downwind fire travel routes and subsequent treatment areas.

For purposes of comparison of the spatial optimization, the spatial fuel treatment module linked to PPE was enabled to perform a random selection of forest stands.

Modeling Landscape-Effectiveness of Fuel Treatments

The performance of the various fuel treatment patterns at each decade were evaluated in terms of the responses of fire growth (Finney 2002b) under the 99th percentile "target conditions. Effects of treatment are measured entirely assuming an absence of fire suppression because the weather conditions targeted for fuel treatment performance have historically been associated with large fires for which suppression efforts were ineffective (i.e. 99th percentile). However, reductions in overall fire growth rates, fire intensity, and fire sizes that would be expected to facilitate suppression action in treated areas and by linking or connecting treatment units by fire control lines (Bunnell 1998).

Wildfire responses were measured with the following metrics:

1. Total fire travel time (and thus, aggregated spread rate across the landscape) under the target weather conditions
2. The sizes of a randomly ignited fires on the landscapes, and
3. The average relative burn probability for all places on the landscape by randomly ignited fires.

The fire travel time was used to calculate the aggregated average fire spread rate of a fire from the upwind to the downwind edge of the landscape. This was performed by igniting the upwind edge of the landscape and running the simulation until it arrived at the downwind edge. The fire size distributions were obtained from simulations of 3,000 randomly located fires across each landscape. These fires were simulated for the same weather conditions identified as the "target" conditions used for the optimization because the fires targeted for treatment performance are those that escape initial attack efforts. This assumes that fire management policies attempt to suppress all fires, leaving to spread only those that cannot be controlled under extreme weather conditions (Table 2). The simulated fires are used to estimate the relative burn probability for the landscape which is derived by tallying the total number of fires that cross each grid cell of the landscape.

Study Areas and Simulation Scenarios

A large number of scenarios were developed for simulating five decades of vegetation dynamics and treatment activity. The main variables evaluated were:

1. Treatment amount (e.g. proportion of the landscape, from 0 to 50%),
2. Maximum treatment unit size (400 to 1600 meters per unit),
3. Treatment unit pattern (optimal vs. random),
4. Reserves of randomly selected areas in the proportion of 15% to 65% of the landscape,
5. Fire simulations under weather percentiles of 90th, 95th, to test treatment performance designed at the 99th percentile.

The study areas were selected to represent some of the variability in forest conditions that exist in the western U.S. The study sites selected for modeling actual landscapes are based on data availability and differences in the fire regime, policy, land ownership, and social context. The variety of conditions

Table 2—Summary of study area attributes and fire weather conditions simulated for fuel treatment optimization.

Study Area, Location and size	Land Ownership	Fire Regimes (general severity classes)	Fire Weather conditions used for fire modeling
Blue Mountains, OR 54,600 ha	• Wallowa-Whitman NF • Umatilla NF • Tribal (Umatilla) • Private (non-industrial) • Private (industrial)	• Low-Mixed Severity	• Wind 48kph, West • Fuel Moisture (1hr 3%, 10hr 4%, 100hr 5%, Live Herb 100%, Live Woody Shrubs 100%)
Sanders County, MT 51,700 ha	• Lolo NF • Kootenai NF • Private (non-industrial) • Private (industrial) • Salish and Kootenai Tribes • MT Department of Natural Resources & Conservation • Sanders County, Montana•	• Low, Mixed, High	• Wind 48kph, West • 10hr 4%, 100hr 5%, Live Herb 100%, Live Woody Shrubs 100%)
Stanislaus NF, CA 40,500 ha	• Stanislaus National Forest • Private (non-industrial) • Private (industrial)	• Currently Mixed-High, but historically low-mixed.	• Wind 48kph, West • 10hr 4%, 100hr 5%, Live Herb 100%, Live Woody Shrubs 100%)

at these sites is intended for comparison of how fuel management objectives (specific in both space and time) can be accomplished in the context of realistic variability, constraints on management activities, and understanding of fire weather conditions. Table 2 contains the fire weather conditions used for each study area associated with 99th percentile Energy Release Component (ERC) from the U.S. National Fire Danger Rating System (Deeming et al. 1977).

Sanders County, Montana—Sanders County consists of 680,000 ha in western Montana along the Idaho border from which a study area of 51,700 ha was selected (Figure 2, Table 2). Land ownership is about 65% National Forest, 10% Plum Creek Timberlands, 5% school trust lands administrated by the Montana Department of Natural Resources and Conservation, and 20% small private landowners. Topography consists of the Bitterroot Mountains with the Flathead and Clark Fork Rivers flowing the length of the county. A wide variety of fuel types are present, with sagebrush/grasslands at the lower elevations in the eastern half of the county, frequent fire interval ponderosa pine (*Pinus ponderosa*) stands throughout, western red cedar (*Thuja plicata*) stands at the west end of the county and lodgepole (*Pinus contorta*) and whitebark pine (*Pinus albicaulis*) stands perpetuated by stand replacement fires at higher elevations. Private lands with the associated towns and improvements are concentrated in the lower elevations along the rivers and consist of the flashier fuel types. Barriers to fuel treatment include habitat concerns for a variety of endangered species; grizzly bear, wolves, lynx, and bull trout. Other issues are water quality limited streams and checkerboard ownership.

Figure 2—The study areas were located in western Montana (Prospect, Sanders County), the Sierra Nevada mountains of California (Stanislaus National Forest), and eastern Oregon (Mill Creek).

Data for the study area of Sanders County, Montana consisted of continuous polygon coverage across all land ownership categories attributed with tree list data for the forested polygons. The polygon coverage was derived from that used in the Northern Region Vegetation Mapping Project (Brewer 2004). Data from USDA Forest Service Forest Inventory and Analysis (FIA) and Salish-Kootenai Tribe Continuous Stand Inventory (CSI) plots (commonly referred to as stand exam, forest inventory data, or observations) were used to create tree lists. Each tree list location or observation was attributed to the polygon it was located in and then imputed to other similar polygons, using nearest neighbor analysis, resulting in all forested polygons having a tree list attributed.

Two sub-areas were chosen from Sanders County (labeled Prospect and Baldy) because of the large size of the County and varying forest types and treatment options. The Prospect area represents the north Idaho forest types such as western hemlock (*Tsuga heterophyla*) and true firs (*Abies* spp.), limited past management activities, continuous dense forest cover, prevalent brush fuels beneath the forest canopy, and predominance of National Forest ownership. The Baldy landscape was smaller and more variable than Prospect. It contained a large rocky area at high elevation surrounded by drier forest types including ponderosa pine and Douglas-fir and was composed of lands administered by Indian tribal governments (Salish and Kootenai tribes) and U.S. National Forest. Significant past management activities have created a variety of age classes, forest structures, surface and aerial fuel conditions.

Stanislaus National Forest, California—The Stanislaus National Forest is 363,000 ha and lies in the heart of the central Sierra Nevada from which 40,500 ha was selected for simulation (Figure 2, Table 2) with 7,754 tree-list polygons. The administrative boundary includes industrial private timberlands and small private parcels, many of which have been developed for housing. Vegetation varies from hard chaparral (*manzanita* species), oak (*Quercus* species) woodlands and ponderosa-pine (*Pinus ponderosa*) stands at the lower elevations to the west to mixed-conifer and red fir (*Abies mognifica*) forest at middle and upper elevations to the east. The western edges of this area are representative of the wildland-urban intermix of the Sierra Nevada foothills. The fire management strategy for the area was outlined recently in the forest plan amendment Record of Decision. This directs the forests in the Sierra Nevada to reduce threats to urban intermix areas and maintain 30 to 40% of the landscape in strategically placed treatments. Treatment effectiveness, landscape design, and monitoring effectiveness are key implementation questions. The fire regime has changed from a predominantly surface fire regime among all forest type prior to settlement to more of a mixed-high severity fire regime since about 100 years of fire exclusion. Surface and crown fuels on all lands now contribute to a relatively continuous fuel complex with the potential for broad destruction and loss of life if a fire should occur under extreme conditions. The foothills of the central and northern Sierra Nevada have recently been prone to these kinds of fires and result in losses and costs in the hundreds of millions of dollars.

Data for the California study area consisted of continuous polygon coverage across all land ownership categories attributed with tree list data for the forested polygons. The Pacific Southwest Region Vegetation Inventory Strata map was used for the polygon coverage. USDA Forest Service, Forest Inventory and Analysis (FIA) data, supplemented with additional plots in rare types and plantations, were used for the tree lists. Each tree list location or observation was attributed to the polygon it was located in and then imputed to other similar polygons, using most-similar-neighbor analysis, resulting in all forested polygons having a tree list attributed.

Mill Creek, Oregon—The Mill Creek study area consists of 256,780 ha of federal and privately owned lands situated southeast of Walla Walla, WA. (Figure 2, Table 2). A subset of this area (54,600 ha) was used for the simulations with a total of 5,732 different stand polygons simulated. The entire area is situated on the west slope of the Blue Mountains, bordered by agricultural lands on the west and the USFS wilderness on the east. The private lands are located on the western edge. About half of the study area is forested with the remaining area covered by a mixture of dry grasslands, wet meadows, and shrubs. Elevations range between 500 m along the lower western edge to over 1,800 m in the east. The forest composition follows elevation, with dry forests of ponderosa pine (*Pinus ponderosa*) intermixed with grasslands in the west, cold forests dominated by subalpine-fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) in the east, and a transition zone containing grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*) in the mid elevations.

Forest stand delineations on the Forest Service portion of the study area were obtained from existing vegetation GIS layers on file at the Umatilla National Forest. Vegetation data and fuel loadings for these stands were obtained from the Umatilla National Forest vegetation database. Tree lists were a mix of field exams and data obtained from nearest neighbor analysis. Stands outside the Forest Service boundary were digitized on orthophotos flown in year 2000, and vegetation and fuels data obtained by field surveys. Photo series including Fischer (1981) were used to estimate initial surface fuel loadings.

We simulated stand-level treatments that consisted of selective thinning from below, mechanical fuels treatment, and underburning. The thinning prescription used the stand density index (SDI), and we triggered a thin in FVS when a stand's SDI exceeded 65% of the maximum SDI as specified in Cochran and others (1994). The thinning prescriptions targeted removal of late-seral, fire intolerant species like grand fir in mixed-species stands, favoring early seral species such as ponderosa pine, western larch and Douglas-fir. We simulated site removal of fuels and underburning after thinning.

Results

The simulation system was designed for multi-processor computers because of the intensive nature of the treatment optimization program and fire growth model. The fire growth algorithms (Finney 2002a) and the treatment optimization module were the most intensive and were run on 16-processor systems. Run times for five decades of simulation ranged from 6 hours to several days depending on the size of the landscape (area and number of cells) and the resolution of the treatments. Treatment units were identified by the treatment optimization (Figure 3) for each landscape for the target weather conditions.

The performance of the treatments was measured in terms of the change in landscape-level fire behavior, including average spread rate, conditional burn probabilities, and average fire sizes. All measures showed identical responses to the treatments (Figure 4) because slower moving fires burning for a specified period of time will be smaller and thus contribute to a lower overall probability of burning any portion of the landscape. Thus, only the relative spread rate is reported for the remaining simulation results. All measures revealed that the landscape fuel conditions, and thus fire behavior, were changing over time even in the absence of treatment (top line in all graphs on Figure 4). The treatment effects must be evaluated with respect to the untreated condition at each decade.

Optimal patterns of treatment units were found to reduce the average fire spread rate efficiently for all study areas in comparison to random patterns (Figure 5). Treatment unit size varied from 400 m to 1,600 m but unit size had little influence on the effect of optimal treatment patterns on fire spread rate regardless of the rate of treatment, simulation time, or study area (Figure 5). The Baldy study size (Sanders County, Montana) showed the greatest variation of relative spread rate (Figure 5f) in relation to treatment sizes from 200 m to 1,600 m, especially as the percentage of area treated increased.

For each study area, the average fire spread rate decreased with percentage of treatment but the amount of reduction varied by study area (Figure 5). Treatments were found to be more efficient for the Prospect study site in Montana than for any of the other study areas (Figure 5). With 10% treatment per

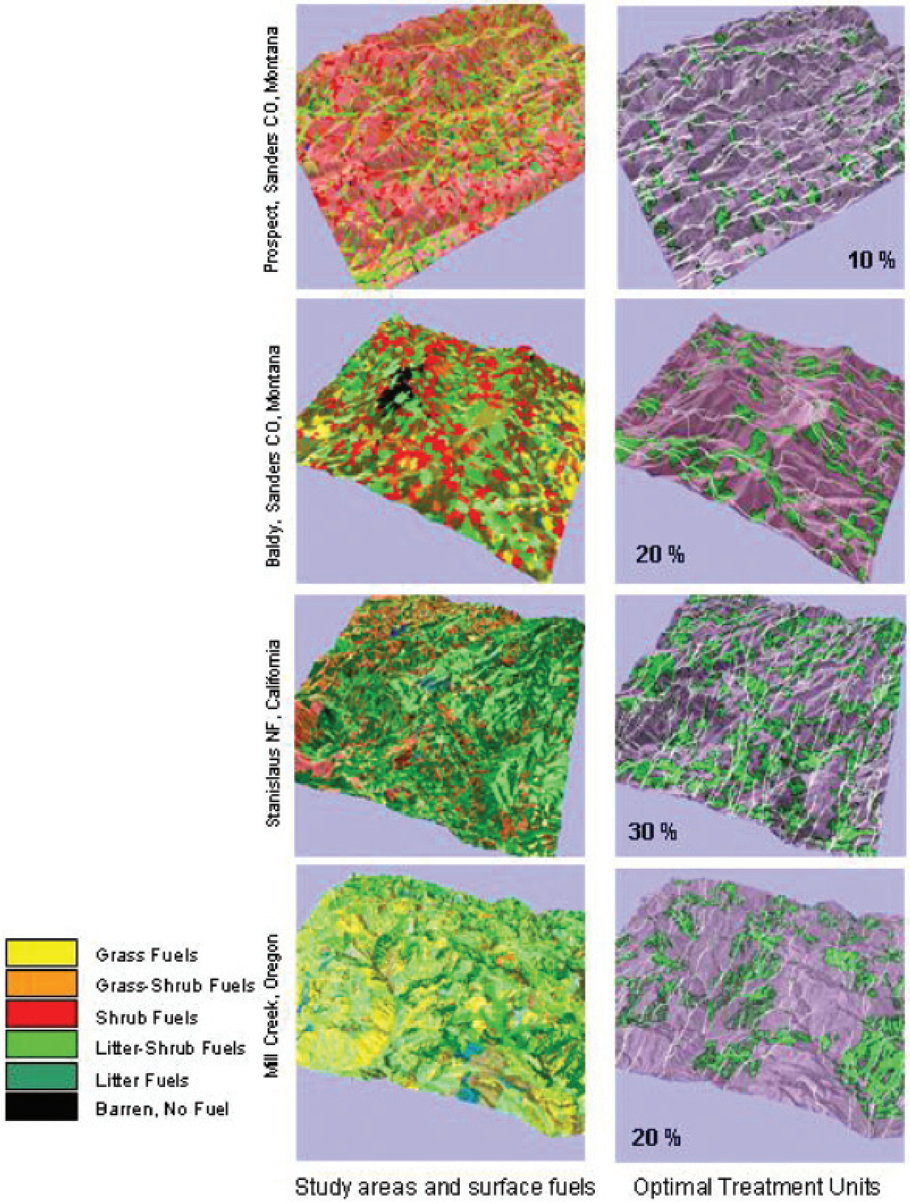

Figure 3—Example data and outputs from the Montana, California, and Oregon study areas showing surface fuel types and examples of optimized treatment locations along with major fire travel routes prior to placement of treatment locations (treatment location are intersected by travel routes).

decade, the fire spread rate was reducing to about 40% at Prospect, Montana (Figure 5a), 60% at Baldy Montana (Figure 5b), and 80% in California (Figure 5c), and 60% in Oregon (Figure 5d). Increasing rate of treatment to 30% per decade improved the overall reduction in spread rate to 20% for Prospect, Montana (Figure 5e), 40% for Baldy Montana (Figure 5f), 60% for California (Figure 5g), and 40% for Oregon (Figure 5h). For all study areas and treatment rates the effects of treatment were the greatest the first decade and the cumulative effect of additional treatment was negligible after the second decade of simulation. These trends occurred irrespective of the amount of treatment but were more noticeable with high treatment rates.

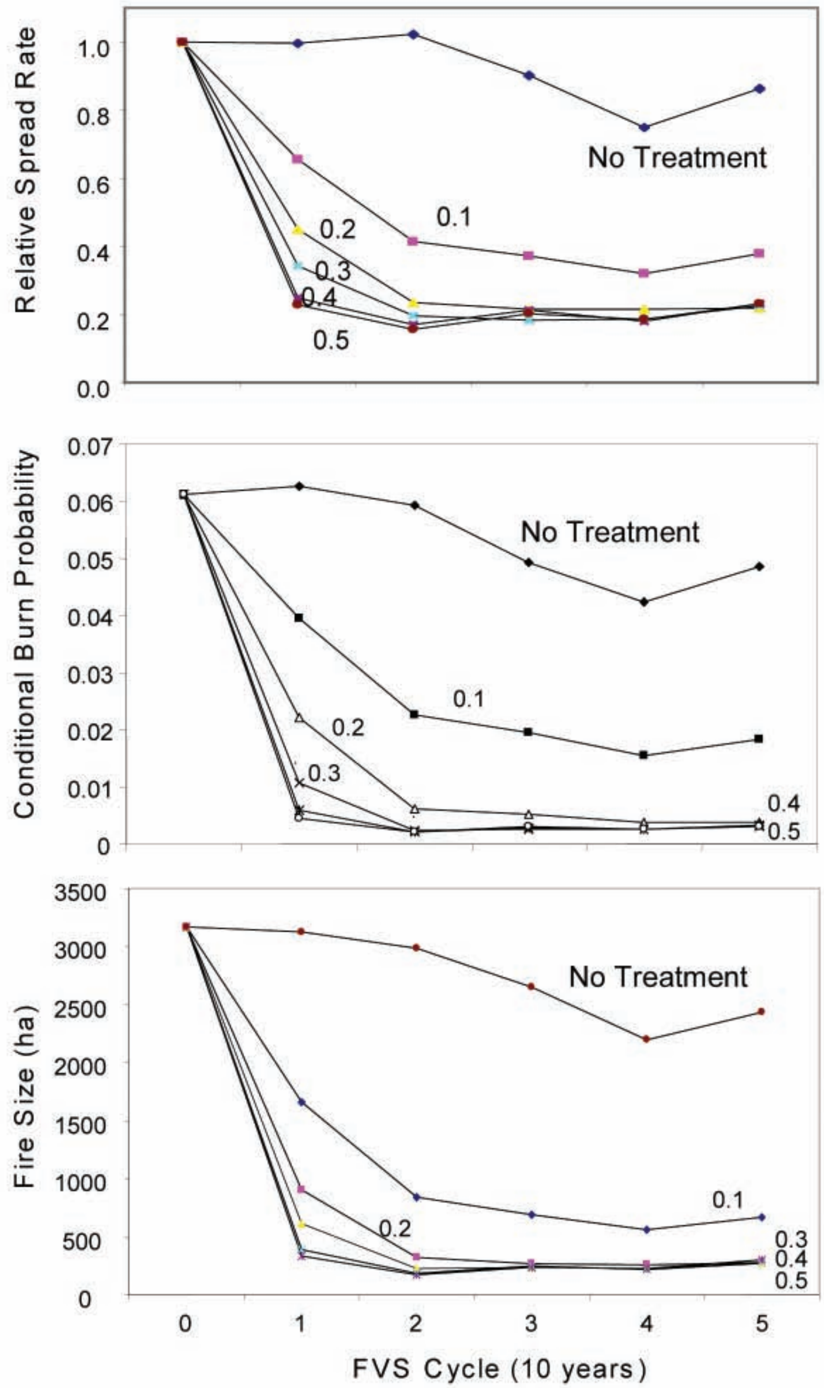

Figure 4—Average fire spread rate across the landscape, conditional probability of burning produced by simulating 3,000 fires (conditional upon having a large wildfire), and the mean fire sizes revealed nearly identical trends. Shown here are only the results for the Prospect, Montana study area, although all study areas had identical comparisons among the response variables.

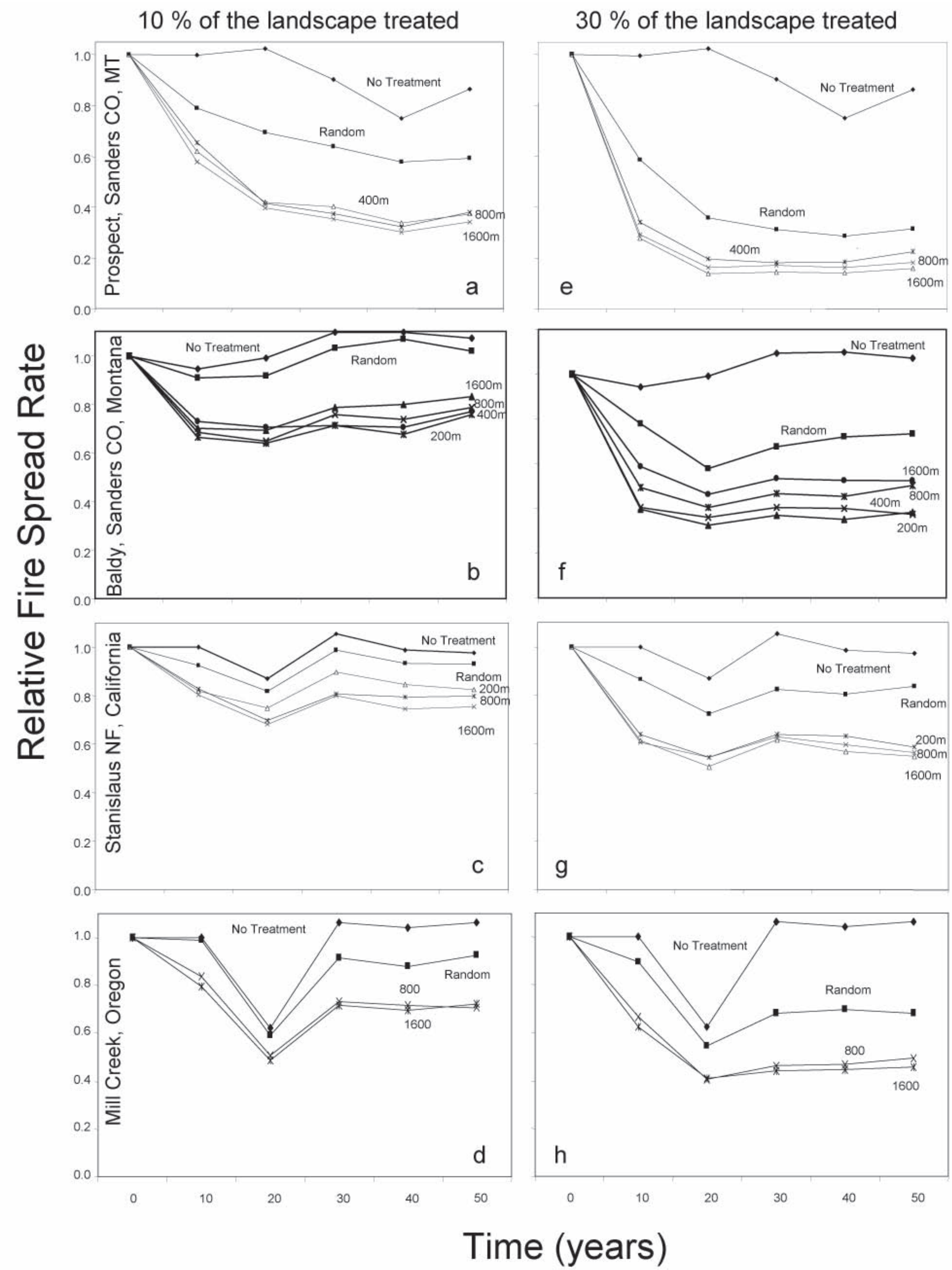

Figure 5—The magnitude of the treatment effect on average fire spread rate varied by study area although the cumulative effects over time of random and optimally placed treatments were similar for all areas. Treatment unit size had little effect on the average fire spread rate.

The rate of treatment in optimal patterns had a large effect on the cumulative treatment effectiveness up to approximately 20% per decade (2% per year) for all study areas (Figure 6). Increasing treatment rate beyond this point had little effect on the ultimate fire spread rates. For each rate of treatment (1% to 3% per year), the results suggested that cumulative effects of the optimal patterns reached a steady state after the second decade (Figure 6) as well as for random treatment patterns (Figure 5). Higher rates of treatment (40% to 50% per decade) produced little cumulative benefit to landscape fire spread beyond the first decade.

Effectiveness of optimal treatment patterns in reducing fire spread rate was little affected by randomly reserving less than about 20% of the area from consideration from treatment (Figure 7). However, reserving 45% to 65% of the area from treatment diminished the effectiveness of optimal patterns to about the level of random patterns.

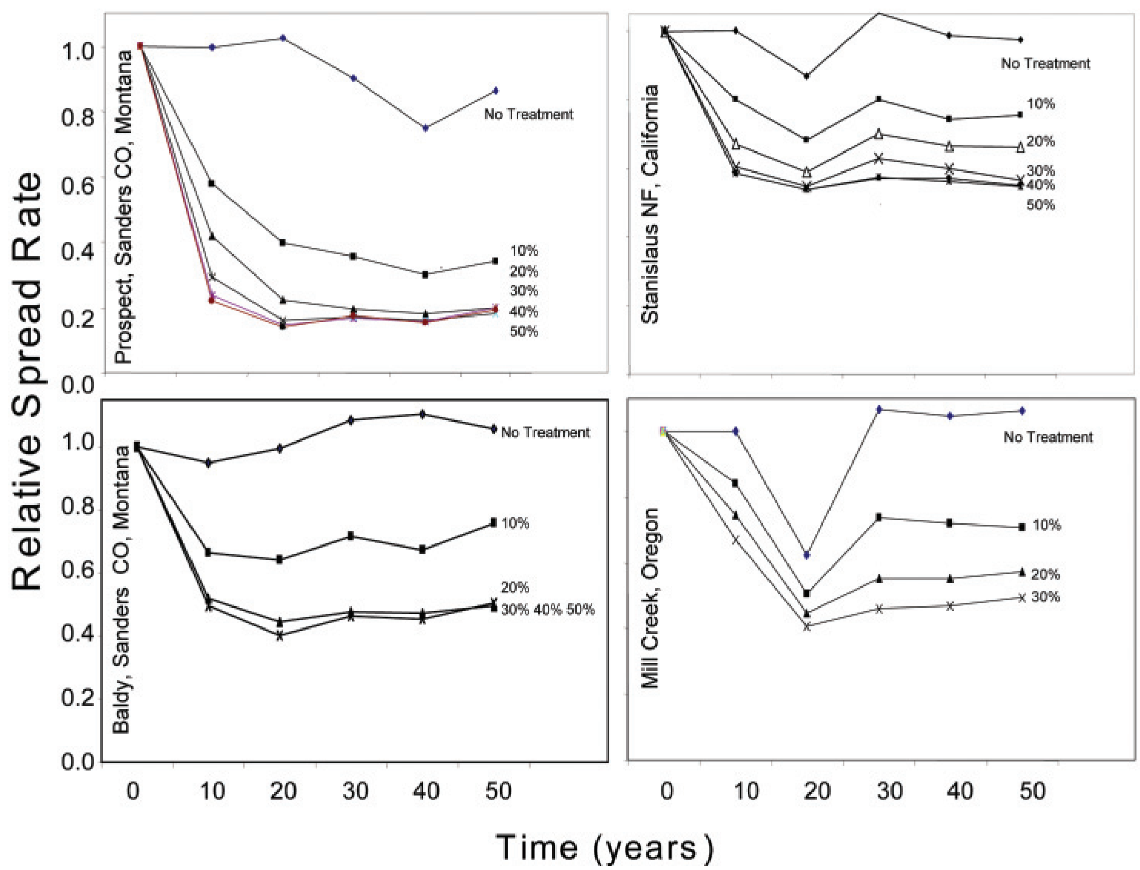

Figure 6—Treatments implemented at a rate of about 20% per decade produced overall reductions in average fire spread rate similar to higher treatment rates for all study areas. Treatment rates of up to 20% per decade required about two decades to reach the cumulative benefit reached in the first decade for higher rates of treatment. All results are displayed for 800 treatment units, but trends are nearly identical for unit sizes of 200 m, 400 m and 1,600 m.

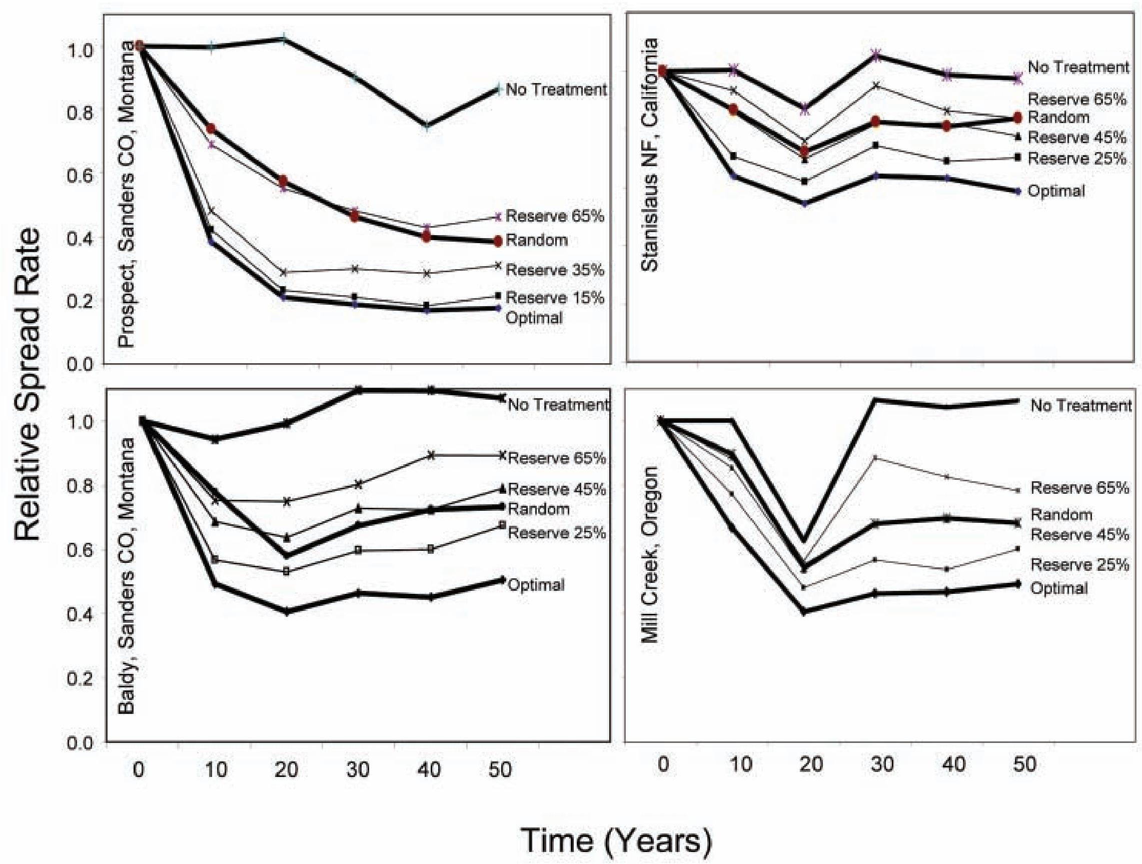

Figure 7—Simulated reserves of land area from fuel treatment reduced the effectiveness of optimal treatment patterns to the point that reserving 45% to 65% produced results similar or even less effective than random patterns.

The treatment preferences for re-treating or maintaining fuel conditions in the optimal patterns was increasingly different from a random pattern as the rate of treatment increased beyond 10% (Figure 8). The trends were so similar for study areas that only the Prospect, Montana results are shown in Figure 8. The random treatments produced the expected Poisson distributions of treatment frequency (Figure 8a) which were similar to the treatment frequency produced for optimal patterns at a rate of 10% per decade (Figure 8b). However, treatment frequency was not random at higher rates of treatment in optimal patterns (Figures 8c-8f). Specifically, about 35% of the landscape would never be treated in an optimal pattern even with the highest rate of treatment (50% per decade). Where treatment rates were the highest (40% to 50% per decade), most fuel treatments were not maintained every decade (Figure 8e, 6f).

Optimal treatments in all study areas remained more effective than random treatments (Figure 9) in reducing fire growth rate under weather conditions more moderate (90th and 95th percentile) than specified in the design (99th percentile). The relative benefit of treatment, however, decreased as conditions became more moderate because fire behavior contrasts decrease between treated and untreated areas.

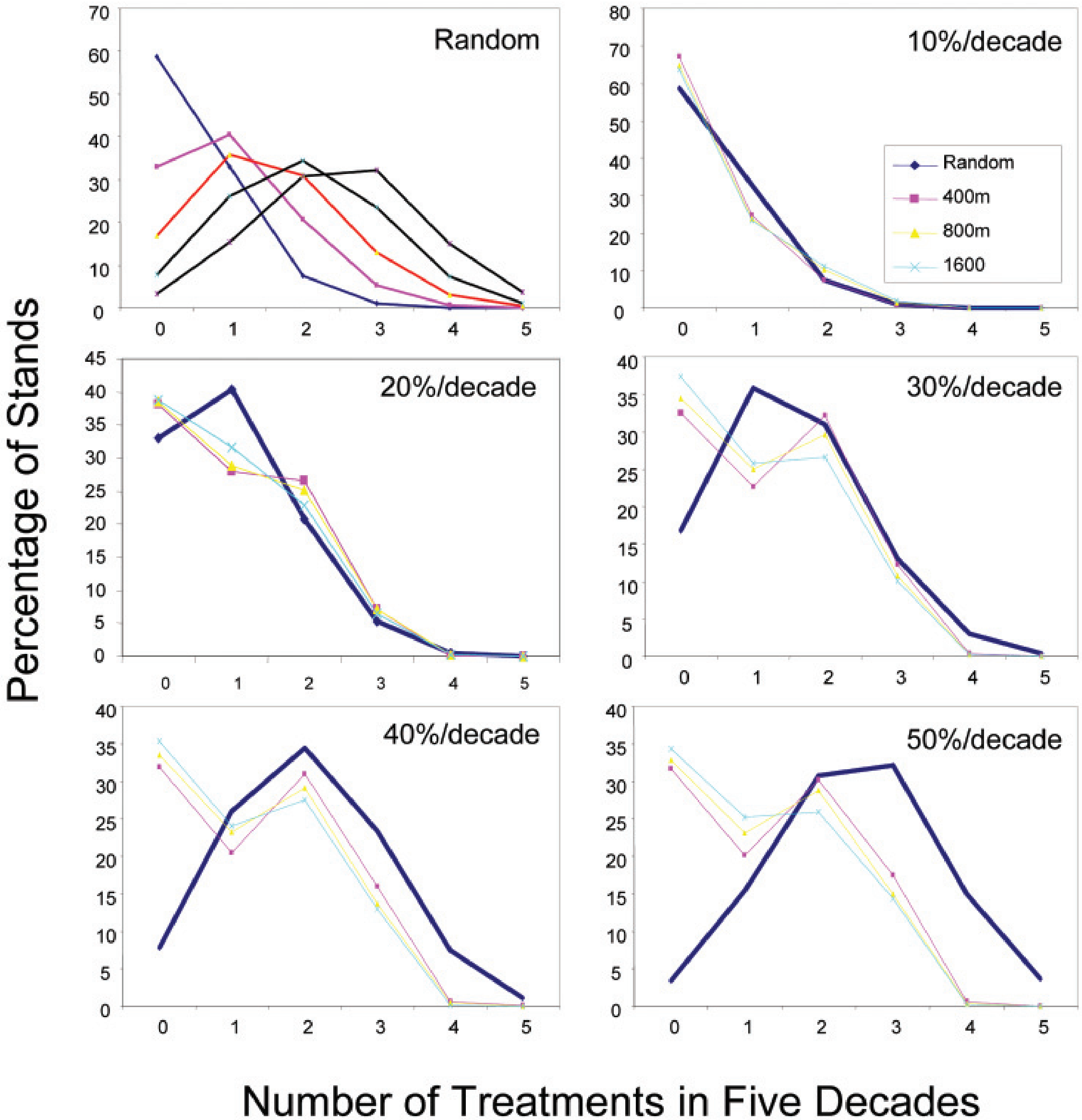

Figure 8—The question of maintaining treatment areas or implementing new treatments was summarized by the frequency of treatment over five decades. Random treatment resulted in Poisson frequency distributions. At treatment rates of 20% and greater per decade, the optimal treatment strategy consistently excluded some areas from treatment more frequently than random selection and refused frequent treatment for other areas.

Discussion

The simulations for the three study areas consistently suggested that all treatment rates (10% to 50% per decade) accumulated benefits to reduced fire spread rate, wildfire sizes, and burn probability out to about two decades in all study areas. This is probably a result of the inherent fuel accumulation and decomposition rates which determine longevity of individual treatments. Beyond that point, additional treatments produced little cumulative reduction in the landscape fire metrics. Additionally, treatment rates beyond approximately

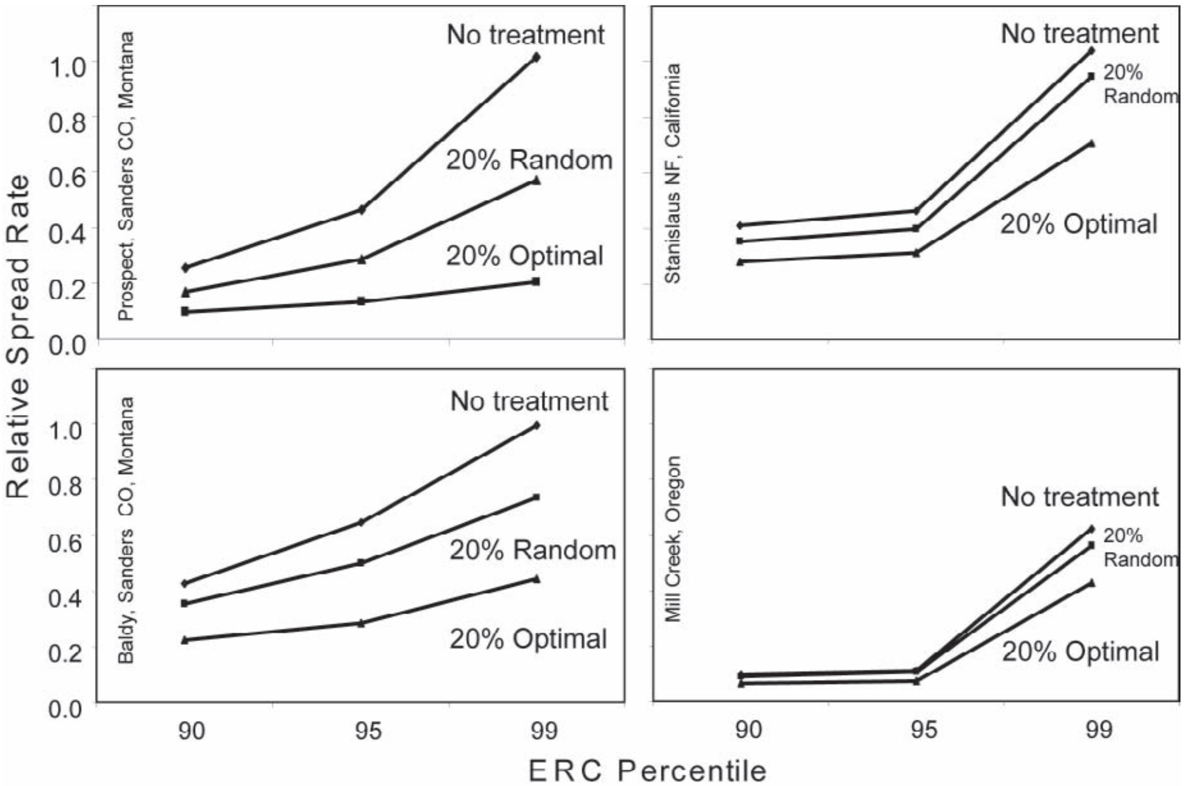

Figure 9—Comparison of fuel treatment effects on relative fire spread rate across a range of fire weather percentiles suggests that optimal treatment effects are robust under weather more moderate than the conditions specified for optimization (99th percentile). Spread rates are shown for the 2nd decade of simulation (when collective treatment effects are maximal) and normalized for each study area relative to the spread rate at the beginning of the simulation (i.e. zero years). Weather percentiles are expressed in terms of Energy Release Component (ERC) from the National Fire Danger Rating System and primarily reflect changes in moisture content.

20% per decade in optimal patterns produced little added benefit for the study areas. Few studies have directly measured fuel accumulation, but van Wagtendonk and Sydoriak (1987) found that litter and fine twigs returned to preburn levels in 5-7 years in the Sierra Nevada mountains of California. The results of this study are generally similar to the findings of Biswell et al. (1973), Fernandes et al. (2004), Finney et al. (2005) who reported fuel treatment mitigation of wildfire severity out to 15 years, 13 years, and 9 years, respectively. These timeframes for treatment longevity imply certain rates of treatment by land management planners, namely that a substantial level of effort is required over the course of about two decades to realize the cumulative benefits to mitigating large fire behaviors. Such effort has long been advocated as a critical part of overall fire management (Brackebusch 1973, Arno and Brown 1991). Evidence for effectiveness of such large scale-efforts were documented by Weaver (1957) and showed prescribed burning in eastern Washington State over 11 years, which covered about 6% of the landscape, reduced fire occurrence on the treated lands by 97% and area burned by 90% compared to the untreated areas. We did not study the trajectories of treatment benefit related to changing the treatment rate through time, but, since higher treatment rates certainly accelerated the production of benefits, higher rates might be desirable in the first decade followed by later decreases.

The three response variables of large fires (growth rate, fire sizes, burn probabilities) all showed identical trends in relation to fuel treatments. Fire growth rates (aggregated spread rate across the landscapes), mean fire size, and the burn probability all decreased as fuel treatment amounts increased, both for optimal and for random patterns. The explanation is straightforward, given that faster fires will produce larger fires in an equal amount of time; larger fires burn a larger fraction of the landscape each time and thereby increase the burn probability. This is useful information for landscape fuel treatment planning in the context of risk assessment (Miller et al. 2000, Priesler et al. 2004, Finney 2005) because burn probabilities are a main component of risk. Fuel treatments can be designed to decrease burn probability by considering both the treatment prescription at the stand level and the spatial arrangement of the stands at the landscape level.

Differences in the maximum reduction of fire spread rate were found among study areas for random and optimal treatment patterns, probably because of different fuel treatment prescriptions and the changes simulated by FVS in the forest structures for those geographic locations. Differences could also be a function of the particular spatial configurations of fuel types for each landscape because treatments that dictated the areas suitable for treatment. Both of these factors likely affect the outcome of the simulations because the differences among study areas were consistent regardless of the use of optimal or random spatial fuel treatment patterns. Thus, either rapid recovery of fuels after treatment or limited positions of candidate treatment areas would have similar effects on reducing overall effectiveness on the landscape-level fire metrics.

Despite the complexity of the landscapes studied here and the complexity of modeling required to characterize fuels, fires, and treatment units, these results of the optimal and random landscapes correspond well with those based on the theoretical analysis of simple landscapes (Finney 2001a,b, 2003). For spatially optimal patterns, increasing the treatment rate reduces fire spread rate and exhibits a negative-exponential-type shape. This was found for all study sites and treatment unit sizes, although the magnitude of the decrease depends on the particular landscape. This is interpreted to be the consequence of different patterns of fast- and slow-burning fuel types on the real landscapes that dictate the opportunities and impacts of the particular treatment units. The decrease in spread rate with increasing treatment amount arranged in random patterns did not exhibit the sigmoidal trend found from analysis of simple spatial landscapes (Finney 2003), however, the random pattern was much less efficient in reducing large fire spread than the optimal patterns. The inefficiency of random patterns is also verifed by other theoretical studies (Loehle 2004, Bevers et al. 2004). Together, these results are useful for drawing general conclusions about the role of spatial treatment patterns on fire movement. The theoretical and spatially simple results apply quite well to the expected trends for treatments on actual landscapes.

The benefits of optimal treatment patterns appear to be robust to uncertainties in weather (wind speed and fuel moisture) as revealed for weather conditions more moderate than those for which the patterns were designed (Figure 9). Under moderate weather conditions, the contrast in fire behavior between treated and untreated areas is diminished (fire spread rate and intensity tend toward similar values). This means that the treatments will result in a smaller proportional reduction in fire area than under extreme conditions. However, the primary reason that treatments are not designed for moderate fire weather is that modern suppression policies do not permit large wildland fires to spread when suppression organizations are generally successful in limiting fire spread. Thus, fire behavior is generally more benign, fire suppression more effective, and treatments less necessary for changing fire behavior when weather conditions are moderate.

The effects of reserving areas from treatment, irrespective of the location or need for treatment, decreased the effectiveness of an optimal treatment pattern and compromised the optimal solutions entirely at about 50% reserved. This has bearing on the treatment planning process in land management operations where restrictions are imposed for a variety of reasons, including concern for treatment impacts on wildlife habitat, restrictions on proximity to streams or rivers, road access, budget limitations, or ownership. These simulations generally suggest that treatment restrictions amounting to more than about 40% of a landscape would diminish any advantage an optimal solution would achieve over purely random treatment placement. The specific topology of the various fuels and restrictions for a particular landscape, however, would likely be different than this generalization. Nevertheless, if land managers intend to achieve reductions in large fires, collaboration with all concerned parties would likely be necessary to accommodate treatment locations to achieve landscape-level effects.

The five-decade simulations suggest that both maintenance of existing units and implementation of new units are important to the optimization of spatial treatment patterns. The frequency of re-treatment in the optimal landscape was different than produced by chance with the random treatments (Poisson distributed) which indicates that the choice of fuel treatment activity was driven by functional concerns. Compared to the random patterns, the optimization attempted more treatments on new stands than on re-treating old stands, probably because the treatment benefits endured for more than one decade. It is unknown how the pattern would change if the simulation were to have continued for 100 years, for example, that would have greatly exceeded the time-frame of treatment performance.

Variation in treatment unit sizes had the least impact on modifying large fires compared to treatment pattern and rate of treatment. Large and small units typically produced similar reductions in fire sizes, spread rates, and burn probabilities at all levels of treatment. Slightly lower efficiency (e.g. amount of reduced spread rate per unit treated) of the smallest treatment unit sizes for all study areas, however, suggests that emphasizing small units may restrict opportunities to block fire movement in some critical locations which require large units. That is, small units cannot effectively block the movement through large corridors where fire easily moves. The optimization algorithm used here is not flexible enough to effectively mix both small and large units.

Conclusions

The simulations suggested that long-term treatment effects are primarily dependent on the rate of application of treatments and the spatial patterns of treatment units. Treatment rates of 10% to 30% per decade reached a cumulative maximum effectiveness in about two decades in all study areas. Higher rates of treatment did not improve the cumulative effects beyond the first decade. Random treatment patterns also produced cumulative effects on fire behavior but were less efficient than the optimized patterns, requiring about twice the area to be treated compared to optimal patterns.

Acknowledgments

This study was funded by the U.S. Joint Fire Sciences Program and the U.S. Forest Service, Missoula Fire Sciences Laboratory. Special thanks to Nick Crookston for his willingness to make custom modifications to PPE for our uses and to Howard Roose with the Bureau of Land Management who also provided funding.

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A Wildfire Risk Modeling System for Evaluating Landscape Fuel Treatment Strategies

Alan Ager[1], Mark Finney[2], and Andrew McMahan[3]

Abstract—*Despite a wealth of literature and models concerning wildfire risk, field units in Federal land management agencies lack a clear framework and operational tools to measure how risk might change from proposed fuel treatments. In an actuarial context, risk is defined as the expected value change from a fire, calculated as the product of (1) probability of a fire at a specific intensity and location, and (2) the resulting change financial or ecological value. The expected value definition accounts for landscape-scale wildfire spread, intensity, and damage in a single measure, providing a relatively robust metric for comparing the effects of fuel treatment scenarios. New advances in calculating burn probabilities and recent work on resource valuation has set the stage for actuarial risk analysis in fuels treatment planning. To demonstrate this approach, we estimated expected net value change on 16,000 ha wildland-urban interface using 12 fuel treatment scenarios and four hypothetical value schemes. Burn probabilities were estimated by simulating 200 randomly-ignited wildfires. The results showed a non-linear response in expected value with increasing treatment area. Fuels treatments on a relatively minor percentage of the landscape (20%) resulted in 20% to 50% increases in expected net value for most scenarios. The modeling advances the application of actuarial science to wildfire risk management and fuels treatment planning*

Introduction

Despite an overwhelming literature concerning wildfire risk, field units in the federal land management agencies lack a clear framework and the appropriate risk assessment tools for prioritizing and measuring the effectiveness of proposed fuel treatment projects. It has been suggested that the lack of risk assessment tools has led to short term, risk-averse management that has perhaps exacerbated longer term risks from natural disturbances (Irwin and Wigley 2005). With few exceptions, existing wildfire risk systems are not well founded in the actuarial sciences. None we know of model the interactions among landscape-scale wildfire spread, fire intensity, and wildfire effects on the net value of resources. The actuarial definition of wildfire risk is the *expected net value change* calculated as the product of (1) probability of a fire at a specific intensity and location, and (2) the resulting change in financial or ecological value (e.g., Bachmann and Allgöwer 2001; Brillinger 2003; Finney 2005). The net value change can include both present and future discounted values. Assumptions about the effects of wildfire suppression on wildfire probability and value change can also be incorporated into the expected net value change equation. The process of wildfire *risk assessment* is concerned with changes in expected loss in response to fuel treatments, structure improvements, and assumptions about fire weather and suppression capabilities.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Major advances in the spatial modeling of burn probabilities (e.g. Finney 2005; Miller and Parsons 2005; Parisien and others 2005) has set the stage for rapid improvements in tools and methods for wildfire risk assessments. Extensive work on resource valuation and ecosystem services has also provided many frameworks for valuing resources in the expected loss equation (Calkin and Hummel 2005; Calkin and others 2005; Rideout and Ziesler 2005). We believe that a risk assessment model for fuels treatment planning is now within our grasp, and such a model would significantly improve our ability to measure the performance of fuel treatments over existing methods, especially those that do not consider fuel contagion (Parisien and others 2005). Even simplistic valuation schemes that weight key resources such as homes, wildlife habitat, visual areas, combined with coarse estimates of burn probabilities would provide far more robust measures for comparing fuel treatment options compared to existing methods often used by field units.

In this paper we describe a wildfire risk model based on established concepts and definitions of risk from the actuarial sciences. The modeling approach was designed to be compatible with project level application on federal lands in terms of resolution and data requirements. The system estimates expected change in net value considering wildfire spread, intensity, and the effects of fire on resources of concern. We tested the model on a 16,000 ha wildland-urban interface in eastern Oregon, USA, using several hypothetical valuation schemes. We report our initial findings here and discuss further work towards an operational risk model for fuels treatment planning.

Materials and Methods

Study Area and Data

The Mt. Emily wildland urban interface extends 30 km along a north-south ridge immediately north of La Grande, Oregon, where the forested slopes of Mt. Emily and adjacent ridges descend to the agricultural lands in the Grande Ronde Valley. For analysis purposes, a boundary was established around the area using major drainages and natural breaks in vegetation, and the area within contained 16,296 ha of federal, state, and privately owned lands. About 12,471 ha within the study area are classified as forested lands based on inventory data. Approximately 9,432 ha are managed by the U.S. Department of Agriculture, Forest Service. The forest composition ranges from dry forests of ponderosa pine (*Pinus ponderosa*), cold forests dominated by subalpine-fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*), and a transition zone containing grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*). Surface fuel loadings exceed 140 metric tons/ha in some areas, with high loading of dead ladder fuels in a large number of the stands (Wallace 2003). Fuel accumulations accelerated after the 1980-1986 Western spruce budworm (*Choristoneura occidentalis*) epidemic. Vegetation and surface fuels data acquisition was accomplished in concert with a fuels reduction project on the La Grande Ranger District and have been described in detail elsewhere (Ager and others 2005; Wallace 2003).

Modeling Overview

We used a three step modeling process that involved: (1) Simulating landscape fuel treatment scenarios with the Forest Vegetation Simulator linked to the Parallel

Processing Extension (PPE, Crookston and Stage 1991), (2) Calculating fire spread parameters (elliptical dimensions) with FlamMap, and (3) simulating random fires and net value change with the mechanistic fire spread program RANDIG (developed by M. Finney). We integrated the first two steps into ArcGIS using Visual Basic scripts (Pattison 1998) and the ArcObjects library (Chang 2004) to facilitate the design and simulation of fuel treatment scenarios. Step three involved batch processing landscapes with the RANDIG program.

Simulating Fuel Treatment Scenarios

We simulated fuel treatments using the Blue Mountains variant of the PPE and the Fire and Fuels Extension (FFE, Reinhardt and Crookston 2003). PPE simulates multiple stands in a parallel fashion, i.e., the simulation is completed for all stands each time period before cycling to the next time period. PPE can model multiple, spatially explicit treatment constraints and priorities at the stand scale for a given landscape (Crookston and Stage 1991). We simulated 12 treatment scenarios by combining six treatment intensities with two treatment priorities. Treatment intensities were created by constraining the total treatment area to 0, 10, 20, 30, 40, and 66 percent of the forested lands. The 66 percent constraint represents treating every overstocked stand in the landscape (Ager and others 2005). The treatment priorities were based on stand density index (SDENS) and residential density (RDENS). SDENS chose stands for treatment based on their level of overstocking as defined by the current SDI relative to the site potential (Cochran and others 1994). RDENS prioritized stands based on the spatial density of homes in the surrounding area. Residential density (residences/km^2) was calculated from a point layer of homes obtained from the Oregon Department of Forestry using a kernel density estimator with a 2 km search radius. Each stand polygon was assigned the average residential density of the pixels within the polygon. In the RDENS scenario, stands were also required to meet the same stand density as in the SDENS scenario.

Fuel Treatment Prescriptions

The fuels treatment prescription consisted of selective thinning, site removal of surface fuels, and underburning. We triggered a thin when a stand's SDI exceeded 65 percent of the maximum. Removal of trees was ordered from smallest to largest so that the thinning treatments were effective at reducing ladder fuels. Stands were thinned to a target SDI of 35 percent of the maximum for the stand. The thinning prescriptions targeted removal of late-seral, fire intolerant species like grand fir in mixed-species stands, favoring early seral species such as ponderosa pine, western larch and Douglas-fir. The species preferences were varied slightly by plant association group as described in Ager and others (2005). Although the treatment prescriptions were simplistic in relation to the diversity of ecological conditions in the project area, they conformed to overall management practices in the area. Underburning and mechanical treatment of surface fuels was simulated with the FFE (Reinhardt and Crookston 2003). Fuel loadings were initialized in FFE for each stand using the surface fuels data in the vegetation database. We simulated mechanical treatment of surface fuels to remove 90 percent of the 7.6 cm to 14.8 cm and 40 percent of the 2.5 cm to 7.6 cm surface fuels (Wallace 2003). Underburning was simulated using weather conditions and fuel moisture guidelines provided by fuels specialists on the La Grande Ranger District. The treatment simulations were performed on a 1600 mhz single processor PC and required about 5 minutes per scenario.

FVS database outputs (Crookston and other 2006) for crown bulk density (kg/m^2), height to live crown (ft), total height (ft), canopy closure (percent), flame length, and crown fire activity were examined to quantify the effects of the treatments on stand structure. For space considerations those results are omitted from the present paper. We converted the databases to FlamMap landscape files using Visual Basic scripts (Ager 2005). After finding problems with the post thinning, FFE fuel model selection logic, we overrode the FFE fuel model selection on treated stands and, based on expected fire spread rates and behavior for the treated stands, assigned them to fuel model 181 (Scott and Burgan 2005). This assignment was based on expected fire spread rates in the post-treated stands.

Wildfire Simulations

For each management scenario, wildfire spread parameters (elliptical dimensions, Finney 2002) for each 30 x 30 pixel in the study area were calculated with a command line version of FlamMap (M. Finney). A fixed set of weather conditions and fuel moistures were used to represent 97th percentile weather conditions generated from local RAWS weather stations (Ager and others 2005; Bradshaw and McCormick 2000). The spread parameters for each 30 x 30 m pixel were then used as input for the RANDIG.fire simulation program. RANDIG simulates fire spread using the minimum travel time methods (Finney 2002) and inputs on wind, fuel moisture and topography. We used RANDIG to simulate 200 random ignitions for each of the 12 fuel treatment scenarios. The number of ignitions was chosen after preliminary runs showed that burn probability estimates rapidly stabilized at this value, which is similar to the findings of Parisien and others (2005 fig. 16). The duration of each fire was determined using a Monte Carlo approach that sampled a frequency distribution of spread event days developed from a database of recorded fires on the Umatilla National Forest from 1970 to 2005 (data on file, Umatilla National Forest). We simulated a range of wildfire burn periods with FlamMap for the study area, and then assigned a burn period value to each fire in the database by matching it to a FlamMap simulated fire with similar size. We recognize a number of assumptions and limitations in this approach, although alternative methods are not readily available.

Calculating Risk

Using the definition of risk as the expected net value change, we incorporated risk calculations into the RANDIG program with the following process. We created four pairs of landscape value grids (30 x 30 m), each pair containing data on the potential positive and negative impacts from wildfire (table 1), and representing a particular valuation scenario. Loss functions were then created for each valuation scenario that defined proportional changes in value for different flame lengths (table 1). RANDIG was then modified to tally the value change at each pixel for each simulated wildfire and report the net change at the end of simulation (200 fires per scenario). It is important to note that the loss functions and value layers were purely hypothetical and created for the purpose of demonstrating the utility of the wildfire risk approach in the current study area. The first valuation scenario (FX) assumed a fixed value of $500 per ha, and the loss function specified a loss directly proportional to flame length (table 1). The scenario was included to demonstrate a simple method to incorporate both fire intensity and spread in measuring landscape effects of fuel treatment scenarios. The second valuation scenario was developed using home locations. We assigned a fixed value of $200,000 to each of the 176 homes in the WUI and then smoothed the point data using a kernel density

Table 1—Loss functions for different valuation schemes used in the study. Data in the table are the proportional change in the value of each pixel at different flame lengths. Positive values represents benefits, negative values represent losses. Loss functions are hypothetical and were developed to illustrate the process for modeling expected change in net value.

Flame length (m)	Valuation scenario: Fixed value (FX)		Residential values (RES)		Wildfire benefits (WB)		Residential and wildfire benefits (RES+WB)	
	Loss	*Benefits*	*Loss*	*Benefits*	*Loss*	*Benefits*	*Loss*	*Benefits*
0.0 – 0.30	–0.1	0.0	–0.1	0.0	0.0	1.0	0.0	1.0
0.30 – 0.61	–0.2	0.0	–0.2	0.0	0.0	1.0	0.0	1.0
0.61 – 0.91	–0.3	0.0	–0.3	0.0	0.0	1.0	0.0	1.0
0.91 – 1.22	–0.4	0.0	–0.4	0.0	0.0	1.0	0.0	1.0
1.22 – 1.52	–0.5	0.0	–0.5	0.0	0.0	0.0	–0.5	0.0
1.52 – 1.83	–0.6	0.0	–0.6	0.0	0.0	0.0	–0.6	0.0
1.83 – 2.13	–0.7	0.0	–0.7	0.0	0.0	0.0	–0.7	0.0
2.13 – 2.44	–0.8	0.0	–0.8	0.0	0.0	0.0	–0.8	0.0
2.44 – 2.74	–0.9	0.0	–0.9	0.0	0.0	0.0	–0.9	0.0
>2.74	–1.0	0.0	–1.0	0.0	0.0	0.0	–1.0	0.0

function with a search radius of 200 m to generate a smooth grid of home values. The goal was to represent the value of individual homes on a number of pixels to reflect the uncertainty in the modeling about loss from direct ignition, and the fact that significant value in the rural residences exists around the main structure. Each residence was represented by 125 pixels having a maximum and minimum value of about $2000 and $8,000 respectively. A loss function was then created that assumed linear damage with increasing flame length (table 1). No benefits from fire were assumed in this scenario. Again, the scenario was purely hypothetical and built to demonstrate the utility of the risk system. A third valuation scenario assumed that flame lengths under 1.2 m (4 ft.) constituted a fuels treatment, and generated a positive value of $350/ha. Negative values were not included in this scenario. A fourth scenario (RES+WB) combined portions of the third and second scenarios to consider both the loss of residences at flame lengths > 1.2 m, and the benefits of low intensity fire when flame length was less than 1.2 m.

Within each simulated fire, the flame length at each pixel was used to calculate the net value change using a loss function. The loss function translated flame length into an expected change in value expressed as a proportion. We simulated 200 wildfires for each combination of management intensity, treatment priority, and valuation scheme, for a total of 9,600 fires. For demonstration purposes we ignored a number of important factors including the cost of fire suppression and fuel treatments, and revenues from harvests. These factors will be considered in future work

Results

Burn Probabilities

Burn probability (BP) and average wildfire size decreased linearly with increasing treatment intensity for both the RDEN and SDEN scenarios (Table 2). The highest BP's were observed for the scenarios without treatments, and were in the range of 0.049 – 0.060, averaging 0.057. At the maximum treatment rate, where all overstocked stands were treated (8,495 ha, 66 percent),

Table 2—Results from wildfire risk simulations on the Mt. Emily study area. Each scenario represents a management intensity (0, 10, 20, 30, 40, 66 percent of forested area treated) and spatial treatment priority (SDEN = stand density index, RDEN = residential density). Two-hundred random ignitions were simulated for each management scenario. Four resource valuations schemes were used to calculate an expected net change in landscape value. Valuation schemes are: FX= flamelength, RES = value of residences, WB = wildfire benefits from low intensity wildfire, RES+WB = combined RES and WB. The reported average and range is for the 4 simulations per management scenario (one for each valuation scheme).

Scenario	Ha treated	Average burn probability	Range in average burn probability	Average wildfire size (ha)	Expected net value change ($/ha) by valuation scheme			
					FX	RES	WB	RES+WB
SDEN-0	0	0.057	0.049 – 0.060	883	–53.4	–47.7	40.6	10.9
SDEN-10	1690	0.040	0.038 – 0.045	624	–28.4	–34.0	37.1	6.6
SDEN-20	3255	0.038	0.036 – 0.040	624	–30.0	–34.3	32.0	–4.9
SDEN-30	4887	0.029	0.027 – 0.032	499	–25.6	–24.4	24.2	2.0
SDEN-40	6547	0.025	0.024 – 0.026	408	–19.5	–23.5	21.8	–6.9
SDEN-66	8495	0.017	0.017 – 0.018	278	–12.8	–16.9	14.4	–74.6
RDEN-0	0	0.053	0.052 – 0.056	893	–46.6	–38.4	46.9	18.2
RDEN-10	1690	0.040	0.037 – 0.041	683	–40.5	–22.2	31.1	–40.7
SDEN-20	3255	0.033	0.032 – 0.035	552	–32.7	–19.1	28.6	–16.8
RDEN-30	4887	0.026	0.025 – 0.028	435	–21.1	–14.9	23.2	–17.9
RDEN-40	6547	0.021	0.018 – 0.024	344	–15.0	–12.8	18.0	–46.1
RDEN-66	8495	0.016	0.016 – 0.017	273	–12.8	–12.4	13.1	–58.4

average BP was reduced to 0.016 for the RDEN and 0.017 for the SDEN management scenarios. Thus, treating every overstocked stand reduces the average probability of a 30 x 30 m pixel burning by 0.04. The BP estimates varied only slightly among the four different simulations for each scenario with the range averaging 0.0043. Considerable spatial variation in BP was observed, with the largest values (0.22) along the eastern edge in the middle of the study area. This same area also showed the largest reduction in BP from the thinning treatments. For instance, BP was reduced from 0.22 to 0.07 between the no treatment and treating 66 percent of the landscape using the SDEN treatment priority.

Average Wildfire Size

Wildfire sizes in the 9600 simulations (12 management scenarios by 4 valuation schemes x 200 fires) ranged from 1 to 5,600 ha. Average wildfire size decreased linearly with increasing treatment at the rate of about 0.07 ha per ha treated for both the RDEN and SDEN (table 2). Thus, for every 100 ha treated, the average wildfire on the entire study area was reduced by 6 ha. On a proportional basis, treating 20% of the landscape (3,255 ha) reduced the average wildfire size by about 34%. Differences among the spatial treatment scenarios (RDEN, SDEN) in terms of wildfire size were minor.

Expected Loss

The hypothetical valuation schemes (FX, RES, WB, RES+WB, see table 1) showed large differences among the six management intensities and only slight differences for the two different treatment priorities (fig. 1, table 2). Average net change for the FX valuation scheme, where we arbitrarily valued each ha at $500 and assumed a loss function directly proportional to flame length (table 1), equaled -$46.65 and -$53.35 per ha for the SDEN and RDEN treatment priorities at the 0 percent treatment level (table 2).

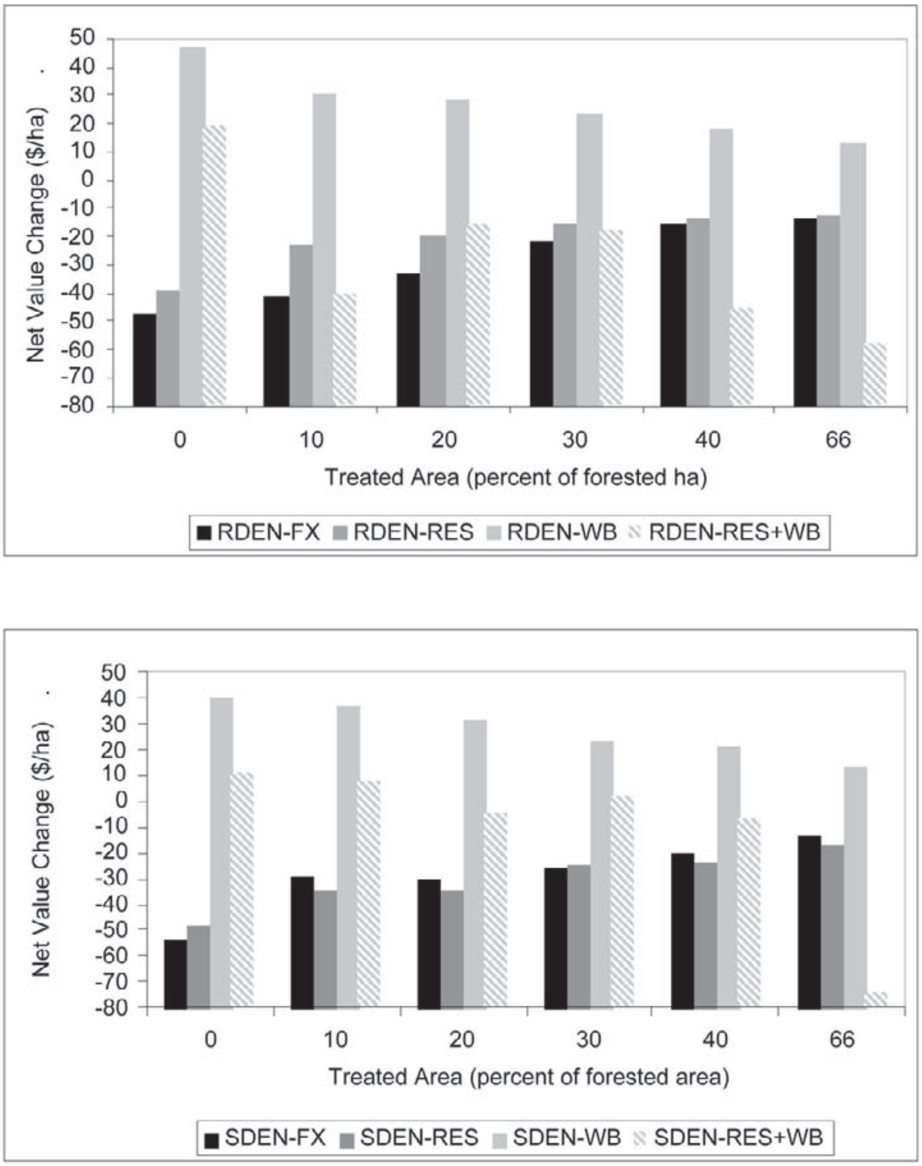

Figure 1—Expected net value for the SDEN (top) and RDEN (bottom) treatment priorities by treatment level (percent of landscape treated) and resource valuation scheme. SDEN and RDEN prioritized stand treatments based on stand density and residential density, respectively.

At the maximum level of treatment (66 percent of landscape), the net value increased to -$12.8 per ha for both treatment scenarios. On a proportional basis, there was a 44% increase in net value when the treatments rate was increased from 0% to 20%. We observed a slightly more rapid increase in value with the SDEN versus the RDEN spatial priority between 0 percent and 10 percent treatment levels, perhaps due to the treatment of stands with higher SDI and more extreme fire behavior.

Maps comparing the expected loss (FX) between two treatment priorities (RDEN, SDEN) at 20 percent treatment showed distinct treatment patterns (fig. 2). At higher treatment levels, the difference between spatial priorities was diminished (fig. 1). The SDEN treatment priority resulted in a relatively

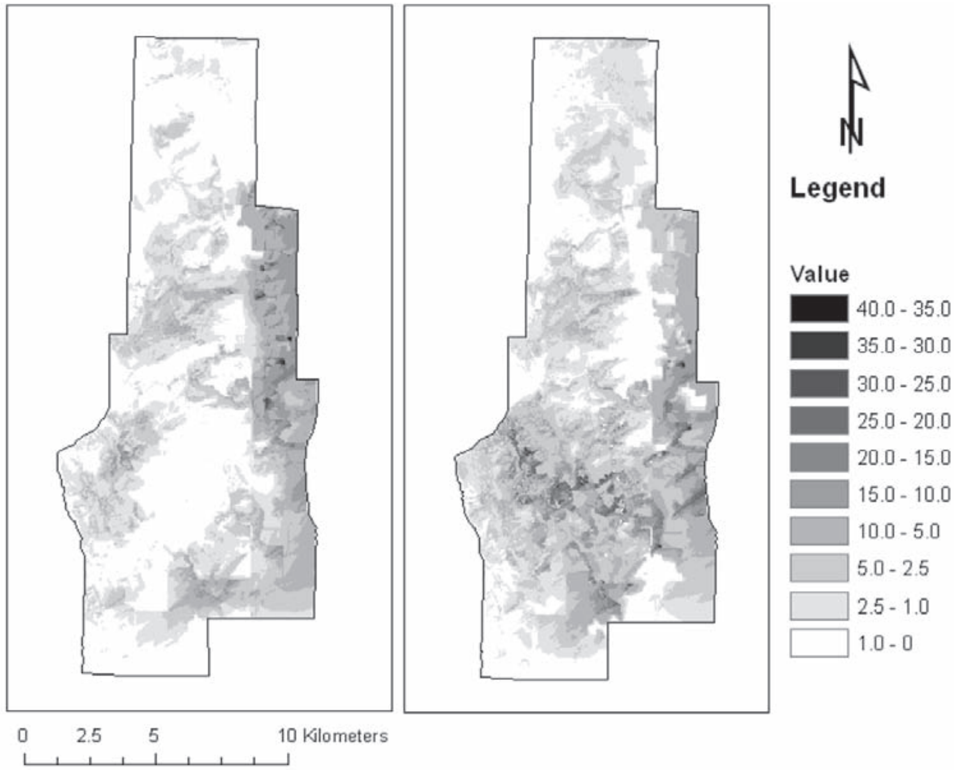

Figure 2—Map of the study area showing expected value loss ($ per ha) from wildfire for the SDEN (left panel) and RDEN (right panel) treatment priorities with 20 percent of the landscape treated and fixed land values ($500 per ha). Values shown in legend represent value loss.

large increase in the net value in the central portion of the project area which currently supports a higher proportion of overstocked stands. In contrast, the RDEN treatment priority, which selected stands for treatment along the eastern edge of the study area near residences, showed relatively low expected values in the central portion of the project area.

Mapping the difference in expected value (FX) between the untreated and treating 20 percent of the forested area for the SDEN treatment priority was used to compare the effects of fuel treatments on expected loss inside and outside the treatment areas (fig. 3). Changes in expected loss were apparent especially in the treated areas (fig. 3). However, the effect of the treatments outside the treatment units were also apparent (fig. 3), thus illustrating the secondary (landscape) benefits of the treatments.

Simulation results for the RES valuation schemes, which valued homes at $200,000 with a linear loss function (table 1) appeared very similar to the FX valuation scheme, with increasing net value with increasing treatment levels. The effect of prioritizing treatment according to residential density (RDEN) versus the stand density (SDEN) was evident in the results, with the expected value for the former scenario substantially higher for the lower treatment levels (10 to 30 percent, table 2). For instance, at the 30 percent treatment level the expected value for the RDEN spatial treatment priority was about $15 per ha higher as compared to SDEN where stands were treated based only on their SDI. The expected value for the RES valuation scheme

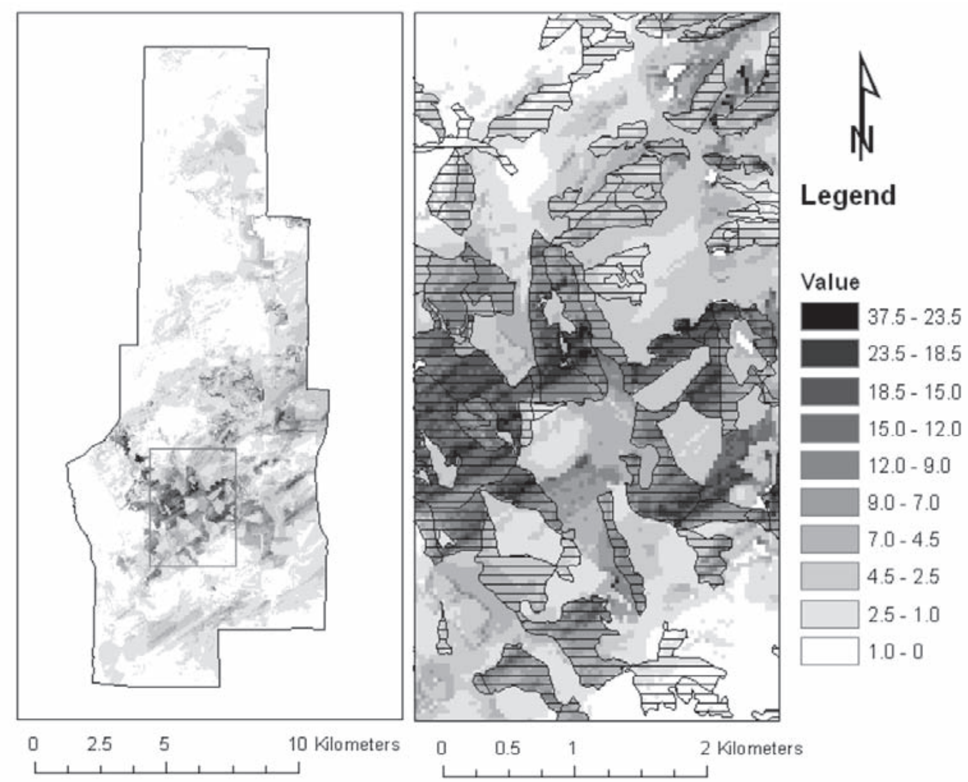

Figure 3—Difference in expected loss between no treatment and treating 20 percent of the landscape (left panel) for the SDEN treatment priority, and fixed land valuation ($500 per ha). Darker areas represent benefits (reduced loss) from the fuel treatments. Left panel is a zoomed image of the central portion of the study area showing the same data and treatment units (horizontal hatching). Darker shading shows the off-site, landscape effect of the fuel treatments in terms of reducing burn probability and intensity, and potential loss from fire.

and RDEN treatment priority increased about 50% when the treatment rate was increased from 0% to 20% of the landscape. The increased expected value (decreased loss) between the SDEN and RDEN treatment priorities were largely due to localized treatments around residences (fig. 4). Nevertheless, treating stands based on density alone, which resulted in the bulk of the treatments several kilometers from the residences, reduced the expected loss in the RES valuation scheme (fig. 4, lower right panel)

As expected, the WB scenario, which valued wildfire fuel treatments at $350 per ha when the flame length was less than 1.2 m showed decreasing expected value with increasing levels of treatments (fig. 1). The drop in expected value with increasing treatment intensity mirrored the reduction in average wildfire size (table 2). With less area burned by wildfire under the higher treatment levels the expected value would be expected to drop.

The valuation scheme that considered both residential values and wildfire benefits (RES+WB) produced some erratic results, although in general the decrease in wildfire benefits with increasing treatment levels overshadowed the effects on residential values (table 2, fig. 1). The variable results are difficult to explain and are perhaps a larger number of simulated fires are required to estimate expected values when there are multiple valuations on a landscape.

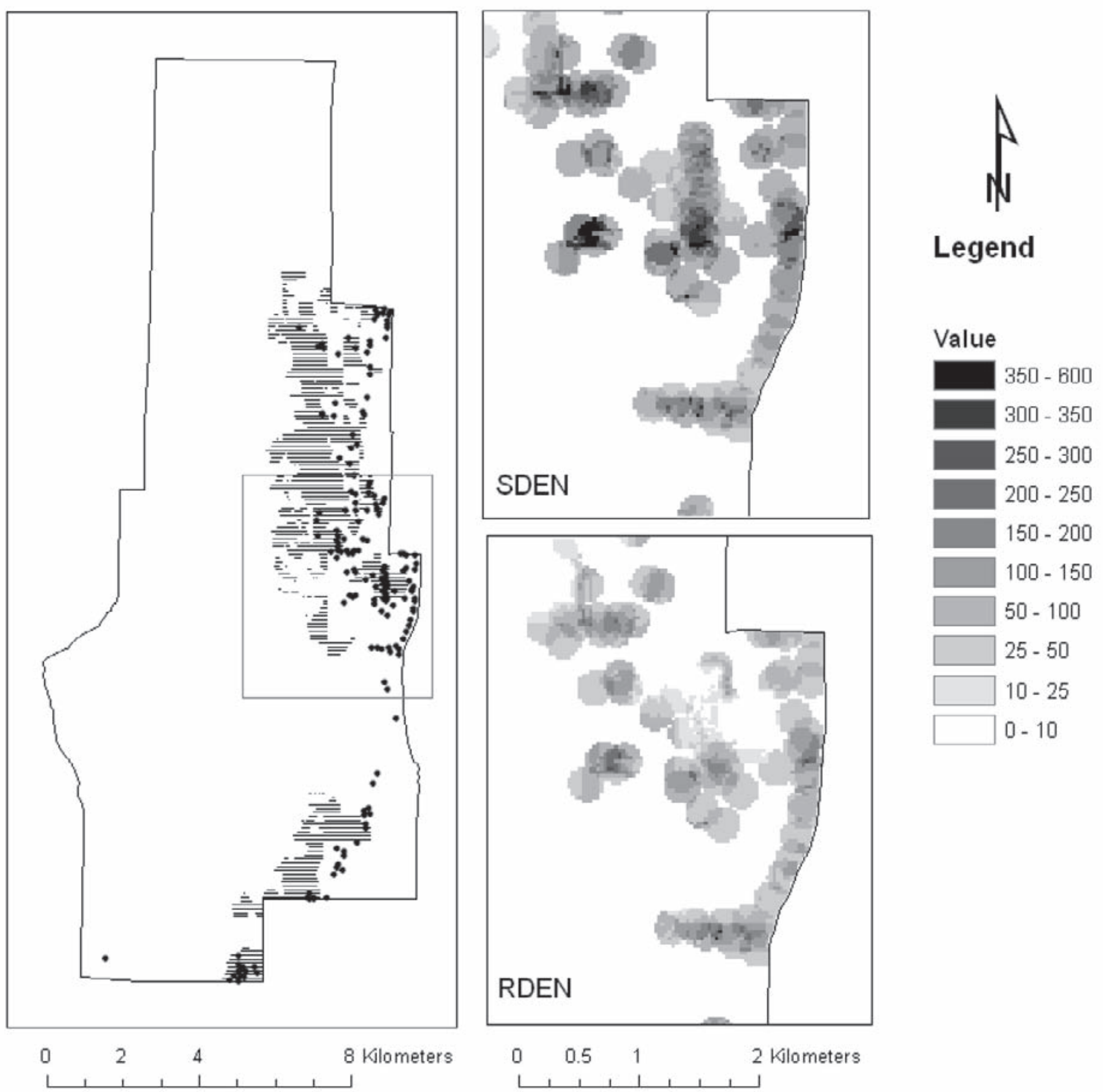

Figure 4—Expected loss for the RES valuation scheme at the 20 percent treatment level for the RDEN and SDEN treatment priorities. The RES valuation scheme valued each home at $200,000. Left panel shows treated stands (horizontal hatching) for the RDEN treatment priority where stands were prioritized for treatment based on residential density. Black circles denote residences. Panels on right show the expected value change for the stand density (SDEN, upper right) and residential (RDEN, lower left) treatment priorities. Values in the legend represent expected loss.

Discussion

The results demonstrate a wildfire risk assessment process that incorporates important interactions among wildfire spread, intensity, and resource values, and illustrates how landscape fuel treatment strategies may affect the expected net value change. The simulations assumed that, from a risk standpoint, the primary concern is escaped fires and extreme fire conditions (Finney 2005), since these are the fires that are responsible for the most damage. Suppression activities are generally ineffective in these types of fires, and thus were excluded from the model. Modifying the expected value equation to account for mitigation such as suppression capability is discussed by Smith (2001).

We envision this modeling framework as a useful one for simulating fuel treatment scenarios and analyzing their performance with measures like burn probability and net value change, especially within the context of collaborative fuels treatment planning (Bahro 2004; Gercke and Stewart 2006). For instance, the change in expected value per ha treated could be used as a measure of treatment performance. This measure can be partitioned between the treated area and non-treated area to measure the efficiency of the treatment package in terms of local (treated stands) versus landscape-scale (non-treated stands) effects.

From a research perspective, this modeling framework could also help resolve one of the key risk assessment questions concerning fuels treatment on federal lands: the tradeoff between potential short term impacts of fuel treatments versus long term benefits of wildfire mitigation (Irwin and Wigley 2005). In this case the net value formulation will require discounted, future losses and benefits, and the vegetation simulations will require a temporal component. This type of problem is tractable with the FVS-Parallel Processing Extension and the RANDIG program.

There are important differences between the methods used here to estimate burn probabilities versus probabilistic models built with historical fire occurrence and size data (Martell and others 1989; Mercer and Prestemon 2005; Preisler and others 2005). We have estimated a conditional burn probability to compare the effects of management, and set the number of fires to a value that sample the landscape in terms of fire spread, intensity, and value. Until we factor in spatio-temporal probabilities for ignition, escape, and burn conditions (Davis and Miller 2004; Miller 2003; Parisien and other 2005), there is most likely little relationship to the burn probabilities estimated here and the actual probability of a wildfire on the Mt. Emily area. However, precisely what parameters most influence burn probabilities and whether a more complex model is necessary for modeling the effectiveness of fuel treatments remains to be seen.

Although our resource value layers were hypothetical, they were useful for demonstrating the application of the system. The modeling framework is also well suited for analyzing long-term risk tradeoff between wildland fire benefits and the cost of wildfire suppression and fuels treatments (Calkin and Hyde 2004). More realistic valuation and loss scenarios have been used in other studies to examine treatment costs, potential timber revenues, and wildlife habitat impacts over time (Hummel and Calkin 2005).

Resource valuation is a complex problem (Freeman 2003) especially on federally-managed lands where planners need to integrate monetary and non-monetary valuations for analyzing and comparing risk among fuel treatment alternatives. Valuation schemes that use a common, relative weighting system for multiple resource values have been proposed for federal lands (Rideout and Zielser 2005). Many other kinds of valuation data are readily available online or in agency GIS systems. The risk framework described here could be easily expanded to accommodate multiple loss and benefit grids and loss functions in an integrated measure of risk.

Future work will involve experimenting with a number of factors that affect burn probabilities, such as ignition location, weather conditions, and the effectiveness of suppression. We also plan to simulate treatment scenarios through time to address the temporal aspects of wildfire risk assessment.

Acknowledgments

We are indebted to Carol Miller and Marc Parisien for discussions on estimating burn probabilities. We thank Dave Calkin and Carol Miller for reviewing an earlier version of the paper. The simulation of fuel treatments on Mt. Emily was funded by a Joint Fire Science Program grant (03-4-1-04) to the senior author. Additional support was provided by the Forest Service Western Wildlands Environmental Threat Center, Prineville, OR.

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Automating the Fireshed Assessment Process with ArcGIS

Alan Ager[1], Bernhard Bahro[2], and Klaus Barber[3]

Abstract*—A library of macros was developed to automate the Fireshed process within ArcGIS. The macros link a number of vegetation simulation and wildfire behavior models (FVS, SVS, FARSITE, and FlamMap) with ESRI geodatabases, desktop software (Access, Excel), and ArcGIS. The macros provide for (1) an interactive linkage between digital imagery, vegetation data, FVS-FFE, and SVS, creating a map-based interface for designing and testing stand fuel treatments; (2) rapid scale-up of stand-specific treatments to simulate project-wide changes in vegetation and fuels; (3) data linkages between FVS outputs and FlamMap/FARSITE to allow for simulation of landscape-scale fire behavior and evaluation of fuel treatment scenarios; and (4) data linkages between FVS outputs and ArcMap for rapid mapping of FVS database outputs. The library is distributed as an ArcMap project file (.mxd) and is implemented on custom toolbars on the ArcMap interface. The system was designed to automate geospatial analyses performed in the Fireshed process to design and test fuel treatments in a collaborative setting. A beta version of ArcFuels is available from the senior author.*

Introduction

Planning fuel treatment projects on large forested landscapes requires a number of wildfire and vegetation models to simulate and test the merits of proposed management activities (Finney and Cohen 2002; Stratton 2006). Treatment scenarios are typically constructed by iteratively selecting stands for treatment, and subsequently evaluating the aggregate effects of treatments on landscape-scale wildfire behavior by using wildfire simulators. Ideally, the selection of specific stands is based on both the potential fire behavior within the stand, and the stand's topological relationship to other treated stands (Finney 2004). Fuel treatment projects that do not address both stand and landscape aspects of the problem may be ineffective in terms of reducing the threat from large wildfires (Finney 2004; Finney and Cohen 2002).

The process for designing fuel treatments is complicated by multiple management goals and constraints on public lands (Hayes and others 2004). A further, perhaps more challenging problem for federal land managers is that wildfire does not recognize land ownership boundaries, and thus treatments must be designed in collaboration with other landowners. To address these problems, a cadre of Forest Service fire specialists created a collaborative process for building multi-ownership fuel treatment plans (Amboy 2006; Bahro 2004; Bahro and others 2006). The process integrates multiple land and resource management objectives when addressing and evaluating fuel treatments (Ewell and others 2006). The "Fireshed" process starts with the delineation of geographic units (10,000 to 50,000 ha) with similar fire regimes, fire history, and wildland fire risk issues. In a collaborative setting, fuel treatments are designed and tested in near real time with wildfire simulation

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models (FARSITE, FlamMap). The process requires a number of support staff including geographic information system (GIS) specialists, database analysts, and fire modelers, as well as a library of GIS macros and other programs. The Fireshed process represents a major advance in fuel treatment planning, and led to the Stewardship and Fireshed Assessment Pilot Program in the Forest Service (Gercke and Stewart 2006). The framework is increasingly being used as an organizing and operational framework for landscape fuel treatment planning (Gallagher 2005). The concept of a fireshed also has ecological science value and is being used as a research framework (Jordana and others 2003).

In 2004, one of the authors (Ager) received funding from the Joint Fire Science Program to streamline the process of fuel treatment planning (Ager and McGaughey 2003). The project proposal identified a gap in the integration and data linkages among fire behavior models, vegetation and fuel data, GIS, and desktop software. The Fireshed process was adopted as the design template for the work. In this paper, we describe our progress to streamline and integrate fuel treatment planning and the Fireshed process, and a new library of macros (*ArcFuels*) within ArcGIS.

ArcFuels

Overview

We used the ArcObjects library (Chang 2004) and Visual Basic for Applications (VBA) (Pattison 1998) within ArcMap as the development framework. The VBA development interface is integrated within ArcMap and Microsoft (MS) Office products (Excel and Access); ArcFuels macros are distributed within ArcGIS project files (.mxd). The project file is loaded into ArcMap, and the macros appear as toolbars. Project defaults that specify the paths of installed fire behavior models, vegetation databases, GIS themes, and various other parameters are stored in a MS Access database.

The selection of models and linkages within the ArcFuels interface was aimed at providing the user with the following functionality for fuel treatment planning: (1) an interactive system within ArcMap to develop stand-specific silvicultural prescriptions and fuel treatments, including thinning, underburning, and mechanical fuel treatment; (2) automated generation of data plots showing how stand fuel treatments change wildfires in terms of flame length, fire behavior [surface or crown], and stand mortality over time; (3) rapid scale-up of stand-specific treatments to simulate project-wide changes in vegetation and fuel from proposed management activities; (4) tight data linkages to FlamMap or FARSITE to simulate landscape-scale fire behavior and measure the treatment performance in terms of wildfire probabilities, spread rates, and fireline intensity (Finney 2004); (5) ability to easily modify and reevaluate fuel treatment scenarios; and (6) integration of fire modeling spatial outputs into ArcGIS and other programs to facilitate the evaluation of fuel treatments with multi-resource objectives.

Data

Detailed modeling of fuel treatments for project-level planning requires tree list data and information on surface fuel loadings. Forest Service tree list data are stored within the FSVEG database system. In many projects, data for polygons without stand exams are imputed by using a most similar neighbor approach (Crookston and others 2002). The Forest Service FSVEG system can generate spatial vegetation databases that are compatible with the FVS database extension (Crookston and others 2006). For the Fireshed process, these databases can be augmented with key information about land management strata and other factors important for building management scenarios (for example ownership, management emphasis) and prescriptions.

Stand Modeling of Fuel Treatments

Developing and testing treatment prescriptions for specific stands is an iterative process that seeks to find the best prescription to meet multiple objectives. ArcFuels provides interactive linkages to the Forest Vegetation Simulator (FVS) (Dixon 2003) and the FVS Fire and Fuels Extension (FFE), which are widely used to simulate thinning, prescribed fire, and mechanical treatment of downed fuels, and the post-treatment potential fire behavior. These simulations use a well-defined weather scenario, usually generated from field weather stations (http://www.fs.fed.us/raws/) by using FireFamily Plus (Bradshaw and McCormick 2000). Stand prescriptions are developed with a number of FVS keywords (for example THINSDI, SIMFIRE, FUELMOVE, see Dixon 2003). FVS and FFE can also be used to examine the longer term (for example 50 years) effects of the treatments on forest density and dead fuel dynamics provided a forest regeneration model is available.

In the fuels treatment planning process, significant work is required to validate stand data, define values for model parameters, and design stand-specific treatments. To automate this process, we built a *stand query* function into ArcFuels to allow users to interact with stand data and fire models within the ArcMap interface. Users can also load digital color imagery for their project area (http://www.apfo.usda.gov/NAIP.html) and overlay stand polygon maps, and then test different management prescriptions by clicking on specific stands to execute one or more fire models. For instance, clicking on the stand within ArcMap can be used to: (1) simulate management activities and potential wildfire within FVS; (2) generate Excel graphs of stand metrics, fuel loadings, and fire behavior and; (3) Visualize treatments and wildfire effects in the Stand Visualization System (SVS, McGaughey 2002). A direct link on the ArcFuels forms to the FVS prescription keywords allow for rapid changing of management prescriptions and testing of different fuel treatment options. The system provides a rapid method for browsing a landscape in a spatial context, examining and visually validating the data representing the stand, and iteratively testing stand-level treatment prescriptions within a GIS.

Landscape Design and Testing of Fuel Treatments

Landscape analysis of fuel treatment scenarios examines the aggregate effect of all treatments on potential wildfire behavior. The effects of fuel treatments on other landscape-scale goals are measured at this stage. Goals for wildlife, visuals, aquatics, and forest restoration may also be examined (Hayes and others 2004). Of key importance is the spatial arrangement and size of the fuel treatments relative to the direction of a likely wildfire event. Testing the performance of fuel treatment strategies can be accomplished with the FlamMap program in terms of fire spread, travel time, and burn probabilities. The FVS parallel processing extension (Crookston and Stage 1991) is a key part of this system. FVS-PPE is a little used extension that recognizes stand contagion and can model harvest constraints, treatment goals, fuels, and generates many of the specific inputs needed by landscape fire models.

ArcFuels automates the process of selecting and/or assigning stand-specific prescriptions within a Fireshed and building the input files required by FlamMap. The assignment of treatments to stands is accomplished in six ways: (1) ArcGIS selection; (2) stand query function; (3) database queries that key off of data in the stand database; (4) importing a treatment optimization grid from FlamMap; (5) dynamic selection by using FVS-PPE variable; and (6) external algorithms. FVS-PPE can prioritize and constrain on multiple activities and land strata. The external algorithm approach was used by Finney (2004) for fuel treatment optimization.

ArcFuels builds scenario files for the FVS-PPE from MS Access vegetation databases (Crookston and others 2006). Subsets of a landscape can be selected by using the Select command in ArcMap, providing a simple method to interactively simulate landscape subunits or specific stand types (for example, select all stands within 200 meters of homes). FVS database outputs can be automatically joined to stand GIS coverages for rapid mapping of the simulation outputs. ArcFuels macros can be used to convert FVS database outputs to the binary landscape files required by FlamMap and FARSITE. This system can be used to generate sets of landscape files for multi-period and multi-scenario FVS simulations.

ArcFuels uses a database approach to organize management prescriptions for stands within a project area, and codes prescriptions within the stand database required by FVS (Crookston and others 2006). This simplifies the process of replicating complex constraints and management goals for multi-owner Firesheds. Key information about land management strata and other factors important for building management scenarios (for example, ownership, management emphasis) are stored in the FVS stand database.

Mapping Outputs

With the database extension, FVS outputs can be written to an Access database containing tables for stand summary statistics, potential fire behavior, fuels, and others (See Crookston and others 2006). A VBA script on the simulation interface joins these tables to the Arc feature class layer representing the stand polygons. Once joined, an array of map queries can be performed with ArcMap commands to analyze FVS outputs in a spatial context. The joining of other databases can be automated by editing the underlying VBA macro.

Summary and Future Work

Our work addresses a major gap in the integration of wildfire behavior models with GIS and desktop software used for the Fireshed process. The approach was made possible by the recent development and release of ESRI's ArcObjects, and integration of the Visual Basic development tools within ArcMap. The development strategy here permits rapid integration of new models within ArcGIS, and sharing of the VBA macros among other applications and projects. We are continuing to test ArcFuels in several Fireshed projects in the western United States. Further development is ongoing, including a system for modeling and manipulating grid-based fuel data (for example Landfire) for projects where tree-list type data are not available.

Acknowledgments

This work was funded by a Joint Fire Science Program grant (03-4-1-04) to the senior author. We thank Chuck Tilly for providing ArcObjects code early in the project, Linda Dillavou for editorial assistance, Andrew Lacey and Andrew McMahan for technical reviews.

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An Analytical Framework for Quantifying Wildland Fire Risk and Fuel Treatment Benefit

Joe H. Scott[1]

***Abstract**—Federal wildland fire management programs have readily embraced the practice of fuel treatment. Wildland fire risk is quantified as expected annual loss ($ yr^{-1} or $ yr^{-1} ac^{-1}). Fire risk at a point on the landscape is a function of the probability of burning at that point, the relative frequency of fire behaviors expected if the point does burn, and the response of various resources to those expected fire behaviors (net value change). The probability of fire burning at any point on the landscape is a function of the spatial arrangement of fuel, weather, topography, and ignition locations surrounding the point of interest, but not characteristics of the point itself. Relative frequency of fire behavior is a function of the local fire environment and the likelihood of burning at various portions of an assumed elliptical fire. Fire loss is assumed to be a function of fire behavior characteristics. Fire behavior can be measured by the Fire Intensity Index (FII), the common logarithm of fireline intensity. A risk reduction treatment is an investment of capital today for a benefit to be reaped in the future. The benefit of a risk reduction treatment is the present value of the difference in risk with and without treatment. Cost is the present value of current year and future treatment expenditures. Fuel treatment benefit-cost ratio is a measure of efficiency; it is one of many factors that inform a fire management decision.*

Background

The 1995 Federal Wildland Fire Management Policy and Program Review established that (1) life safety as the highest fire management priority, (2) wildland fire is a natural ecosystem process, and (3) fire management decisions must be consistent with approved land management plans. The 2001 review and update of the 1995 Federal Wildland Fire Management Policy included as guiding principles that (1) "sound risk management is a foundation for all fire management activities," and (2) "fire management programs and activities are economically viable, based upon values to be protected, costs, and land and resource management objectives." The document establishes the objectives and priorities of fire management on federal land in the United States, but does not require that the objectives be achieved in any particular way.

In the late 1990s the United States Forest Service refocused its fire management program and budget toward hazardous fuel reduction. Congress established the Joint Fire Sciences Program in 1998 to better assess fuel management problems and solutions. In 1999, the General Accounting Office (GAO) noted that significant barriers existed to achieving the agency's stated goal of mitigating wildland fire threat by 2015, and recommended development of a cohesive wildland fire mitigation strategy (GAO 1999). In 2000, the Secretaries of Interior and Agriculture prepared a report to

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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President Clinton outlining how to (1) respond to the still-burning fires of that year, (2) reduce the impacts of wildland fires on rural communities, and (3) ensure sufficient firefighting resources in the future. That report recommended a budget increase of $1.2 billion for the next fiscal year, including $390 million for fuel treatment and burned area rehabilitation. Under the heading of investing in projects to reduce fire risk, the report recommended the “establishment of a collaborative effort to expedite and expand landscape-level fuel treatments.”

The National Interagency Fuels Coordination Group (NIFCG) was chartered in 2004 with the purpose of developing and implementing “an effective, interagency fuels management program to address risks from severe fires…” One of the group’s enumerated objectives is to “[d]evelop strategies that safely and effectively mitigate [wildland fire] threats to communities and resource values…” The NIFCG’s 2005 Strategic Action Plan ranks encouragement of landscape-level fuel treatments among its highest priorities.

In 2004, the GAO noted that “Without a risk-based approach at the project level, the [United States Forest Service and Bureau of Land Management] cannot make fully informed decisions about which effects and projects alternatives are more desirable” (GAO 2004). The report recommended the agencies develop a better understanding of the negative effects of wildland fire, and create a systematic framework for landscape-level risk assessment in order to efficiently locate risk reduction activities.

Clearly, federal fire policy as first set in 1995 and updated in 2001 not only allows but encourages a holistic, risk-based approach to wildland fire management. Federal fire policy recognizes that wildland fire is neither good nor bad; it simply exists, and causes both losses and benefits at different places and times. Federal fire policy suggests that the cost of our response to the existence of wildland fire (prevention, suppression, fuel treatment, *etc.*) should be in balance with the benefits and losses that it confers. Despite the lack of a systematic framework for assessing wildland fire risk, fuel treatment has emerged as a significant risk management tool of the new millennium. Even so, no scientifically defensible metric has yet emerged to guide managers in deciding *where*, *when*, and *how* such treatments should be implemented, much less to confirm *whether* they are even cost-effective to implement.

This paper presents a framework for quantifying wildland fire risk and the benefit of risk reduction activities, including fuel treatment. The analysis framework suggests alternative strategies for mitigating wildland fire loss, as well as a means of comparing the relative efficiency of the alternatives.

Introduction

A fuel treatment is an intentional modification of fuelbed characteristics (load, bulk density, horizontal and vertical continuity, fuel particle size class distribution, *etc.*) for the purpose of mitigating negative fire effects (fire loss), either *directly* by making fire characteristics more benign, or *indirectly* by reducing the probability of fire burning a particular area. Negative fire effects include (1) socio-cultural losses, and (2) uncharacteristically severe wildfire. Socio-cultural losses—damage to or destruction of buildings, utility lines, recreation facilities, watersheds, commercial timber, *etc.*—can occur wherever those values are exposed to wildland fire. In fact, protection of socio-cultural values from fire is the primary reason for suppressing fire in the first place. Thus, to the extent that fuel treatment is undertaken to reduce the ultimate size of a future fire, fire suppression and fuel treatment are two sides of the same coin; the main difference between them is where and when the activities are undertaken.

Modern fire suppression is highly successful at containing incipient fires. As noted in a 2004 panel report to the Wildland Fire Leadership Council, from 1980 through 2002, almost 99 percent of wildland fires were contained to 300 acres or less; cost to suppress the remaining 1.4 percent of fires accounted for 94 percent of the total suppression expenditures. The fires that escape initial attack and burn more than 300 acres are not determined randomly; they are "selected" because their behavior (spread rate, intensity, fuel consumption) exceeds our ability to contain them. In other words, they burn in extreme fire environments that often result in uncharacteristic severity. By eliminating the most benign 99 percent of fire starts from the landscape, fire suppression has resulted in much longer fire return intervals—and higher fire severity when a fire does occur—compared to the historic fire regime. This unintended change in fire-regime is most pronounced in high-frequency, low-severity historic fire regimes (Heinselman 1981), but is also present in longer-interval fire regimes. To paraphrase Shakespeare, we have suppressed fire not wisely but too well. Thus, fire suppression was a solution to one problem (socio-cultural fire loss) that created another (too much uncharacteristically severe fire, too little low-severity fire).

Landscape-scale application of fuel treatments may reduce the incidence of uncharacteristic fires. However, in areas where fire was frequent but not severe, restoring the historic fire regime will also require dramatically *increasing* the incidence of low-severity fires. Increasing the prevalence of low-severity fires—through fire use, prescribed fire and fire surrogates—over time should result in a reduction of uncharacteristic fires. Treating fuel to reduce uncharacteristically severe fire, however, does nothing to increase the desirable fires.

The change in value associated with suppression-caused fire regime change is difficult to quantify (Finney 2005). Socio-cultural fire losses, on the other hand, are amenable to quantitative analysis. Therefore, this framework is focused on socio-cultural resources at risk; a different framework must be used to support fuel treatment decisions regarding restoration of historic fire regimes.

Minimizing cost plus net-value-change ($C+NVC$) is an accepted objective for optimizing fire program level (Althaus and Mills 1982, Mills and Bratten 1982, Mills and Bratten 1988). In this paper, the $C+NVC$ optimization concept is adapted to project-level analysis of fuel treatment options. A fuel treatment is an investment of capital *today* for benefits—reduction in expected annual NVC—to be received *in the future*. Therefore, investment analysis tools such as benefit-cost (BC) ratio should be useful for comparing fuel treatment options.

Quantitative Wildland Fire Risk Assessment

Quantitative wildland fire risk is defined as expected annual NVC (Bachman and Algöwer 2000, Finney 2005, Finney and Cohen 2003) for any spatially explicit land area (plot, pixel, stand, parcel, watershed, *etc.*). Expected annual NVC is the sum-product of NVC_i (cost plus net-value-change should fire occur at the i^{th} fire behavior) and $p(F_i)$ (the annual probability of observing the i^{th} fire behavior). If NVC_i is expressed on a per-acre basis (*e.g.*, \$ ac^{-1}), then annual *risk density* (\$ ac^{-1} yr^{-1}) is

$$E(NVC) = \sum_{i=1}^{N} p(F_i) * NVC_i \qquad [1]$$

The annual probability of observing fire of *any* behavior at a particular location is the sum of probabilities over all fire behaviors. Geographic extent for equation [1] is not explicitly specified; it refers to any homogeneous land unit (pixel, plot, or stand). Risk density is the appropriate quantitative metric for mapping wildland fire risk, especially where mapping units may be of varying sizes. Risk accumulates to larger geographic or political reporting units (*e.g.*, stands, watersheds, or political units like counties or states) composed of many land units. Landscape-level wildland fire risk ($ yr^{-1}) is the sum of risks of the *M* land units that comprise the landscape.

$$E(NVC)_{landscape} = \sum_{k=1}^{M} E(NVC)_k * A_k \qquad [2]$$

where
A_k = the area of land unit k
$E(NVC)_k$ = $E(NVC)$ for land unit k (eqn. [1])

Assessing the effects of a spatial fuel treatment array (Finney 2001) requires calculating risk at this larger landscape scale to fully account for their potential landscape-level effects.

A wildland fire risk assessment consists of two separate parts: $p(F_i)$ and NVC_i. Conceptually, $p(F_i)$ is a function of $p(F)$, the overall probability of fire burning under *any* behavior, and $p(F_i)/p(F)$, the relative frequency of different fire behaviors given that a fire does occur

$$p(F_i) = p(F) * \left(\frac{p(F_i)}{p(F)} \right) \qquad [3]$$

Mitigating risk entails modifying $p(F)$, $p(F_i)/p(F)$ or NVC_i.

Probability of Burning — p(F)

The probability of fire burning any particular point on the landscape is a function of ignition locations and fire travel from the ignitions to the point of interest. The factors affecting whether fire can reach a given point on the landscape from a given ignition point include: spatial and temporal arrangement of fuel, weather and topography across the landscape, and the level of perimeter containment (suppression) attempted. The probability of burning is inversely proportional to the general level of suppression effort. The fire environment at any point of interest has no bearing on *whether* a fire might reach that point—that is determined by the up-fire environment—but does affect *how* the fire would behave if it does reach it.

Two approaches are possible for estimating $p(F)$—simulation modeling and fire data. Simulation modeling, like that implemented in FlamMap (Finney and others 2006) uses a fire spread model in conjunction with spatial and temporal fire environment information and an assumed or measured pattern of ignition locations to estimate the probability of fire burning each landscape element, assuming no suppression action is taken. This approach provides spatially resolved estimates of $p(F)$, as a function of spatial arrangement of the surrounding fire environment and distribution of ignition locations. However, without some kind of verification, the accuracy of the method is unknown.

The fire data approach relies on records of past fires to indicate the probability of burning of future fires. The annual probability of burning for a landscape is estimated as the average annual landscape fraction burned

$$p(F) = \frac{\sum_{t}^{x}\left(B_t/A\right)}{x} \qquad [4]$$

where

B_t is the area burned in year t

A is the analysis area, and

x is the length of the time period

There are many limitations when using this method to predict future burn probability: fire climate, suppression effort, ignition density, and fire regime are all assumed to be constant. The fire-data estimate is not spatially resolved; it applies to the whole landscape regardless of spatial pattern of fuel, weather, topography and ignitions. Increased precision may be obtained with this method by replacing the geography-based landscape with a fire environment classification within which the fire environment and ignition pattern are more homogeneous. For example, applying equation [4] for individual vegetation types will produce an estimate of $p(F)$ for that vegetation type, regardless of geographic location. Although this method may be more accurate because it is based on observation, its poor spatial resolution limits its use for assessing the effects of landscape-level fuel treatments.

The advantages and disadvantages of the simulation and fire data approaches suggest that a hybrid method combining the spatial resolution of the simulation method with the accuracy of the fire data method would be worth pursuing. For example, one could apply the simulation method heuristically, adjusting simulation parameters as necessary until the weighted average landscape level $p(F)$ from the simulation method equals that of the fire data method. More research and development of methods of estimating $p(F)$ is obviously necessary.

Relative Frequency of Fire Behaviors — $p(F_i)/p(F)$

The relative frequency distribution of fire behaviors at a particular point, given that the point does burn, is the final piece of information needed to estimate $p(F_i)$ using equation [3]. Relative frequency distribution of fire behavior at a point is a function of the fuel and topography at the point, the weather at the time it burns, and the direction of spread (with respect to the heading direction) as fire passes the point. Fuel and topographic characteristics can be known and mapped without consideration for any particular fire. The weather history for a location can be analyzed to identify live and dead fuel moisture contents when burning is most likely (that is, during the extreme conditions during which two percent of all fires escape initial attack and go on to burn most acres). Because most acres are burned under very dry conditions (98^{th} percentile ERC), it is reasonable to simplify the analysis by focusing on very dry conditions.

Head fire behavior predicted for very dry conditions is then predicted over a range of open wind speeds (fig. 1a). Fireline intensity, the product of fuel consumption and flame front spread rate (Byram 1959), seems a logical choice for measuring fire behavior as it "… contains about as much information about a fire's behavior as can be crammed into one number" (Van Wagner 1977). Alexander (1982) provides an excellent discussion of the calculation and interpretation of Byram's fire intensity. The Fire Intensity Index (FII; Scott in

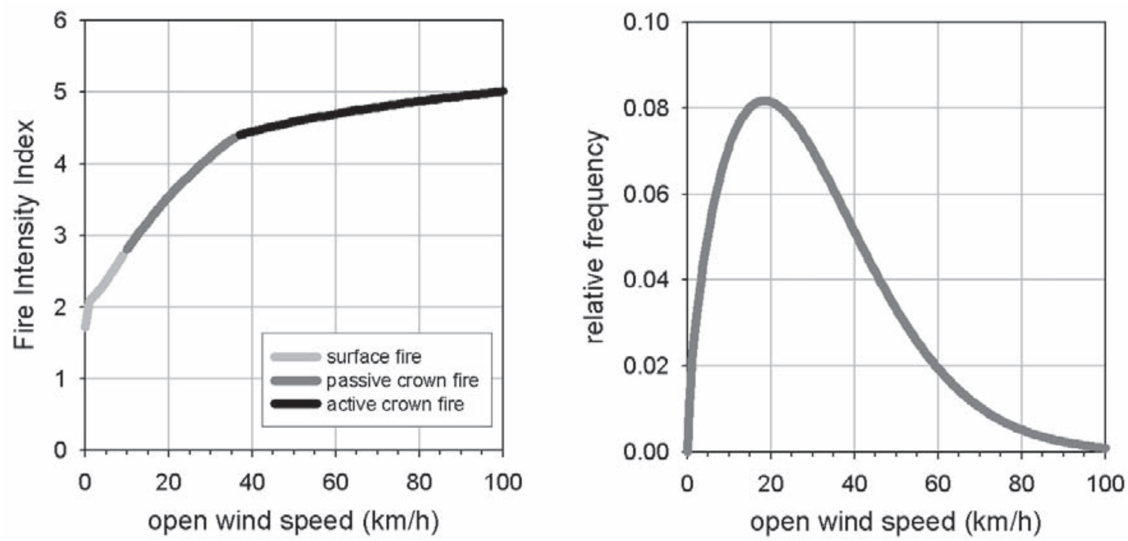

Figure 1—Two components for estimating *p(Fi)*: (a), Fire Intensity Index (FII) over a range of open wind speeds for the very dry moisture conditions during which most acres are burned, and (b) the relative frequency of observing those wind speeds. FII is the common logarithm of fireline intensity expressed in kW/m.

preparation) is the common logarithm of fireline intensity (kW/m). Like the Richter Scale for earthquakes, a unit change on the FII scale corresponds to an order of magnitude change in fire intensity (table 1). Slow-spreading fires burning in very light fuels may exhibit FII < 1; fast-spreading active crown fires through heavy forest fuels may exhibit FII > 5. The effect of wind speed on FII is analyzed separately from fuel moisture because it is not necessarily correlated with fuel moisture. For determining how often the FII predicted in fig. 1a would be observed, a distribution of open wind speeds must be obtained from the weather record (fig. 1b).

Table 1—The behavior characteristics of a wildland fire can be measured using the Fire Intensity Index (FII; Scott in preparation). FII is the common logarithm of fireline intensity (FLI; kW/m). Slow-spreading surface fires in very light fuels exhibit FII < 1; fast-spreading crown fires in heavy forest fuels may exhibit FII approaching 5. FII is classified into six classes (I – VI); each class represents a 10-fold increase in fireline intensity. The range of flame length (FL) as predicted by Byram's (1959) and Thomas' (1963) models is shown for each FII class.

Category	FII	FLI range, kW/m	FL range, m (Byram's FL model)	FL range, m (Thomas' FL model)
I	FII < 1	FLI < 10	< 0.22	FL < 0.12
II	1 ≤ FII < 2	10 ≤ FLI < 100	0.23 – 0.64	0.13 – 0.58
III	2 ≤ FII < 3	100 ≤ FLI < 1000	0.65 – 1.86	0.59 – 2.72
IV	3 ≤ FII < 4	1 000 ≤ FLI < 10 000	1.87 – 5.36	2.73 – 12.7
V	4 ≤ FII < 5	100 000 ≤ FLI < 100 000	5.37 – 15.46	12.8 – 59.42
IV	FII ≥ 5	FLI ≥ 100 000	≥ 15.47	≥ 59.43

The final factor affecting the distribution of FII at a point is the effect of spread direction (relative to the head fire) as fire passes the point. By assuming fire spreads as a simple ellipse (Van Wagner 1969), we can predict the area burned in different FII classes through different areas of a fire (fig. 2). Probability of burning in each FII class is proportional to the relative area burned in those classes.

Using the above factors, a relative frequency distribution of FII for any given fire environment can be constructed (fig. 3). The product of that frequency distribution and probability of burning is $p(F_i)$ (fig. 4a).

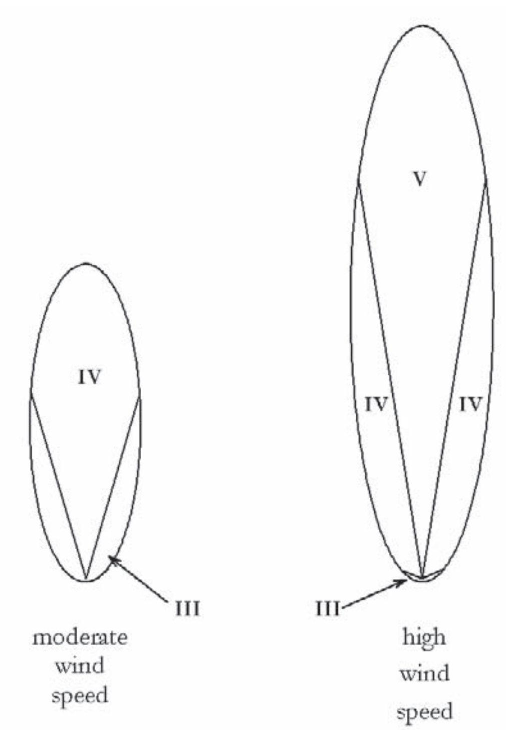

Figure 2—Distribution of FII class as a function of location within an elliptical fire. At moderate wind speed, the head of the fire falls in FII class IV, which extends around to the flank. Backing and flanking intensity fall in class III. At high wind speeds, the head of the fire falls in FII class V, the flanks are in class IV, and the extreme rear of the fire is in FII class III. The probability of burning in an FII class is assumed proportional to the ratio of area in that class to total fire area.

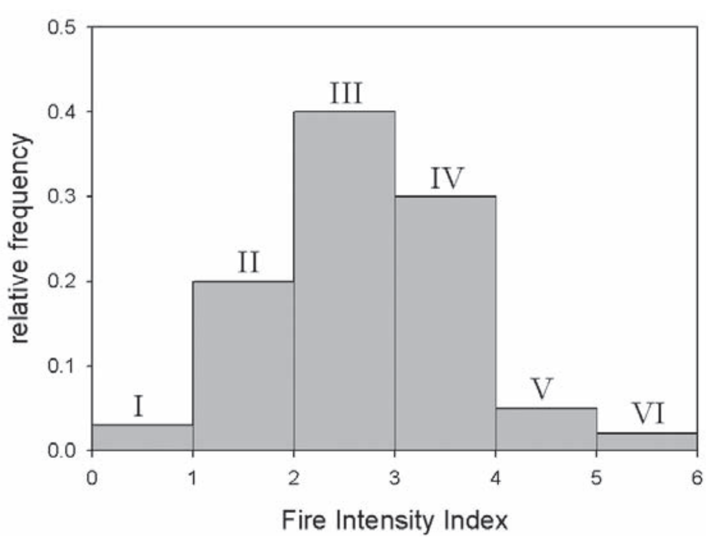

Figure 3—Relative frequency of Fire Intensity Index (the common logarithm of fireline intensity) given that a fire does occur at a given point. The sum of probabilities of observing individual FII classes is one. Relative frequency of FII is a function of the local fire environment at the time of the fire and the distribution of fire intensity at different parts of an assumed elliptical fire. FII class is indicated in Roman numerals.

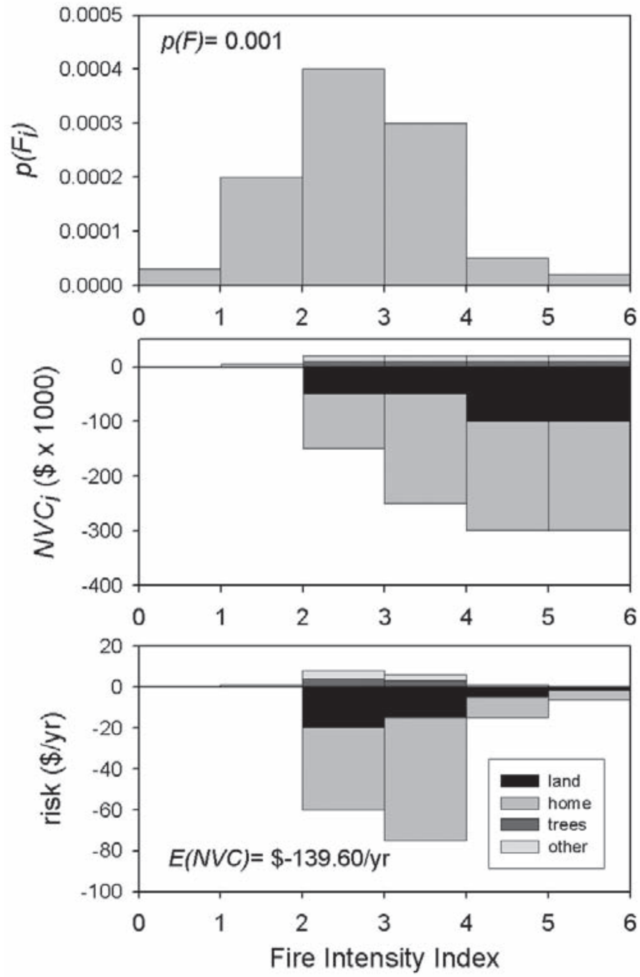

Figure 4—A "Risktogram"—a graphical display of the elements of a quantitative fire risk analysis. Chart (a) displays the frequency distribution of the Fire Intensity Index (FII) at a point. The sum of probabilities in individual FII classes is the annual probability of burning. Chart (b) displays the predicted net change of different values to fire of the various FII classes. Chart (c) displays the resulting wildland fire risk. The sum of *E(NVC)* over all FII classes is wildland fire risk.

Net Value Change — NVC_i

Conceptually, net value change due to fire is a function of initial value and susceptibility. For example, consider two buildings of equal initial value surrounded by flammable wildland fuel, one with a flammable roof covering and the other with a non-flammable covering. The building with a non-flammable roof covering is less susceptible to fire damage—it is more resistant to loss should it experience a fire—and therefore has a lower NVC_i. Conversely, for two buildings of equal susceptibility, NVC_i is proportional to their total value.

Net value change is the post-fire minus pre-fire value of a given place on the landscape (expressed as present value). Net change in land value due to fire is assumed to be a function of fire behavior, and includes both positive and negative effects of fire. NVC_i is quantified by summing over the many different market and non-market values or resources present at a given place.

$$NVC_i = \sum_{j=1}^{n} NVC_{ij} \quad [5]$$

The mix of values and resources that can be affected by fire at any given point depends on ownership and management emphasis. The values can include market values (timber, water, forage, commercial mushroom production, *etc.*), human developments (buildings and infrastructure), and non-market values (recreation, fisheries, clean air, wildlife habitat, ecosystem function, *etc.*). Net value change must include the potential benefits of fire. One often overlooked benefit of an otherwise destructive wildfire is the reduction of future loss it confers [by reducing $p(F)$ or $p(F_i)/p(F)$].

Positive NVC_i indicates that expected benefits of fire exceed losses, such as might occur in uninhabited areas; negative NVC_i indicates a net loss should fire occur (fig. 4b). Estimating NVC_i across a landscape is a difficult yet critical task that would support fire management decisions regarding both fuel treatment and fire suppression. Detailed spatial information on NVC_i could prove to be even more useful to managers of wildfires or fire-use incidents than predictions of fire growth or potential fire behavior. Due to the large areas to be mapped and the wide array of market and non-market values that are affected by fire, it may be necessary to create a stylized set of "value models" for estimating fire loss as a function of FII. Further research into how different values are affected by fire and development operation tools for implementing that research is clearly needed.

Suppression cost is not included in a quantitative risk analysis; it is part of a larger analysis of fire program level. However, suppression efforts influence the burn probabilities as described above.

Wildland Fire Risk — E(NVC)

Equations [1], [3], and [5] form the foundation of quantitative wildland fire risk analysis. Wildland fire risk is the product of three elements: fire probability, fire behavior, and fire effect (fig. 5). Fire probability is the *whether* component and is estimated through fire simulation or using fire data records. Fire behavior is the *how* component, and is estimated by relative frequency distribution of FII. Fire effect is the *so what* component, and is estimated by predicting the positive and negative effects of fire on various values as a function of FII (NVC_i).

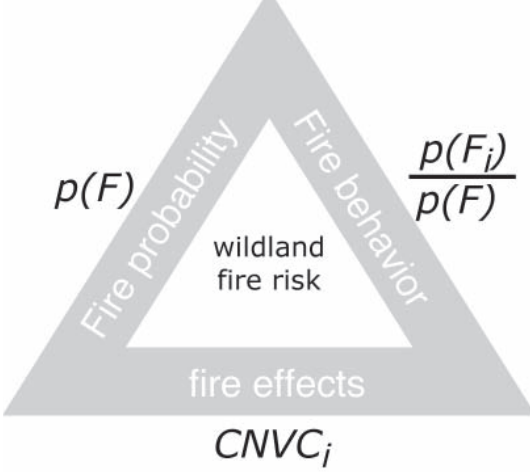

Figure 5—Quantitative wildland fire risk is a function of fire probability, fire behavior characteristics (given that a fire does occur), and fire effects (for given levels of fire behavior). Fire probability at any discrete point on the landscape is a function of the upfire environment (spatial pattern of fuels, weather, topography and ignitions in the area from which fire can be expected to arrive at the point) and suppression actions. Fire behavior is a function of the local fire environment at the time of the fire and the distribution of fire intensity around the perimeter of an assumed elliptical fire. Fire effects are the costs and value changes as a function of fire behavior.

Approaches to Risk Reduction

The framework suggests several theoretical approaches to risk reduction. Wildland fire risk is a function of three main factors: $p(F)$, $p(F_i)/p(F)$ and NVC_i. Reducing any of those components reduces risk. Risk reduction activities fall under two broad categories—fuel treatment and value treatment. A fuel treatment modifies fuel characteristics with the intention of affecting $p(F_i)$. A value treatment modifies characteristics of a value or resource with the intention of reducing NVC_i.

Fuel treatment—Fuel treatments are implemented in discrete geographic units that are generally small in comparison to the large fires whose effects they are intended to mitigate. There are two primary fuel treatment effects on risk reduction —*within-unit*, and *among-units*. Because a treatment unit is small, changing its fuel characteristics does not change its probability of burning; that is determined by the "upfire" fire environment (Finney 2005). Within-unit effects are limited to changing the relative frequency of FII. Within a unit, surface and canopy fuel characteristics are directly modified by a treatment. Dead fuel moisture content and midflame wind speed are indirectly affected by many fuel treatments, usually adversely. The topography and weather elements of the fire environment are not affected by treatment.

Because the probability of burning in discrete treatment unit is determined by the spatial and temporal arrangement of the up-fire environment, only a coordinated array of fuel treatments can potentially reduce the overall probability of burning. The reduction in $p(F)$ is not expected to be constant throughout the fuel treatment array. At the extreme up-fire edge of an array, probability of burning is dominated by the unmodified up-fire environment, and $p(F)$ is not reduced. At the down-fire edge of the array, reduction in $p(F)$ reaches a maximum because the greatest disruption of fire growth can occur. The maximum theoretical reduction in $p(F)$ (as indexed by the pre- and post-treatment fire growth rates), occurs only if the treatment array is as large as the largest fires expected to occur. Otherwise, a fire could grow unmitigated in the untreated area up-fire of the array before encountering the array; the fire's growth could have been further disrupted if treatments were located in that area as well.

Not only does a fuel treatment array potentially reduce $p(F)$, both within and between treatment units, but it can possibly shift the relative frequency of fire behaviors toward lower classes by increasing the amount of flanking fire compared to the predominantly heading fire that would have occurred without the treatment array (Finney 2005). The magnitude of this effect depends on the size of the treatment units relative to fire and the relative spread rates between the treatment unit and the surrounding untreated area. Simulation modeling may confirm and quantify this effect.

Because spatial fuel treatment arrays create effects that occur both within and between treatment units, they must be analyzed at the landscape level (eqn. [2]) rather than at the treatment unit level (eqn. [1]) to be sure that off-treatment benefits are fully accounted for.

Value treatment—A value treatment is a risk reduction treatment that modifies a *value* to reduce NVC_i. Recall that NVC_i is a function of initial value and susceptibility. A value treatment must therefore reduce either initial value or susceptibility. Reducing initial value is not within the scope of risk reduction activities, so value treatments are limited to activities that reduce susceptibility. (However, NVC_i can be mitigated proactively by choosing not to place a susceptible value in a hazardous environment in the first place.) Modifying the physical characteristics of a building—changing to a more fire-resistant roof covering, adding exterior sprinklers, screening attic vents—is one example of a value treatment. Value treatments reduce risk by reducing damage (*NVC*) for any given level of fire behavior without changing exposure to that fire behavior. Instead of making modifications to a building, the owner may instead (or in addition) choose to implement a fuel treatment in the immediate vicinity of the building. Such a treatment, often referred to as defensible space, affects the relative frequency of fire behaviors at the building, but not NVC_i or the overall probability of fire reaching the building in the first place.

Analysis of Risk Reduction Treatment Alternatives

Quantitative wildland fire risk is useful for comparing with other risks faced by a land manager. For example, homeowners and natural resource managers may be interested in knowing how wildland fire risk compares with risk associated with other natural hazards like flood, earthquake, hail, tornado, and hurricane. A homeowner may be interested in comparing his wildland fire risk with technological risks he also faces like structure fire, automobile crashes, and terrorism.

By itself, a quantitative risk analysis is insufficient to prioritize areas for risk reduction treatment because it does not consider the cost or benefit of the possible risk reduction activities. High-risk areas may not respond well to treatment (the relatively high risk may not be easily reduced). Low-risk areas may be so inexpensive to treat that they are a cost-effective option (many more acres can be treated). To make efficient fuel treatment decisions, we must compare treatment benefits with their costs. The benefit-cost ratio of a risk reduction treatment is the present value of its benefits divided by the present value of its costs.

The nominal benefit of a risk reduction treatment is a reduction in risk—that goes without saying—and is quantified as the difference between risk *without* treatment and risk *with* treatment. For example, if risk without treatment is $-\$50$ ac^{-1} yr^{-1} and a treatment reduces that risk to $-\$40$ ac^{-1} yr^{-1}, then the benefit of the treatment in that year is $[-\$40 - (-\$50)]$, or $\$10$ ac^{-1} yr^{-1}. Unless periodic maintenance is incorporated, the amount of risk reduction due to fuel treatment will diminish with time since treatment due to fuel accumulation and vegetation growth. Even without treatment, risk is not necessarily constant over time. NVC_i may change as new values are added to the landscape, increase in value, or become more (or less) susceptible to fire; and $p(F_i)$ may change due to fuel accumulation, vegetation growth, human activity, climate change, or natural disturbance. The present value of fuel treatment benefits (*PVB*) over some period of time is therefore

$$PVB = \sum_{t=1}^{x} \frac{E(NVC_t)_{Treatment} - E(NVC_t)_{noTreatment}}{(1+r)^t} \qquad [6]$$

where

r is the discount rate

x is the planning horizon (yr),

$E(NVC_t)_{Treatment}$ is the risk in year t if the treatment is implemented, and

$E(NVC_t)_{noTreatment}$ is the risk in year t if no treatment is undertaken.

Choice of planning horizon and discount rate can affect present value of benefits. Different landowners have different planning horizons—a forest homeowner might not care about benefits further than a decade or two in the future, while government-managed land is generally planned up to 100 years into the future. Because treatment effectiveness diminishes over time, and because of the time value of money, marginal fuel treatment benefit (present value) diminishes to near zero after just a couple of decades, so little is to be gained with longer planning horizons. Also, natural and anthropomorphic changes in the fire environment during that time are likely to require reassessment of risk.

Risk reduction expenses are comparatively straight-forward to calculate. Expenditures for improving fire resistance or implementing a fuel treatment can occur in any year, especially if the fuel treatment plan calls for a spatial array of treatments installed over time. Also, maintenance of the fuel treatment may be prescribed for future years or even annually. Therefore, present value of risk reduction treatment cost is

$$PVC = \sum_{t=1}^{x} \frac{C_t}{(1+r)^t} \qquad [7]$$

Expenditures associated with fuel treatment activities are routinely documented and modeled. For treatments that generate revenue (for example, commercial thinning), cost is net cost after accounting for revenue. If a treatment generates more revenue than the treatment costs to implement, then BC ratio analysis is no longer an appropriate analysis tool—there's no economic downside. Such treatments can be ranked by present net value rather than BC ratio. Treatment costs depend on many factors, including the type and intensity of treatment, location on the landscape, size and shape of the treatment unit, access to treatment area, distance to forest products markets, and regulatory analysis requirements.

As an investment of capital *today* for benefit *tomorrow*, potential fuel treatments should be analyzed in a manner similar to any other forestry investment. When choosing among possible projects for which capital is the only limiting resource, the economically optimal solution is to implement the projects with the highest BC ratios until the available capital is expended (Gilles and BuonGiornio????). In reality, many resources may be limiting, and operational or political constraints may not allow the optimal economic solution. The BC ratio is just one of many factors that inform a fire management decision. Investments with BC ratios less than one cannot be justified based on quantitative analysis of benefits and costs alone; other benefits not included in the analysis must presumably be present to offset the otherwise negative return. BC ratio less than one implies that available capital is better invested at the specified discount rate and proceeds used to fund any losses when a fire does occur.

Prioritizing Risk Reduction Treatments

In the absence of an analytical framework for estimating the efficiency of alternative fuel treatments, such as that presented here, fuel treatment planners must resort to experience and instinct in selecting the type and location of individual fuel treatments. Their selection criteria include potential fire behavior reduction, the general location and value of resources-at-risk and variables related to treatment cost (access, ability to meet NEPA analysis requirements, etc.). Treatment locations selected through such a process have been termed "easy acres" because they were often the easiest areas to treat.

Such treatments are placed individually without regard for an overall spatial pattern that may reduce *p(F)*. Their locations have been considered random for comparison against a theoretically optimal spatial pattern designed to reduce large fire growth (Finney 2001). While their locations on the landscape may be random in terms of spatial pattern (and therefore sub-optimal in terms of reducing *p(F)*), they are anything but random in terms of treatment cost. In fact, the factors used to select the "easy acres" also result in relatively low treatment cost. Treatment units that are truly random would be quite costly to implement, because factors that affect treatment cost are not considered; randomly located treatments could require costly road construction, fireline building, and NEPA analysis. Fuel treatments located based on a theoretically optimal spatial pattern can be considered random with respect to treatment cost. The BC analysis framework outlined here can shed light on the relative cost efficiency of each strategy.

This analysis framework suggests a new risk reduction treatment strategy—optimizing landscape-level risk by selecting a spatial and temporal risk reduction treatment regime that maximizes the BC ratio.

Discussion

Following significant wildland-urban interface fires in 1923 and 1991, it is well established that the fuels, fire weather and fire-susceptible values in the Oakland-Berkeley Hills of Northern California present a significant wildland fire risk to area homeowners. That same area is also exposed to potentially devastating earthquakes on several faults in the area. According to a recent USGS study, there is a 27% chance of a Richter magnitude 6.7 or larger earthquake occurring in the immediate vicinity of the Oakland-Berkeley Hills between 2003 and 2032 (Hyndman and Hyndman 2005), an annual probability of 0.009 (nearly one in one-hundred). Given the proximity of the probable fault rupture and magnitude of the potential earthquake, significant damage to or total destruction of homes and utilities is likely. Assuming an earthquake loss of just $250,000 per home, the resulting annual earthquake risk is $2250 per home.

Clearly, *eliminating* risk of any natural hazard is well beyond the capability of both individuals and governments. In the face of limited mitigation resources, a strategy for optimally managing risk is required. It is tempting to simply compare the quantitative levels of risk from all natural and technological hazards and allocate mitigation resources to the hazard posing the highest risk, or to each hazard in proportion to its relative contribution to total risk over all hazards. Neither strategy is efficient, however, because they do not consider the cost of mitigation efforts in relation to the benefit. The economically optimal solution would be to allocate resources to efforts with the highest return on investment (that is, the highest BC ratios) until all resources have been used up, regardless of the absolute or relative level of risk. The economically optimal solution may not be feasible for technological or political reasons, so calculation of risk reduction treatment BC ratio must simply be part of a larger decision support framework that accounts for constraints other than available capital.

This analysis framework estimates treatment costs and benefits without considering to whom those benefits and costs accrue. Costs may be borne by one party while benefits are reaped by another. For example, federal or state governments may implement a fuel treatment on public land that benefits nearby private ownerships, or a government agency may subsidize fuel treatment on private land. Potential fire losses may also be transferred among parties. Insurance is a risk management tool used to deal with risks that include potential for catastrophic loss. In exchange for a periodic premium, an insurance company agrees to repair or replace insured values if a loss should occur. The insurance premium is composed of the insurance *rate* and the insured value. Insurance rate is a function of the hazardousness of the environment in which the value resides (the physical situation). Insured value represents *NVC*. In other words, an insurance premium is a function of quantitative risk; the higher the hazard or *NVC*, the higher the premium. This is a potentially helpful concept because insurance rates and premiums can be used as surrogates for hazard and risk. The majority of wildland homes are covered by an insurance policy that includes coverage for fire loss (no distinction is made between wildland fire loss and fire loss due to other causes). In other words, some of the fire risk a homeowner faces has been transferred to an insurance company. In such cases, benefits of risk reduction treatment are received by the insurance company rather than the homeowner. The analysis here makes no consideration for disconnected costs and benefits.

The exclusion of fire suppression costs from this analysis of fuel treatment may seem unjustified. Fire suppression and fuel treatment are similar endeavors—fire suppression is just-in-time fuel treatment; fuel treatment is fire suppression without prior knowledge of where or when a fire will escape initial attack. Both activities are intended to mitigate fire loss. In a risk analysis we wish to account for the *NVC* incurred if an area burns, whereas suppression is an attempt to prevent areas from burning. Therefore, suppression costs should be assigned to the acres that did *not* burn rather than to the areas that did. In this analysis framework, suppression is assumed constant at some level. The effects of fuel treatment are simulated as (1) a shift toward more benign fire behavior (lower FII) within treated areas, and (2) a reduction in fire size and therefore $p(F)$ in fuel treatment arrays. A holistic fire management approach would seek the optimal mix of fuel treatment and fire suppression that minimizes their combined cost plus *NVC*.

When a fire near homes escapes initial attack, it is common to witness last-minute fuel treatments around the homes (defensible space) or preparation of the home itself to resist fire damage (a value treatment). Fire suppression organizations discourage homeowners from relying on these just-in-time mitigation efforts. Instead, homeowners are urged to create defensible space and make their homes resistant to ignition well in advance of a fire start. However, the just-in-time mitigation behavior may actually be quite rational from a purely economic standpoint. Without a nearby ignition, $p(F)$ at a home is quite small, perhaps as low as 1 in 1000 per year, resulting in relatively low risk and corresponding low benefit of defensible space and value treatments; their costs may far exceed potential benefit. Once a fire has ignited nearby, however, $p(F)$ increases drastically, thereby increasing risk, and therefore treatment benefit, by as much as two orders of magnitude. Suddenly, the treatment benefits may exceed treatment costs by a wide margin. Of course, there may not be time or resources available to treat fuels and homes immediately before a fire, and homes will be destroyed. Unfortunately, that does not make treating the home when no fire is present a better investment.

Just-in-time fuel treatment behavior is not restricted to private landowners. Government property is frequently managed in the same manner. The headquarters area of Glacier National Park, in West Glacier, Montana, which includes office, industrial and residential buildings, is located in a fire-prone landscape with a recent history of large fires in the region. Despite the obvious need, defensible space was not maintained throughout the headquarters area. Only when the 2003 Robert fire threatened to burn through West Glacier did activities to create defensible space commence. One reason often cited for this type of behavior is the availability of suppression resources assigned to the fire. Because those suppression resources are not funded by the local unit. Since treatment cost to the local unit decreases to zero, they have even more incentive than a homeowner to engage in just-in-time mitigation. Aggressive suppression actions prevented the Robert fire from reaching West Glacier. Interestingly, after experiencing a rapid rise in $p(F)$ when the Robert fire started nearby, $p(F)$ in future years should be expected to fall below pre-Robert levels because the fire acts as a large fuel modification directly upfire from West Glacier. The corresponding reduction of risk is an example of an unexpected benefit of an unplanned, unwanted wildland fire.

The analytical framework presented here considers only values for which benefits and losses can be quantified. Non-market values are not easily quantified and therefore difficult to bring into such an analysis. Two possible solutions to this problem are (1) attempt to quantify non-market values through techniques such as contingent valuation, or (2) implement the framework with the full understanding that it does not account for all values, and should be used as one piece of information among many to support a fuel treatment decision.

Conclusion

Managing wildland fire risk is an important function of any fire management program. Fire risk exists wherever human values are located in areas where wildland fire can occur. Wildland fire risk is a function of probability burning, potential fire behavior, and fire effects on human values. Fire risk is mitigated by affecting one or more of those factors. The benefit of a risk reduction treatment is the present value of risk reduction. The cost-efficiency of a risk reduction activity can be measured by its benefit-cost ratio.

Acknowledgments

This work was supported by the Fire Modeling Institute, Missoula Fire Sciences Laboratory, Rocky Mountain Research Station.

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Strategic Placement of Treatments (SPOTS): Maximizing the Effectiveness of Fuel and Vegetation Treatments on Problem Fire Behavior and Effects

Diane M. Gercke[1] and Susan A. Stewart[2]

Abstract*—In 2005, eight U.S. Forest Service and Bureau of Land Management interdisciplinary teams participated in a test of strategic placement of treatments (SPOTS) techniques to maximize the effectiveness of fuel treatments in reducing problem fire behavior, adverse fire effects, and suppression costs. This interagency approach to standardizing the assessment of risks and proposing strategically placed treatments to mitigate that risk uses an iterative, collaborative strategic approach to proposing landscape scale treatment patterns. The pilot teams used FARSITE and FlamMap, spatially explicit fire behavior prediction models, to evaluate the effectiveness of proposed treatments on fire behavior and effects at scales appropriate to address the expected problem fire event. A primary objective was to develop a consistent, systematic approach that integrates multiple land and resource management objectives when addressing and evaluating fuels risks. This paper discusses the accomplishments and challenges the pilot project teams faced as they tested strategic placement of treatments methods in different landscapes, vegetation, fire regimes, and ownerships.*

Introduction

In 2005, the USFS in partnership with the Bureau of Land Management (BLM) tested the strategic placement of treatments concept using sophisticated spatial analysis tools in eight pilot areas across the country. This process is not just designed for fire and fuels planning, but as a holistic land management process. While problem fire is the filter through which potential treatment patterns are tested, the objectives for many of the treatments planned are related to timber management, silviculture, forest health, wildlife, and watershed issues, as well as protection of assets from unwanted wildland fire. The national objectives for the SPOTS pilots were to develop a consistent, interagency, systematic approach to evaluating and mitigating risks, test a variety of data sets, models and tools, and to identify barriers or restrictions to meaningful progress.

The SPOTS concept contributes to overall understanding of spatial dynamics of fuel and related fire behavior through use of a collaborative planning process and fire modeling tools that describe fire potential on a specific landscape. The placement of fuels treatments has shown promise in reducing the undesired effects of large fires and acres burned and in the modeling environment. (Finney 2005; Bahro 2006 in press; Stratton 2004). The Fireshed team in California has successfully implemented this concept since 2003. The California Fireshed team conducts integrated workshops to develop long-term

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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strategic objectives and proposed treatment patterns as the basis for program of work planning required for United States Forest Service (USFS) compliance with the National Environmental Policy Act (NEPA).

The SPOTS process broadens fuels projects planning opportunities. Since fires do not stop at ownership boundaries, neither should our planning process. Planning should happen not only at the project level, but also the interagency broad scale fire planning level, where budgets are allocated. Integrating other resources upfront with fireshed-scale planning happening ahead of the NEPA process' "purpose and need" phase would reduce pressures on land managers and allow for a balanced, clear process.

These strategically placed fuels treatments are not intended to exclude fire from the landscape, but to change the character and ultimate effects of an unplanned fire. Treatments on a fraction of the landscape may or may not be sufficient to restore ecosystems, but may effectively disrupt or reduce large wildfire growth as well as being a step right direction toward the long-term goal of restoration of desired conditions at the large scale. Restoration is rarely fully realized in the first entry and may be achieved through multiple entries over many years. The initial strategic entry, if successful can reduce the probability of a large, uncharacteristically severe fire, and can serve to buy more time for mangers to continue working toward the long-term restoration goal.

Methods

A steering committee with members from USFS management and research and the Department of Interior was established to guide the pilot efforts, evaluate the proposals and participate in selection, interact with ongoing pilots, and ultimately develop a performance measure for 2006/2007. Eight pilot teams were selected. The projects represent a range of geographic areas, vegetative types, potential fire problems, data sources, and ownership mixes (Figure 1, Table 1).

The SPOTS pilot teams were required to attend training with the California Fireshed team and report on their lessons learned and current status. Each team was asked to define their specific problem fire scenario in an analysis area larger than the expected problem fire, prepare their data for integrated spatial analysis, and hold a workshop in which they designed potential treatment patterns in an iterative manner. The workshop was expected to feature testing the treatment scenarios with FARSITE or FlamMap fire behavior and spread models (Finney 1998; Finney et al. 2004) and other spatial analysis tools to test effects on other resource objectives. An expected outcome of the workshops was a transparent spatial, tabular, or graphic display of the trade-offs made in the proposed action.

Results

Pilot project teams reported the results of their efforts in October of 2005 (Table 2). All eight teams were able to describe the problem fire scenario, including probable weather, fire behavior, and undesired effects. Seven out of eight project teams calibrated the FARSITE landscape by validating outputs against known fire behavior or a recorded fire event. Seven of eight teams

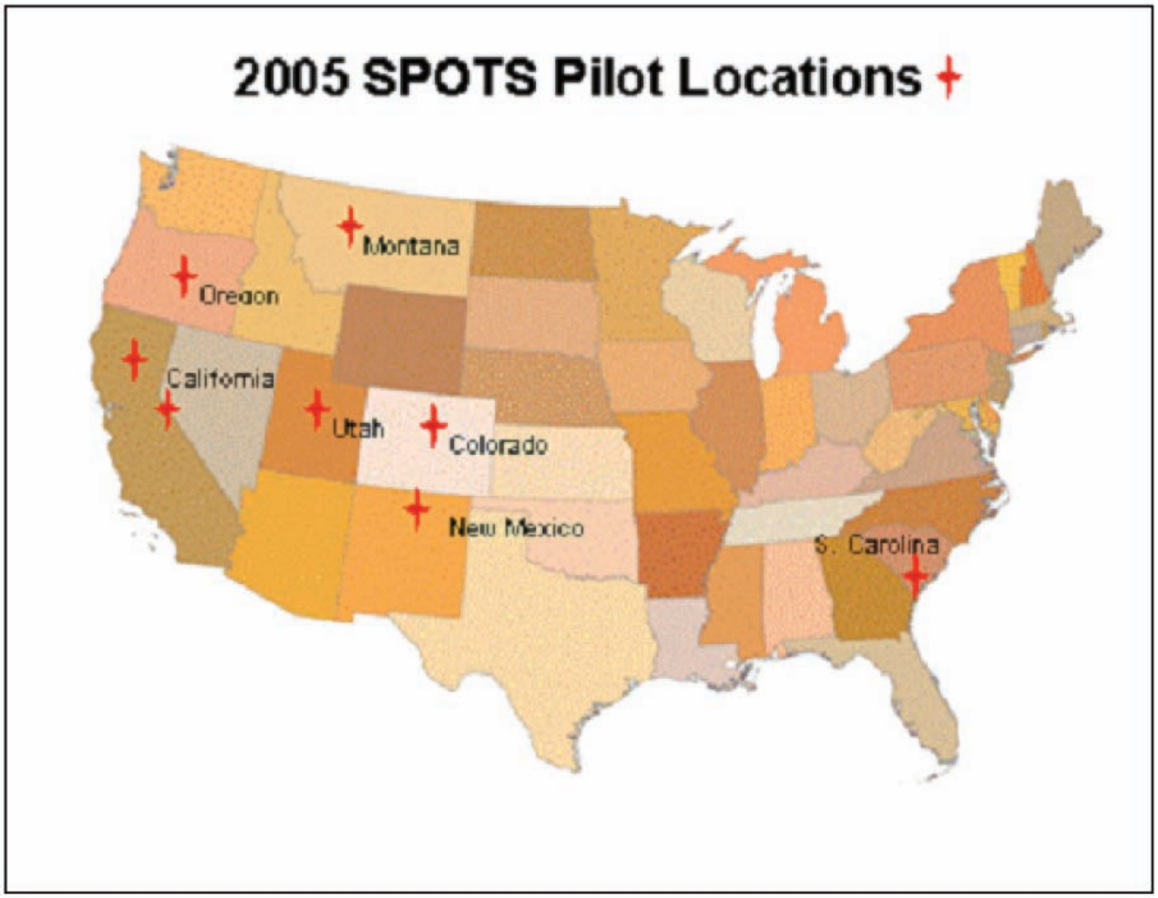

Figure 1—Location of the final 8 pilot projects selected across the country.

Table 1—Participating pilot projects are identified by project name, management unit, location, and a brief study area description.

USFS region	Project name	Unit	State	Study area size and vegetation
1	Butte North	Beaverhead-Deerlodge NF	MT	45,000 acres mixed lodgepole pine forest
2	Yankee Hill	Arapahoe Roosevelt NF	CO	35,600 acres high elevation Rocky Mountain mixed conifer and lodgepole
3	La Jara	Carson NF	NM	6,000 acres within the 42,000 acres Taos Canyon, fuels range from low pinyon/juniper to ponderosa to high elevation conifer
4	Upper Provo	Wasatch-Cache NF	UT	90,000 acres, 7-12,000 ft elevation; aspen, lodgepole, spruce-fir, mixed conifer, and mountain-shrub/oakbrush
5	Alder Springs	Mendocino NF	CA	31,000 acres; Sierra conifer and chaparal
5	Sagehen	Tahoe NF	CA	8,000 acres; mixed conifer, red fir, eastside pine, and pine plantation
6	Cascade Front	Deschutes NF and Prineville BLM	OR	150,000 acres. BLM and FS. Five Buttes/LaPine interface Pondo/mixed conifer, lodgepole
8	ION/Wando	Francis Marion NF	SC	1,030 acres: Longleaf pine, loblolly regeneration, pocosin, hurricane blowdown

Table 2—Summary of results from the 2005 SPOTS pilot projects.

Project area	Defined problem fire	Collected historic weather and wind data and evaluated for PF	Identified analysis area appropriate to the problem fire size	Created FARSITE landscape from vegetation and other data	Completed an iterative process to answer strategic placement of treatments "So What?"	Calibrated the model by validating outputs against known fire event or behavior	Completed an iterative process to answer strategic placement of treatments "So What?"	Created an estimate of how proposed treatments changed the problem fire outcome (screenshots, graphs or tables)	Workshop and duration	Categories of persons attended
North Butte, MT	X	X	X	X		X			Plan to	Public, city government, local fire departments
Yankee Hill, CO	X	X	X	X	X		X	X	Yes: 2 days	Public, state FS, environmental groups
La Jara, NM	X	X		X		X		Yes = Informs burn severity maps for before and after treatment	Yes: 1 day	Public, inter-agency partners and the Taos Pueblo Tribal Council
Upper Provo, UT	X	X	X	X	X	X	X	Yes = FARSITE and FlamMap screenshots for 2 treatment options	Yes: 3 days	FS ID team, summer homeowners and 1 county commissioner
Sagehen, Tahoe, CA			X	X	Plan to	X	Plan to		Plan to	
Cascade Front, OR	X	X	X	X	Plan to	X	Plan to		Plan to	TNC, BLM, USFS, public
ION/Wando, SC	X	X	X	X		X		Yes = FARSITE screenshot	Yes: 1 day	USFS, public, collaborators

identified an analysis area of appropriate size, sufficiently large to contain the expected fire event. Five of the eight pilot projects completed some sort of collaborative workshop or public meeting. Of the five teams that had a workshop, only two teams used FARSITE in an iterative way at the workshop so the participants could test various treatment patterns. Two additional teams used FARSITE outside of the workshop environment, modeling and displaying results from ideas provided by workshop attendees at a later date. One team simply used FARSITE to test their existing program against the no action alternative, but chose not to evaluate alternative treatment patterns. Five teams created an estimate of how proposed treatments changed the fire size or behavior using screenshots, graphs, or tables. A single team shared maps of different ultimate fire sizes in different treatment scenarios.

Pilot teams used several models, but did not even begin to explore the dozens of tools available. FARSITE and FlamMap fire behavior and spread models were the common tools used to evaluate treatment patterns. Though FARSITE has been taught for a decade, it has been used primarily for incident support and has yet to be embraced by the planning community. The projects universally recognized the utility of the FARSITE model for fuels planning purposes. These fire modeling programs should become the centerpiece of a suite of interconnecting software programs that are designed to evaluate treatment patterns.

Four overall national objectives were identified at the start of the 2005 Pilot Projects. The following is a summation of results concerning those national objectives:

1. **Develop a consistent, systematic approach for evaluating and addressing landscape-level risks in an integrated and collaborative way.**

This objective was fully met. The seven-step framework outlined in the discussion section of this paper was developed as a direct result of lessons learned from the national SPOTS pilots.

2. **Test a variety of available data sets, models, and tools in partnership with researchers to determine applicability of some of the many tools available.**

A total of eleven tools and data sets were tested by the various pilot projects. Two teams tested prototype LANDFIRE data.

3. **Identify barriers or restrictions to implementing the selected pattern, intensity or timing of fuel treatments that may be imposed by existing Land and Resource Management Plans.**

The most common barriers reported by the pilot project teams were:

- Analyst skills are universally in short supply.
- The complexity and effort required to generate data layers was extraordinary.

4. **Devise an appropriate measure of success to describe accomplishments developed and implemented using the *landscape-scale effectiveness* approach.**

A performance measure will not be built for SPOTS at this time. The Forest Service will collect data in the next two years on the use of the seven step framework and begin to document cases where strategic treatment patterns are tested by wildland fire.

Discussion

At the October 2005 SPOTS pilot project meeting, teams identified barriers and successes concerning their efforts. Key themes in this discussion included the time and labor-intensive nature of planning and data preparation and calibration, the lack of skilled personnel to complete the preparation and analysis, and the overall success of the process as a communication tool. Where pilots failed to move forward in the process, lack of line officer support was most often the cause.

The collaborative workshop is perhaps the most critical step in the process, because the participants can actively test their ideas about treatments, and see the results almost immediately. This is the step that allows for transparency regarding the trade-offs for the decision maker. The best possible fire solution may not be desired because of impacts to wildlife, watersheds, or scenic quality objectives. The best solution for timber management may not meet the fire objectives. The workshop displays the outcomes of those choices on expected fire behavior as well as the implications for other resources.

The most successful workshops used fire behavior models to inform and support the process. Models increased understanding of fuels and fire spread on the landscape, helping to define the problem and align participants towards a common goal. Fire models run on properly calibrated landscapes were very successful in demonstrating how well treatments worked to interrupt theoretical large fire spread on the landscape. Seven out of eight project teams calibrated the FARSITE landscape by validating outputs against known fire behavior or a recorded fire event. Model calibration gives confidence in model output and contributes to overall participant support. The models were most useful where live modeling was available within the workshop and multiple treatment scenarios could be compared in an iterative manner.

The pilot teams acknowledged the need to identify problem fire behavior within the context of the workshop. This aim establishes modeling parameters, facilitates the discussion of treatment intensities, and helps to create "buy in" regarding the final outputs. Many of the pilot areas identified multiple fires of concern. Developing a shared understanding of the problem fire can be challenging. The members must understand that the task is not to describe everything that could happen under a variety of different conditions, but to discuss the worst case scenario with as defined by the known local fire history or recorded weather conditions.

A change in the planning culture emphasizing partnership and shared decision-making was recognized as a key success by all of the pilot project teams. Communities and collaborators appreciated inclusion in the process, increasing perceived "buy-in" to decisions and decreasing the perceived likelihood of litigation. Internal cooperation was also a success in many areas, when multiple resource disciplines were able to use the tools and collaborative process to understand overall fire risk and achieve hazardous fuels project planning and multiple resource benefits.

Multiple barriers to the process were identified including: perceived conflicts between fuels treatments and the protection of threatened and endangered species habitat, smoke issues, limited budgets for project implementation, and the tendency for large chunks of these budgets to be spent in the planning process. Traditionally, fuels treatments may be constrained by cost-per-acre, with acres accomplished taking precedence over higher dollar wildland urban interface or remote area treatments. Litigation or the potential for litigation was also perceived as a planning constraint.

Conclusion

A framework was developed, based on the experiences of the eight SPOTS pilot project teams, giving general guidelines to follow when attempting to implement fireshed-level fuels treatment planning on individual landscapes. While strategic approaches will vary throughout the country to account for different fuels, topography, weather, and social factors, all spatial modeling approaches targeting undesired fire behavior should feature:

1. Explicitly defining an analysis area
2. Identifying assets and protection targets
3. Defining the "problem fire"
4. Designing treatment patterns
5. Testing multiple treatment patterns with a spatial fire behavior model
6. Clearly displaying the trade-offs
7. Monitoring and adaptive management

This framework is discussed in depth at www.nifc.gov/spots. The framework meets the need, described by the United States General Accounting Office (2000, 2003, 2004, 2005), to establish a consistent way to define risk and test potential solutions. The framework can be used collaboratively across agency boundaries and would be useful even lacking complex modeling software or data. Critical innovations provided by this framework are tying the size of the analysis area directly to the 'problem fire', the development of a treatment pattern specifically designed to impede fire spread and severity, and the iterative testing that allows team members to have immediate feedback on their ideas.

Challenges to the wide spread adoption of SPOTS seven step approach remain. The lack of analyst skills is a critical need that must be filled with training and employee development. The Fire Modeling Institute at the Fire Sciences Lab in Missoula is beginning to supplying skilled analysts who may be available to teams that are trying to develop a skills base locally. A great deal of work remains to select and integrate models that would form a unified national corporate software package. Teams using a SPOTS approach will be the early customers of the national LANDFIRE data set. SPOTS analysis approaches should dovetail with Fire Program Analysis (FPA) System, and could be critical in supporting land and resource management planning.

The seven-step framework for SPOTS is an excellent way to aid in collaboration with a variety of partners and supports policy directives like the National Fire Plan and Healthy Forests Initiative. Fire modeling shows that a deliberate pattern of slower burning fuels can lead to fires that are smaller and less intense. Fuel treatments and vegetation management efforts can change the outcome of the problem fire consequently reducing suppression costs. SPOTS approaches encourage a landscape-level, cohesive fuels treatment strategy that may provide biomass and encourage the development of businesses that can use our hazardous fuels to bring value added products to market or increase our capability to generate energy.

SPOTS approaches may not be meaningful on all lands, for all problems. In an environment where the land management agencies currently only fund treatments on about 1% of their lands per year, planning to treat 20% of the entire landscape seems unrealistic. The strategic placement of fuel treatments should be used in high profile, high priority areas to increase the likelihood of success and secure future treatment opportunities. SPOTS treatment patterns may allow managers time to implement long-term management strategies to restore ecosystems. The enhanced understanding of wildland fire potential gained by participants of the SPOTS approach as well as the distribution of treated acres with lower fire severity potential across the landscape may provide some comfort to local decision makers considering the highly effective fuels treatment option provided by broad-scale Wildland Fire Use.

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Landfire: Landscape Fire and Resource Management Planning Tools Project

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***Abstract**—Managers are faced with reducing hazardous fuel, restoring fire regimes, and decreasing the threat of catastrophic wildfire. Often, the comprehensive, scientifically-credible data and applications needed to test alternative fuel treatments across multi-ownership landscapes are lacking. Teams from the USDA Forest Service, Department of the Interior, and The Nature Conservancy are completing the LANDFIRE Project, which produces consistent and comprehensive spatial data describing vegetation composition and structure, wildland fuel, historical fire regimes, and ecosystem status across the entire United States. LANDFIRE provides a scientific foundation for assessments of wildland fuel conditions, fire hazard, and ecosystem status. While LANDFIRE products will fill immediate needs for testing alternative fire management scenarios, planning fuel treatments, and allocating resources, the data and models have much broader applications in research, biodiversity conservation, and strategic forest and resource management planning. This paper provides a synopsis of the background, objectives, and deliverables of the LANDFIRE Project and the management challenges LANDFIRE products address. Presented are potential applications of LANDFIRE data for use in fire research and vegetation ecology studies and in wildland fuel treatments and restoration projects to protect communities at risk.*

Introduction

LANDFIRE is a five-year wildland fire, ecosystem, and wildland fuel mapping project that generates consistent, comprehensive products describing vegetation, fire, and fuel characteristics across the United States. Wildland fire managers faced with requirements for reducing hazardous fuel, restoring historical fire regimes, and decreasing threats of catastrophic wildfire are often without adequate, scientifically credible data to support their planning and decision-making processes. LANDFIRE was conceived to fill this need. The main objective of LANDFIRE is to generate relevant, integrated geospatial products that provide a scientific foundation for landscape fire management planning, prioritization of fuel treatments, interagency collaboration, community and firefighter protection, and effective resource allocation. The consistent and comprehensive nature of LANDFIRE methods ensures that products are nationally relevant, while the 30-m grid resolution assures that data can be locally applicable.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Background

The recent United States laws and policies with respect to health and restoration of wildlands share common themes. These include the recognition that 1) fire is a landscape-level biophysical process critical to the maintenance of ecosystem function; 2) solutions to fuel and fire problems require collaboration among stakeholders at all levels of government; and 3) effective collaboration requires consistent, comprehensive, up-to-date data on vegetation, wildland fuel, and fire conditions across the entire country.

In the aftermath of the 1994 fire season — in which 34 fire fighters lost their lives, dozens of communities were threatened, and hundreds of thousands of hectares burned — the Secretaries of Agriculture and Interior adopted a new federal wildland fire management policy directing federal land management agencies to manage wildland fuel and fire on an interagency, landscape-scale (USDA and USDI 1995). Through this policy, fire managers were directed to develop long-term fire management plans that incorporate measures to treat fuel and increase the utilization of biomass. Additionally, this policy called for the implementation of fire behavior prediction to support both strategic planning and tactical suppression and logistics decisions, with special consideration of firefighter safety. Clearly, fire behavior and effects modeling and information system technology play a critical role in all future wildland fire planning and management activities.

In 2000, Congress mandated the implementation of the National Fire Plan (USDA and USDI 2000). The National Fire Plan is a long-term commitment to address problems associated with unsustainable wildland fuel and ecosystem conditions that have evolved over many decades of fire suppression and land use. The plan is based on cooperation and communication among federal agencies, states, local governments, tribes, and interested publics. To supplement the National Fire Plan, the Western Governors' Association, working with federal land management agencies, developed the 10-Year Comprehensive Strategy that directs state and federal agencies to focus high priority on treatments that protect communities and provide defensible space for fire fighters (USDA and USDOI 2001). More recently, the Healthy Forests Restoration Act (HFRA) was enacted to facilitate the reduction of wildfire risk, improve biomass utilization, protect resources, promote the systematic gathering of information on wildland fire, promote the early detection of insect and disease outbreaks, and to protect, enhance, and restore ecosystems.

Managers need for continuous wildland fuel and vegetation data at sufficient spatial resolution to run commonly used decision support tools (such as BEHAVE-Plus [Andrews and others 2005], FARSITE [Finney 1998], FlamMap [Stratton 2004], Nexus [Scott and Reinhardt 2001], and FFOFEM [Reinhardt and others 1997]) led the Wildland Fire Leadership Council, a group of senior administration executives representing all land management agencies in the country, to charter the LANDFIRE Project (see www.landfire.gov for additional project details).

Mapping Vegetation and Fuel

The three general production objectives of LANDFIRE are 1) mapping existing vegetation, 2) mapping wildland fuel, and 3) mapping the departure of current landscape conditions from those that existed historically. Maps describing environmental site potential and existing and historical vegetation are important intermediate LANDFIRE products for assessing wildland fuel conditions and evaluating departure from historical conditions. Both of these assessments are required by federal wildland fire management policy and the HFRA. LANDFIRE describes current and historical vegetation characteristics by mapping existing vegetation (EVT) and modeling two types of potential vegetation: environmental site potential (ESP) and biophysical settings (BpS).

The LANDFIRE environmental site potential (ESP) product represents the vegetation that could be supported at a given site based on the biophysical environment in the absence of disturbance. As used in LANDFIRE, ESP map units represent the natural plant communities that would become established at late or climax stages of successional development in the absence of disturbance. The ESP map is similar in concept to other approaches to mapping potential vegetation in the western United States, including habitat types (Daubenmire 1968; Pfister and others 1977) and plant associations (Henderson and others 1989). It is important to note that ESP is an abstract concept and represents neither current nor historical vegetation. In LANDFIRE, ESP map units are used for site stratification in the processes of mapping surface fuel models and canopy fuel.

The biophysical settings (BpS) product represents the vegetation that can potentially exist at a given site based on both the biophysical environment and an approximation of the historical disturbance regimes. It is based on the ESP map. Unlike the ESP map, the BpS map represents natural plant communities that would become established given uninterrupted natural disturbance processes, such as fire. In LANDFIRE, the BpS map is used to link the ecological process of succession to simulation landscapes in the LANDSUM landscape fire succession model, which simulates historical fire regimes and vegetation conditions (Keane and others 2002). Each BpS map unit is matched with a model of vegetation succession and disturbance pathways, and both serve as key inputs to the LANDSUM landscape succession model. The BpS grid is similar in concept to the potential natural vegetation groups used in mapping and modeling efforts related to fire regime condition class (Schmidt and others 2002; www.frcc.gov).

The third vegetation map, existing vegetation type (EVT), represents the vegetation currently present at a given site. EVT map units are based on NatureServe's Ecological Systems classification (Comer and others 2003). The map of EVT is generated using a predictive modeling approach that relates Landsat imagery and spatially explicit biophysical gradients to field-referenced data that have been classified to LANDFIRE vegetation map units based on the dominant vegetation of the plot. Some field-referenced data are withheld from the map creation process and are used to test and validate maps and model results. To date, the LANDFIRE reference database contains approximately 146,800 field plots from the first 17 mapping zones compiled from existing government and non-government inventory databases, including the U.S. Forest Service's Forest Inventory Analysis Program.

The LANDFIRE existing vegetation maps are integrated with maps of vegetation structure to represent succession classes (termed vegetation-fuel classes in the Interagency Fire Regime Condition Class Guidebook (Hann and others 2004). Succession classes form the foundation of fire regime condition class (FRCC) calculation and represent current vegetation conditions with respect to the vegetation species composition, vegetation cover, and vegetation height ranges of successional states that occur within each biophysical setting.

LANDFIRE is mapping both surface fuel and canopy fuel. Surface fuel represents biomass that occurs on the ground contributing to the behavior of fires burning on or near the surface. Because mapping wildland fuel over large regions is very difficult using standard indirect remote sensing techniques (Keane and others 2001), the LANDFIRE Project relies on combinations of existing vegetation composition and structure and biophysical settings to create wildland fuel products. The 13 fire behavior fuel models described by Anderson (1982) and the 40 Scott and Burgan fire behavior fuel models (Scott and Burgan 2005) are mapped to facilitate the modeling of fire behavior variables such as fire intensity, spread rate, and size using models such as Rothermel's mathematical model for surface fire behavior and spread (Rothermel 1972), BEHAVE Plus (Andrews and others 2005), FARSITE (Finney 1998), NEXUS (Scott and Reinhardt 2001) and FOFEM (Reinhardt and others 1997).

Fuel models integrate the fuel characteristics necessary for fire propagation along the ground; however, additional information on the vegetation canopy is required to predict the initiation, spread, and intensity of crown fires (VanWagner 1977, 1993; Rothermel 1991; Scott 2003). Canopy fuel represents the amount and arrangement of live and dead biomass in the vegetation canopy. Maps of canopy height, canopy cover, and existing vegetation were developed using information from the LANDFIRE reference database, remote sensing methods, and statistical modeling.

In addition to canopy height and canopy density, two more canopy characteristics serve as critical components for predicting crown fire potential: canopy bulk density (CBD) and canopy base height (CBH). CBD describes the density of foliage and branches for a specific vegetated stand and is defined as the mass of available canopy fuel per canopy volume unit; canopy base height (CBH) describes the average height from the ground to a forest stand's canopy bottom. CBD and CBH were calculated for each plot in the LANDFIRE reference database using FUELCALC, a fuel summary application developed by Reinhardt and Crookston (2003). FUELCALC computes a number of canopy fuel characteristics for each field reference plot based on allometric equations relating individual tree characteristics to crown biomass. Geospatial data describing canopy fuel provide information for fire behavior models, such as FARSITE (Finney 1998), to determine areas in which a surface fire is likely to transition to a crown fire (Van Wagner 1977, 1993).

Fuel models and canopy fuel metrics are used to simulate fire *behavior*. Simulation of the *effects* of fire (such as vegetation mortality, soil heating, and smoke production) requires systems that describe and integrate the actual measurements of fuel for vegetated stands. There are two examples of fire effects models that may be produced by LANDFIRE. Both are currently under scientific review and at this time are not fully incorporated into the LANDFIRE production. Mapping of these products will be initiated upon the recommendation of scientific review. The first, fuel loading models (FLMs; Lutes and others, in preparation), use fuel information from the LANDFIRE reference database to characterize representative loading for each fuel component (for example, woody and non-woody) for typical vegetation classification systems such as the Society of American Foresters vegetation classification system (Eyre 1980). FLMs characterize fuel loading across all vegetation and ecological types. The second fire effects modeling system, called the Fuel Characterization Classification System (FCCS) and developed by Sandberg and others (2001), summarizes fuelbeds using canopy, shrub, surface, and ground fuel stratifications. Several fuelbed categories that describe unique combustion environments form the foundation of FCCS. See www.fs.fed.us/pnw/fera/research for more information on FCCS. Both sets of fire effects models are formulated to serve as input to existing fire effects models such as FOFEM (Reinhardt and others 1997) and CONSUME (Ottmar and others 1993). When incorporated into LANDFIRE production, these sets of fire effects models will be assigned to unique combinations of the integrated vegetation products. Geospatial representation of fire effects fuel models may be used to prioritize fuel treatment areas, evaluate fire hazard and potential, and examine past, present, and future fuel loading characterizations. See Reeves and others, this proceedings for a full description of LANDFIRE fuel products.

In addition to products that describe wildland fuel characteristics, LANDFIRE produces a suite of products related to fire regime condition class (FRCC). The discrete, three-level FRCC classification, established by Hann and Bunnell (2001), is defined as a descriptor of the amount of "departure from the historical natural regimes, possibly resulting in alterations of key ecosystem components such as species composition, structural stage, stand age, canopy closure, and fuel loadings." The three condition classes describe low departure (FRCC I), moderate departure (FRCC II), and high departure (FRCC III). LANDFIRE produces maps of FRCC using methods derived from the Interagency Fire Regime Condition Class Guidebook (Hann and others 2004). It is important to note that the LANDFIRE FRCC map represents the departure of current vegetation conditions from simulated historical reference conditions, which is only one component of the FRCC characterization outlined in Hann and others (2004).

The *historical* reference conditions for vegetation succession classes are simulated using LANDSUM (Keane and others 2002). The *existing* succession classes, mapped according to EVT, can additionally represent uncharacteristic vegetation components, such as exotic species, that are not found within the compositional or structural variability of successional states defined for a biophysical setting. In LANDFIRE, current succession class proportions within an analysis area are compared to those of simulated historical reference conditions to calculate FRCC.

LANDFIRE also produces maps of fire regime groups representing an integration of the spatial fire regime characteristics of frequency and severity simulated via the LANDSUM model (Keane and others 2002). These groups are intended to characterize the presumed historical fire regimes based on interactions between vegetation dynamics, fire spread, fire effects, and spatial context (Hann and others 2004). Fire regime groups mapped by LANDFIRE include: 1) Fire Regime I (0 to 35 year frequency, low to mixed severity), 2) Fire Regime II (0 to 35 year frequency, replacement severity), 3) Fire Regime III (35 to 200 year frequency, low to mixed severity), 4) Fire Regime IV (35 to 200 year frequency, replacement severity), and 5) Fire Regime V (200+ year frequency, any severity).

Applications

The consistent and comprehensive fuel and vegetation data produced by LANDFIRE provide managers and scientists with the ability to systematically compare how vegetation, fuel, and fire potential vary between landscapes. LANDFIRE provides the fuel and terrain data necessary for executing the FARSITE (Finney 1998), FlamMap (Stratton 2004), BEHAVE-Plus

(Andrews and others 2005), and Nexus (Scott and Reinhardt 2001) models. Surface fuel models include the 13 fire behavior fuel models (Anderson 1982) and the 40 fire behavior fuel models (Scott and Burgan 2005). Fuel consumption, smoke production, and soil heating calculated using FOFEM (Reinhardt and others 1997) and CONSUME (Ottmar and others 1993). LANDFIRE products provide managers with the ability to predict potential fire behavior in tactical and strategic planning of suppression activities. The ability to model expected fire behavior with and without fuel treatments provides managers with valuable decision support tools for strategic planning (Finney 2001, 2005). The ability to predict and game fire behavior and effects across landscapes provides managers and scientists with a framework to explore biophysical mechanisms that entrain fire regimes and to forecast the implications of climate change (Keane and others 1997), fragmentation (Finney 2005), and other disturbances across landscapes and regions. Finally, the ability to quantify the locations and magnitude of hazardous fuel is critical for designing defensible space and protecting communities.

Acknowledgments

We acknowledge Robert E. Keane; Mark A. Finney, Charles McHugh, and James Menakis with the USDA Forest Service Rocky Mountain Research Station, Missoula, Montana for their thoughtful contributions to LANDFIRE methods. We acknowledge Gregory Dillon, Donald Long, Matt C. Reeves, and Brendan Ward, with the USDA Forest Service Rocky Mountain Research Station, Missoula, Montana and Karen Short with Systems for Environmental Management, Missoula, Montana for their professional support in the development and implementation of software and procedures critical to the creation of LANDFIRE products. A large national project could not succeed without a business management team, and we therefore also acknowledge Daniel Crittenden, Bruce Jeske, and Timothy Melchert with the USDA Forest Service Office of Fire and Aviation Management and Henry Bastian with the U.S. Department of Interior Office of Wildland Fire Coordination, for their professional business support.

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Applying Fire Spread Simulators in New Zealand and Australia: Results from an International Seminar

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Abstract—*There is currently no spatial wildfire spread and growth simulation model used commonly across New Zealand or Australia. Fire management decision-making would be enhanced through the use of spatial fire simulators. Various groups from around the world met in January 2006 to evaluate the applicability of different spatial fire spread applications for common use in both New Zealand and Australia. Developers and researchers from Canada, the United States, and Australia were invited to apply Prometheus, FARSITE, and other similar models to New Zealand and Australian wildfires in grass, scrub, and forested fuel types. Although the lack of site-specific fuel models and weather data were a concern, coarse spatial and temporal data inputs proved adequate for modeling fires within a reasonable margin of error. The choice of grass models proved less important than expected since spread rates were easily manipulated through moisture content values during calibration. The final modeled perimeters are affected by several user inputs that are impossible to separate from model error. These various inputs exist to allow experienced users to approximate local environmental variability as closely as possible to obtain successful outputs. Rather than attempt to quantify direct comparisons, local users concluded it was more important to choose an application that provides an appropriate level of functionality, that is compatible with current data and fire management systems, and that can be easily modified to use unique and varied fire spread equations. Prometheus and FARSITE performed very well and will be further investigated to understand how each might be customized for use with local fire spread models. This paper describes the process and results of testing some existing fire growth simulation models for use on fires in New Zealand and Australia.*

Introduction

Australian and New Zealand fire managers have a need for spatial fire spread simulators for planning and operations. The New Zealand Department of Conservation (DOC) and the National Rural Fire Authority are interested in adopting a spatial fire growth simulation model for enhanced decision-making. New Zealand's native vegetation is not generally fire-adapted, and DOC must measure conservation success by comparing the actual area burned to the potential area burned without suppression. Australia, a more fire-prone nation, has experienced some of its most devastating wildfires in the past two decades with significant damage to property, infrastructure, and the environment, including loss of civilian lives. In response to these wildfires, the Australian government has recommended continued development and

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coordination of wildfire simulation models to enhance decision-making. Unlike New Zealand, Australian land management agencies need to conduct prescribed burning for hazardous fuel reduction. Using a simulator to assess changes in risk over time and space would be helpful. Additionally, private plantation companies in both nations are interested in how various wildfire scenarios might affect their investments. Fire researchers are investigating whether a current model can be adapted for use in Australasia, or whether a new simulator requires development.

In recent years, with advances in computer speed and modeling, storage capacity and graphical capabilities, some fire behavior models have been implemented in spatial fire growth simulation models. These models can aid in understanding strategic placement of fuel treatments on the landscape to reduce overall fire spread and potential fire behavior (Finney 2002; Vojtek 2006). A spatial fire simulation tool allows fire managers to quickly simulate several potential fire scenarios and helps them evaluate fire effects at a landscape scale.

Wildland fire simulators combine spatial and temporal representations of fuels, weather, and topography to propagate point, line or polygon ignitions. Fire simulators are not new fire behavior models. Calculations depend on the underlying mathematical expressions representing what are commonly referred to as 'fire behavior models'. Familiar surface fire spread models include empirical models developed by McArthur (1967) and Forestry Canada Fire Danger Group (1992), and the semi-empirical model developed by Rothermel (1972). Some simulators incorporate additional models to calculate spotting and crown fire initiation (Pastor and others 2003). Worldwide, over twenty spatial wildland fire simulators have been developed for operations, planning, and research (Pastor and others 2003). Most of these simulators are designed to handle specific areas and requirements; few are sufficiently robust for trans-continental applications (Johnston and others 2005). Ensis Bushfire Research hosted an international workshop to evaluate several spatial fire spread simulators that could be adopted in New Zealand or Australia. This paper describes the process and results of testing some existing fire growth simulators for that purpose.

Fire Environments

The fire environments and fire histories of New Zealand and Australia are markedly different.

New Zealand consists of two main islands of 270,000 square kilometers isolated in the southwest Pacific Ocean. Indigenous vegetation types are not generally considered fire adapted and New Zealand experiences relatively few naturally ignited fires. Pine plantations, pasture grasslands, and exotic shrubs comprise the majority of non-native vegetation types that burn readily from human-caused ignitions. Rapidly changing conditions dominate the maritime-influenced weather and unrelenting winds exceeding 80 km/h are common. New Zealand has approximately 2500 rural vegetation fires each year that, combined, burn approximately 7000 hectares. Fires are considered "large" if they are greater than 50 hectares and spread for more than one burn period.

Australia is located between the Indian and Pacific Oceans and is 7 million square kilometers, thus supporting a continental climate. Bushfires are an inherent part of the Australian landscape. Few areas of Australia are free from fire, and every decade, intense and widespread fires burn in southeast Australia. As an example, the spring of 1974 witnessed 15% of Australia's land area burned (Luke and McArthur 1978), and from 1960-2001 there were 224 fire-related deaths, over 4500 injuries, and $2475 million dollars in damages (McMichael and others 2003). As such, this area has a reputation as one of the three most fire-prone areas in the world along with southern California and southern France. Although fire has proven important to the local ecosystems by shaping vegetation mosaics and maintaining biodiversity, it is one of the most significant threats to human populations and infrastructure. Throughout the 20th century, many fires have claimed lives, destroyed homes and livelihoods, and burned thousands of hectares. Land managers and fire management agencies reduce this risk through a range of measures before and during fires.

Fire Spread Models and the Need for a Common Simulator

New Zealand and Australia have approached fire spread modeling somewhat differently. New Zealand fire managers have adapted a limited number of empirical fire spread models, mostly from the Canadian Fire Behavior Prediction system (FBP, Forestry Canada Fire Danger Group 1992; Pearce and Anderson 2004; Opperman and Pearce 2005). Australian researchers have developed empirical models based on experimental burns supplemented by reliable wildfire observations. Both nations use qualified fire behavior analysts to predict fire spread and behavior using computational spreadsheets or calculators and paper maps on fire incidents. The McArthur Forest Fire Danger Meter (McArthur 1967) and Western Australia Forest Fire Behavior Tables (Sneeuwjagt and Peet 1985) are commonly used for fire behavior prediction in open eucalypt forests in Australia, while Pearce and Anderson's guide (2004) is used in New Zealand. Although fire behavior analysts can readily provide point-based calculations and a perimeter for a single weather scenario, this time-intensive process leaves little time to develop potential perimeters for a variety of possible weather scenarios. Often, the Incident Commander has no basis for judging the error associated with the supplied perimeter. In contrast, fire behavior analysts in the United States and Canada have spatial fire simulators in their suite of predictive tools to quickly develop several potential fire perimeters based on different weather scenarios.

Australia and New Zealand would benefit from adopting the same fire spread simulator. Although each nation can see immediate benefits by adopting the simulator that most closely reflects current fire management systems, this may prove difficult to manage in the long term. Fire management organizations in both nations are experiencing a shortage of firefighting personnel and a loss of the technical skill base. Therefore, operational resources are often shared. If one simulator could be used in both countries, the resulting common technology transfer would represent a cost savings and allow skilled fire behavior analysts to be shared. Although New Zealand and Australia differ in regards to fire history, fuels, and fire behavior models, both have a private and public need for fire simulation models.

Simulators Evaluated at the Workshop

Six fire simulators were presented at the workshop. Five of these simulators are systems that combine different fire behavior models with multi-dimensional mathematical models to predict rates of spread in complex environmental conditions varying spatially and temporally. Time-dependent fire spread is calculated appropriate to local conditions to output tabular or graphical representations of fire area, fire perimeter, fire numbers, and fire characteristics. Of the simulators examined at the seminar, FARSITE (Finney 1998) and Prometheus (Tymstra and others 2006) are operational in their respective countries; the Portable Fire Growth Model (Shamir, pers. comm.) and the Bushfire CRC computer simulation project are under development (Johnston, pers. comm.). Networked Fire Chief (Omodei and others 2004) is not a fire spread simulator, but a research decision tool to generate fire scenarios. A new model based on Minimum Travel Time (MTT, Finney 2002) was also demonstrated. This technique solves for fire arrival time across the landscape using Fermat's principle, which is essentially the inverse of Huygen's and produces nearly identical results given homogeneous temporal data. This evaluation focuses on the two mature operational fire spread systems—FARSITE and Prometheus.

FARSITE (Finney 1998) was developed in the U.S. and has been in use since the early 1990s (Finney 1994). It relies on a wave-front expansion technique called Huygens' principle to achieve two-dimensional elliptical fire growth (Anderson 1983; Richards 1990) using existing one-dimensional models of fire behavior. Fire behavior support in FARSITE includes surface fire (Rothermel 1972), crown fire (Van Wagner 1977, 1993; Rothermel 1991), dead fuel moisture (Nelson 2000) and spotting from torching trees (Albini 1979). FARSITE generates vector and raster maps of fire growth and behavior (time of arrival, fireline intensity, rate of spread, flame length, heat per unit area, and fire type), which can be exported as ASCII grids. FARSITE inputs may be used with FlamMap, which computes fire behavior for every landscape cell using a single wind and weather scenario. FlamMap includes the recently developed and experimental fire simulation techniques called the Treatment Optimization Model (TOM, Finney 2001) and Minimum Travel Time (MTT, Finney 2002).

The Canadian fire growth simulation model, *Prometheus*, was also tested. The foundations of the *Prometheus* model are the Fire Weather Index (FWI) and the Fire Behavior Prediction (FBP) Sub-Systems of the Canadian Forest Fire Danger Rating System (CFFDRS) (Van Wagner 1987; Forestry Canada Fire Danger Group 1992). *Prometheus* incorporates two sets of elliptical growth equations to mathematically expand the elliptical wave front: two-dimensional differential equations defined in Richards (1990) and three-dimensional equations defined in Richards (1999) to simulate fire growth over a three-dimensional surface. A variety of FBP outputs (fire intensity, rate of spread, surface fuel consumption, crown fuel consumption, and total fuel consumption) can be exported as ASCII grids. Software engineering of *Prometheus* began in 2000. The Microsoft COM architecture of this model provides for the reusability and extension of its components. As examples, burn probability mapping applications such as Burn-P3 (Parisien and others 2005) and batch routine applications such as Pandora re-use Prometheus functionality.

Methods

Acquiring Simulation Data

Inputs for the fire simulators differed slightly, though each required a digital elevation model (DEM), weather, and fuel data. Although the DEMs were relatively easy to acquire and import into the simulators, it proved difficult to identify wildfires with adequate geospatial records and nearby weather stations or on-site weather observations, fire narratives, or photographs of fire behavior. In New Zealand, all final perimeters are impacted by suppression within the first burning period, which makes it difficult to assess free-burning fire behavior. Conversely, Australia experiences very fast moving, high intensity fires that are difficult to quantify during the event. Weather data, once acquired, had to be manually transformed into unique input files for each application. In some cases, the nearest weather station data were recorded 15 kilometers from the fire and did not reflect conditions at the fire site. Visiting the site, speaking with the Incident Commander, and making insightful adjustments to the wind direction values were necessary to spread the simulated fire in the observed direction.

The required fuel model grids were not readily available. FARSITE requires ASCII grids of Rothermel-based fuel models (Rothermel 1972; Anderson 1982; Scott and Burgan 2005) and canopy cover. Prometheus also requires ASCII grids of FBP fuel models. New Zealand had a local fuel model map derived from the national vegetation database. Australia had fuel maps coded in “grass” and “forest” fuel models. We used a satellite-derived land cover database with vegetation descriptions to assign the required fuel types judged to be reasonably close in fuel depth and loading to those models available for each simulator. Estimates were confirmed through on-site visits and discussions with experienced fire managers, helping to refine fuel maps. Several optional layers can be used in FARSITE for modeling crown fire initiation and spotting firebrands from trees, but the vegetation databases did not contain attributes other than land cover classes. Tree height and crown base height were estimated for each fuel type based on local knowledge; a constant value was used for crown bulk density. Prometheus was designed to use Canadian-based fuel types, and modifications were made to incorporate the custom New Zealand fuel types that are based on the Canadian models. Empirical fire behavior data were available to assist fuel model assignments in some fuel types.

Simulating the Fires

Two New Zealand fires and one Australian fire were modeled during the workshop. Before modelers were asked to predict fire spread, it was necessary to discuss the local fire environments. Invited modelers, Ensis research staff, and local DOC fire managers visited several New Zealand fire sites to discuss local fuels, weather, topography, and burn progression. The Australian fire environment, fire behavior, and fire reconstruction were detailed in a slide presentation (Jim Gould, pers. comm.).

Data were provided to modelers both before and during the workshop. Providing data before the workshop allowed modelers to assess data quality and convert files to formats unique to their applications. New Zealand input data were made available to modelers one month prior to the meeting. These data included tabular fire weather data; shapefiles of fire ignition points and times, final fire perimeters and times; ASCII grids of elevation, aspect, slope, and local vegetation types; and a crosswalk table for creating new ASCII grids of fuel models specific to each application. The final data were provided at the workshop. Australian data were provided at the start of the workshop to test the applications' ability to quickly import data from a new source.

Fire Simulation Results

Participants assembled in one room to concurrently run the simulators on each fire. Input parameters were first discussed to ensure simulators used the most similar and accurate inputs as possible with regard to weather stations, wind speed modifications, use of fire spread barriers, manual fuel type changes, and simulation duration. The group examined the results in detail after each fire was modeled. These results serve to compare not only the applications but also the underlying fire behavior fuel models.

Craigeburn Fire, New Zealand

The Craigeburn Fire was a human-caused point ignition in the Canterbury region of the South Island in January 2004. It burned 548 hectares in tussock grassland with mixed hardwood and native shrub gullies. Full suppression actions with aircraft began within an hour of the ignition. The fire spread for approximately seven hours under strong northerly winds.

Figure 1 illustrates the Craigeburn Fire model results from FARSITE and Prometheus. When the fire was first modeled using the wind stream from the distant weather station, the fires spread east rather than south. Therefore, the teams modified the weather file wind directions, but left the wind

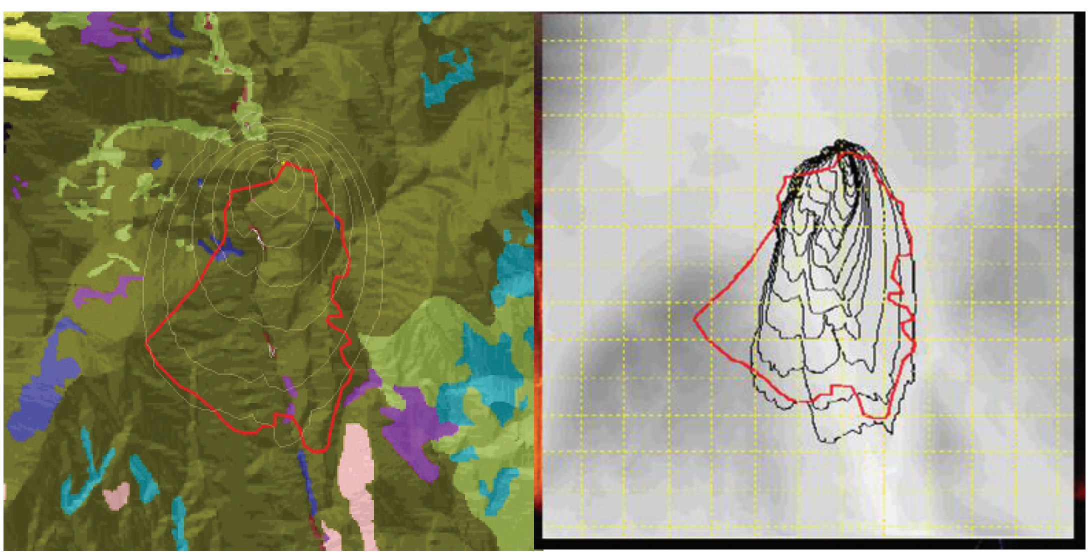

Figure 1—For the New Zealand Craigeburn Fire, FARSITE (left) simulated fire perimeters (white) against the final fire perimeter (black); Prometheus (right) simulated perimeters (black) against the actual fire (red). Both simulations are reasonable, especially if the effect of suppression is considered.

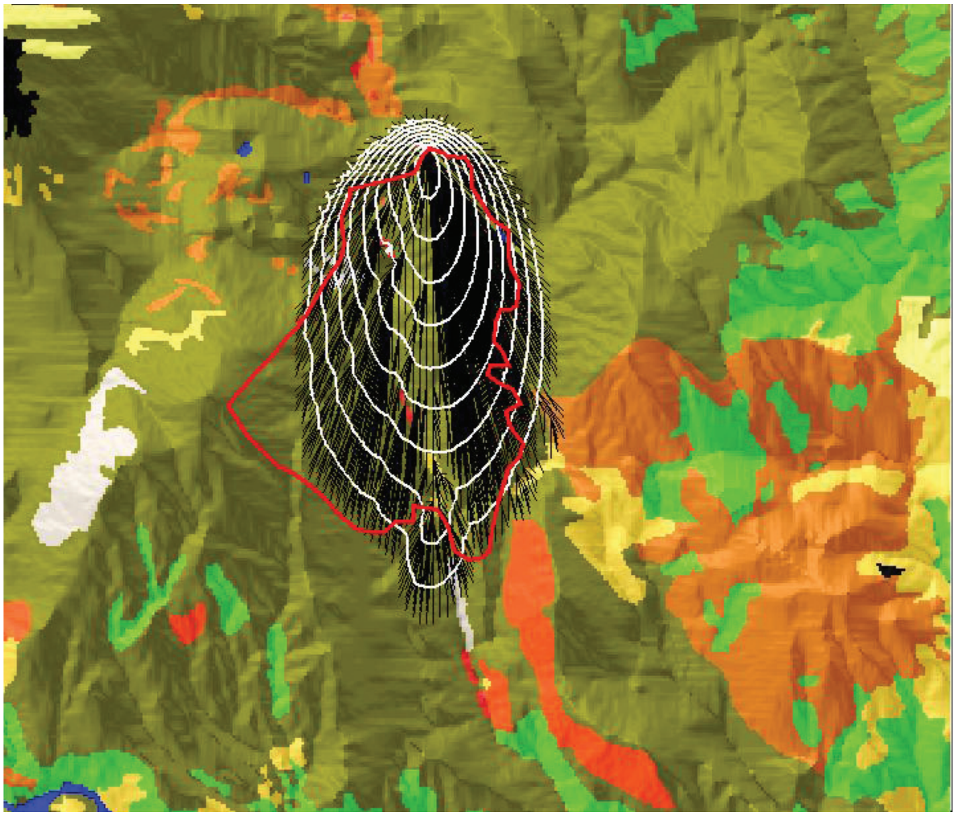

Figure 2—The Minimum Travel Time (MTT) model shows a slightly different shape for the New Zealand Craigeburn Fire. Although it uses the same fire behavior models as FARSITE, it propagates fire through regularly spaced nodes (Fermat's principle) rather than wave fronts (Huygens' principle) and uses constant rather than varied wind and weather inputs.

speed untouched. FARSITE over-predicted the right and left flanks and the extent of the backing fire, while predicting the heading fire well. Prometheus under-predicted the fire's right flank, slightly over-predicted the heading and backing fires, and predicted the left flank well. Considering that suppression dramatically reduced the actual fire extent, both models achieved a reasonable outcome on this relatively simple fire.

Cora Lynn Fire, New Zealand

In March 2001, the Cora Lynn fire burned 360 hectares of grass, native shrubs and native beech forest in steep, rocky terrain. The fire burned for 10 hours with full suppression consisting of several helicopters and ground personnel. The native beech forest fuel type was interesting to model because there are no straightforward fuel models in the Canadian or U.S.-based systems. FARSITE used a moderate load humid timber shrub model (TU2) with increased fuel moisture to model the very slow fire spread appropriately. Prometheus used the custom New Zealand indigenous forest model based on FBP's M-2 (mixed hardwoods), but found the fuel model was spreading fire too rapidly. With some minor calibration and fuel model adjustments from brush to rock, both simulators were able to model the Cora Lynn Fire reasonably well.

Wangary Fire, Australia

The Wangary Fire burned on the Lower Eyre Peninsula in South Australia in January 2005. The fire spread rapidly in grass, brush, and forested fuel types to a final extent of 77,000 hectares. Suppression efforts were hampered by extreme fire behavior during the second burning period when a wind shift pushed the left flank east and northeast. This simulation was unique in that the previous day's burned area was provided, and in that multiple ignition points needed to be modeled only for the second burn period.

The differences between observed and modeled perimeters were within acceptable limits. Prometheus over-predicts the fire's southern edge; this may be because the FBP grass fire model, which was set at 95% curing, is known to over-predict under these conditions (Figure 3). FARSITE uses the stylized Rothermel-based grass model GR6 (moderate load, humid climate grass, dynamic) (Scott and Burgan 2005). The FARSITE simulation more closely approximates the fire's southern edge; however, the fire was simulated using the same ignition time for the four ignition points. Prometheus used the actual, varied ignition times for the four ignition points, and this difference will certainly have an impact on the generated perimeters.

FARSITE over-predicts the northwest fire edge where suppression activities were occurring, while Prometheus did so to a lesser degree. This may also be accounted for by differences in the fuel models and in ignition times. The potential actual fire growth in this direction is difficult to approximate when one considers the amount of suppression that took place in that area.

Prometheus over-predicts the fire at the northeast edge, while the FARSITE simulation is closer in that respect. FARSITE was running at a coarse tolerance for vertex separation (400m); Prometheus was running at a finer tolerance (50m). Interestingly, through our discussions of this simulation we determined that the vertex resolution was deemed inconsequential due

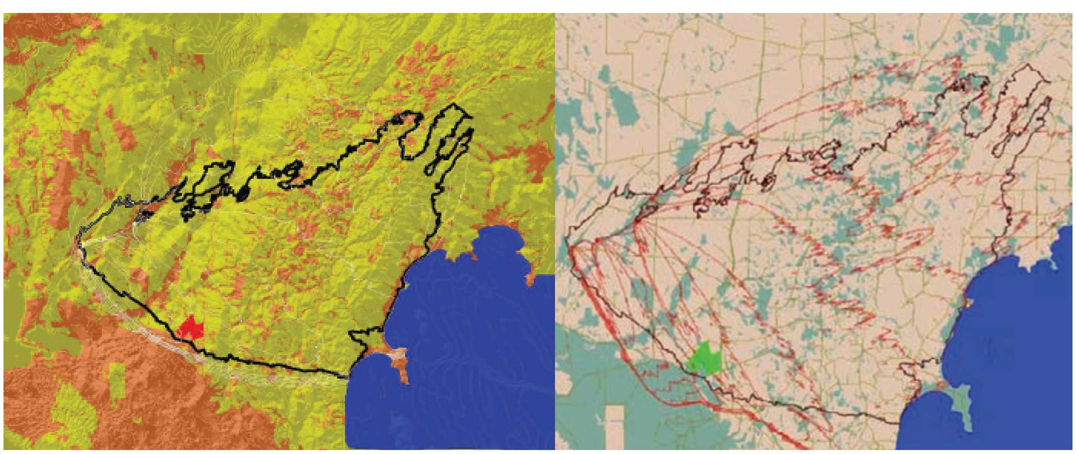

Figure 3—FARSITE (left) and Prometheus (right) modeled Australia's Wangary Fire. Although there are differences in the fire spread model, how suppression was modeled in each simulator, and the starting times of the spot fires, the resulting perimeters still coincide reasonably well with the final fire edge (black).

to the low variability of the spatial data. Despite these differences, both of the modeled perimeters successfully approximated the final fire perimeter in a reasonable length of time.

Discussion: What We Learned

The lack of a site-specific fuel model and weather data was a concern, but our coarse approach regarding crosswalking land cover classes to fuel models proved adequate. Site visits were instrumental in determining the most appropriate interpretation of wind observations several kilometers away from the fire. This was imperative because the simulations were not useful without local wind data. The Craigeburn fire illustrates this well; local winds influencing the final fire shape are impossible to know.

The choice of grass models proved less important than expected since they could be easily manipulated to spread faster or slower through moisture content values during the calibration process. There is great latitude in deciding what fuel types to use, because a particular fire can be modeled well using a variety of combinations of fuels, winds, and moisture contents that are all within the uncertainty of actual data. The coarse vegetation maps and fuel model crosswalks proved adequate for representing fuel conditions in fires we modeled, but they will constrain use of simulators in diverse fuel complexes—a known problem for any simulator.

The ability to adapt the simulators to the local fire environments was mixed. It was necessary to create solar radiation effects from the north rather than the south and simulating summer day lengths in January. Entering a negative latitude in FARSITE changed the sun angle and automatically changed day length for the fire date. Adding six months to the date, and selecting New Zealand and Australian time zone settings in Prometheus were necessary to simulate appropriate conditions. FARSITE was unable to readily input weather streams that crossed into a new calendar year, which was problematic for fires igniting on January 1 and requiring three prior days of fuel conditioning weather data. Several of these identified problems have since been fixed in both simulators.

The disadvantage of both simulators was that each is built around one set of fire spread equations. FARSITE currently implements fire behavior models based on Rothermel (1972), and Prometheus implements fire behavior models based on Canadian fire spread equations (Forestry Canada Fire Danger Group 1992). Although fire spread equation coefficients can be user-manipulated to some degree, neither Prometheus nor FARSITE supports the entry of fully customized fire spread equations with varying parameters. Though some simulation inputs were easily manipulated, the ability to use locally developed equations is an important feature of any Australasian spatial fire simulator because several varied fire spread equations are in use or under development.

Each fire simulator handles timesteps and vertices differently. FARSITE uses an internal dynamic time step that is adjusted to control spatial resolution of the calculations for execution performance. Prometheus employs user-defined fixed timesteps for direct control. FARSITE merges fires and eliminates vertices on the fire perimeters that cross, whereas Prometheus retains the separate identity of individual fires and renders vertices inert. Prometheus uses many more vertices than FARSITE to represent the active fire front. Prometheus by default uses a vertex resolution that matches that of the grid data, and FARSITE by default uses a coarser resolution to address performance concerns, and to intentionally ignore minor variations in the grid fuel map.

In Prometheus and FARSITE, the final modeled perimeter is strongly influenced by several user inputs and settings that are impossible to separate from model error. These various inputs and settings are necessary to allow experienced users to approximate the local environmental variability as closely as possible and to control the computational intensity of the simulation to match time or computer constraints. Interestingly, the two models do not share the same reconfiguration options. This fact complicated direct comparisons of outputs.

Even though both simulators were developed independently, they share very similar functionalities and user interface designs. The differences were influenced in part by their operational roles in their respective countries. FARSITE is more adept at handling different weather stream formats and has more displays of different data. Prometheus can simultaneously simulate and display outputs from differently configured scenarios (variations in user settings, and in spatial and temporal data are allowed) for direct comparisons within the model.

Direct comparison of Prometheus and FARSITE is difficult because modeling fire perimeters is as much art as science. We cannot conclude whether one application is better based solely on the ability to predict fire spread, size, and shape due to differences in underlying fuel models and computation implementations, and an inability to separate user error from model error. Although both models performed reasonably well, they still required minor tuning with respect to the computational implementations of the fuel equations. This suggests that these models should be operated by expert users who are aware of their intricacies. Exact agreement between models and against the observed fires is not possible for many reasons, but the degree of similarity between these systems suggests that the application of Huygens' principle and assumed independence of segments of the fire front is justified for the grass fires tested. Thus, we conclude that it was more important to choose an application compatible with current data availability, current fire management systems, and that can be modified to use unique and varied fire spread equations.

This seminar was an excellent technology transfer opportunity. Modeling fires together in one room with different models was more advantageous than we anticipated; the opportunity to run the applications side-by-side is what made this seminar extraordinary. Modelers gained an appreciation for the need to accommodate a variety of different fire spread equations and parameters in one fire spread simulation system. Application developers, computer scientists, fire managers, fire behavior scientists, and GIS specialists learned from each other, were inspired to try new approaches to problems, considered new concepts, and established relationships with international fire modeling colleagues.

Conclusions

Determining how to pursue adoption of a New Zealand or Australian spatial fire growth simulator requires further consideration and will take place over the next several months.

This seminar provided a first step in sharing available information. Although the scale of wildland fire in New Zealand versus Australia differs significantly, their fire management and research institutions are geographically and politically linked. Currently, there is no spatial fire spread simulator used in either country, but interest is growing among Australasian fire managers to adopt a common tool to enhance decision-making for operations and planning, especially with regard to reconstructing fire events to measure the success of suppression operations or investigate potential fire behavior. Among the numerous considerations, the flexibility in incorporating local fire behavior models into one of these systems will be important. Simulators such as FARSITE and Prometheus both appear to be well suited to modeling fires in New Zealand and Australia.

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An Overview of FlamMap Fire Modeling Capabilities

Mark A. Finney[1]

Introduction

Computerized and manual systems for modeling wildland fire behavior have long been available (Rothermel 1983, Andrews 1986). These systems focus on one-dimensional behaviors and assume the fire geometry is a spreading line-fire (in contrast with point or area-source fires). Models included in these systems were developed to calculate fire spread rate (Rothermel 1972, Albini 1976), fire shape (Anderson 1983, Alexander 1985), spot fire distance (Albini 1979, 1983) and crown fire spread rate (Van Wagner 1977, Rothermel 1991). The FlamMap program was developed for extending the utility of these models to a landscape-level where the necessary inputs have been mapped using geographic information systems (GIS). This paper documents the capabilities in FlamMap 3.0 and discusses some of the uses for such capabilities.

Features of FlamMap 3.0

General Features

All fire behavior calculations assume that fuel moisture, wind speed, and wind direction are constant in time. FlamMap is designed, however, to examine spatial variability in fire behavior, so it utilizes the same set of spatial inputs as the *FARSITE* fire simulation system (Finney 1998). The fire behavior calculations are performed independently for each cell on the gridded landscape.

These spatial inputs include eight GIS raster themes that describe fuels and topography (Figure 1) combined into a Landscape (LCP) File. Any raster resolution (the X- and Y-dimensions of the raster cells) can be used, but all layers must be identical in resolution, extent, and co-registered. The user is required to input initial fuel moisture conditions for each surface fuel model and the fuel model parameters for any custom surface fuel models present. There are two options for using fuel moistures in the calculations,

1. Using a fixed set of fuel moistures (by surface fuel model) is the default and allows direct comparison of fire behavior across the landscape because fuel moisture can be set identically for all surface fuel models.
2. Fuel moistures conditioned by a wind and weather stream is used to calculate localized moisture contents of dead surface fuel size-classes (1hr, 10hr) that are influenced by the elevation, slope, aspect, and canopy cover (Nelson 2000).

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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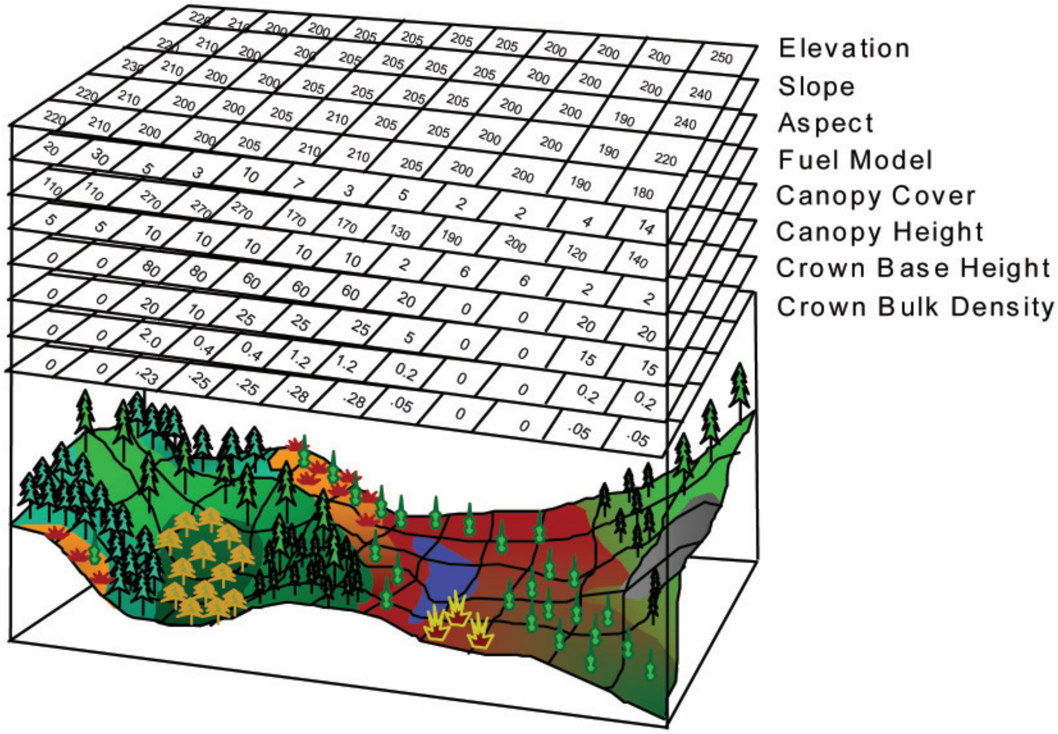

Figure 1—Input data themes required for running FlamMap are the same as those for FARSITE and are contained in a "Landscape" file constructed from ASCII Grid files that are of identical resolution, co-registered, and of equal extent.

Winds are entered as a fixed speed and direction or as spatial wind field grids (separate grids for wind speed and direction) that are generated outside of FlamMap but are useful for examining fire spread in complex terrain where winds are modified by topography.

Ancillary grid and vector themes (besides those in the LCP file or outputs) can also be displayed. All grid and vector themes can be viewed in 2- or 3-dimensions. Outputs can be saved in ASCII Grid or Shapefile format for import and analysis in a GIS.

There are three calculation modes in FlamMap, basic fire behavior, minimum travel time fire growth, and treatment optimization.

Basic Fire Behavior

The simplest use of FlamMap is for use in characterizing fire behavior under a constant set of environmental conditions for an entire landscape. Fire behavior can be generated for all cells on the landscape in a number of ways:

1. For winds blowing uphill, this generates the fastest spread rate because wind will be moving in the same direction as slope.
2. Using a single wind speed and direction combined with the slope to produce the resultant vector for fire spread.
3. Relative to the maximum direction of spread is the default that results in

the heading fire characteristics. A value of 90 calculates fire behavior in the flanking direction and 180 calculates fire behavior in the backing direction.

4. For a direction relative to north (degrees azimuth) allows characterization of the fire behavior in a particular direction and may be useful for looking at fire progress when a specified wind direction is concerned (e.g. winds from west and specifying fire spread rate to the east).

Basic fire behavior outputs are generated in raster format for surface and crown fire calculations (Table 1). These can be displayed and saved to a variety image formats (Figure 2a, b). In addition, a combined output can be requested to display spread vectors that show the spread rate and maximum spread direction of the fire.

Minimum Travel Time

The minimum travel time (MTT) algorithm (Finney 2002) is used in FlamMap for computing fire growth between the cell corners at an arbitrary resolution. Fire growth is computed under the same assumptions as the basic fire behavior – holding all environmental conditions constant in time. Thus, the MTT calculations can generate fire growth in the absence of time-varying winds or moisture content which enables analysis only of the effects of spatial patterns of fuels and topography.

To run the MTT algorithm, ignitions (points, lines, polygons), the desired resolution of the calculations (distance between nodes of a square lattice), and the maximum simulation time are required inputs. Alternatively, ignition points can be generated randomly for a specific number of fires. As the name implies, MTT calculates fire growth (Figure 2c) by finding the paths with the minimum fire travel time among the nodes of the grid. The resolution can be selected independently of the input data resolution. This search produces both the arrival time grid which can be contoured at any time-interval to depict fire progression, but also the minimum time paths (Figure 2d). These paths can be sorted by their flow characteristics or prominence in affecting the landscape as measured by the magnitude of the number of nodes that burn as a result of burning through that node (i.e. logarithm of the number).

Table 1—Outputs from FlamMap.

Fire Behavior Value	Output Type	Units
Fireline Intensity	Raster	kW m^{-1} or BTU ft^{-1} sec^{-1}
Flame Length	Raster	meters or feet
Rate of Spread	Raster	M min^{-1} or ft min^{-1} or ch hr^{-1}
Heat per unit Area	Raster	kW m^{-2} or BTU ft^{-2} sec^{-1}
Horizontal Movement Rate	Raster	M min^{-1} or ft min^{-1} or ch hr^{-1}
Midflame Windspeed	Raster	mph or kph
Spread Vectors	Vector	m min^{-1}
Crown Fire Activity	Raster	Index, 0 1 2 or 3
Solar Radiation	Raster	W m^{-2}
1-hr Dead Fuel Moisture	Raster	Fraction (0.0-1.0)
10-hr Dead Fuel Moisture	Raster	Fraction (0.0-1.0)

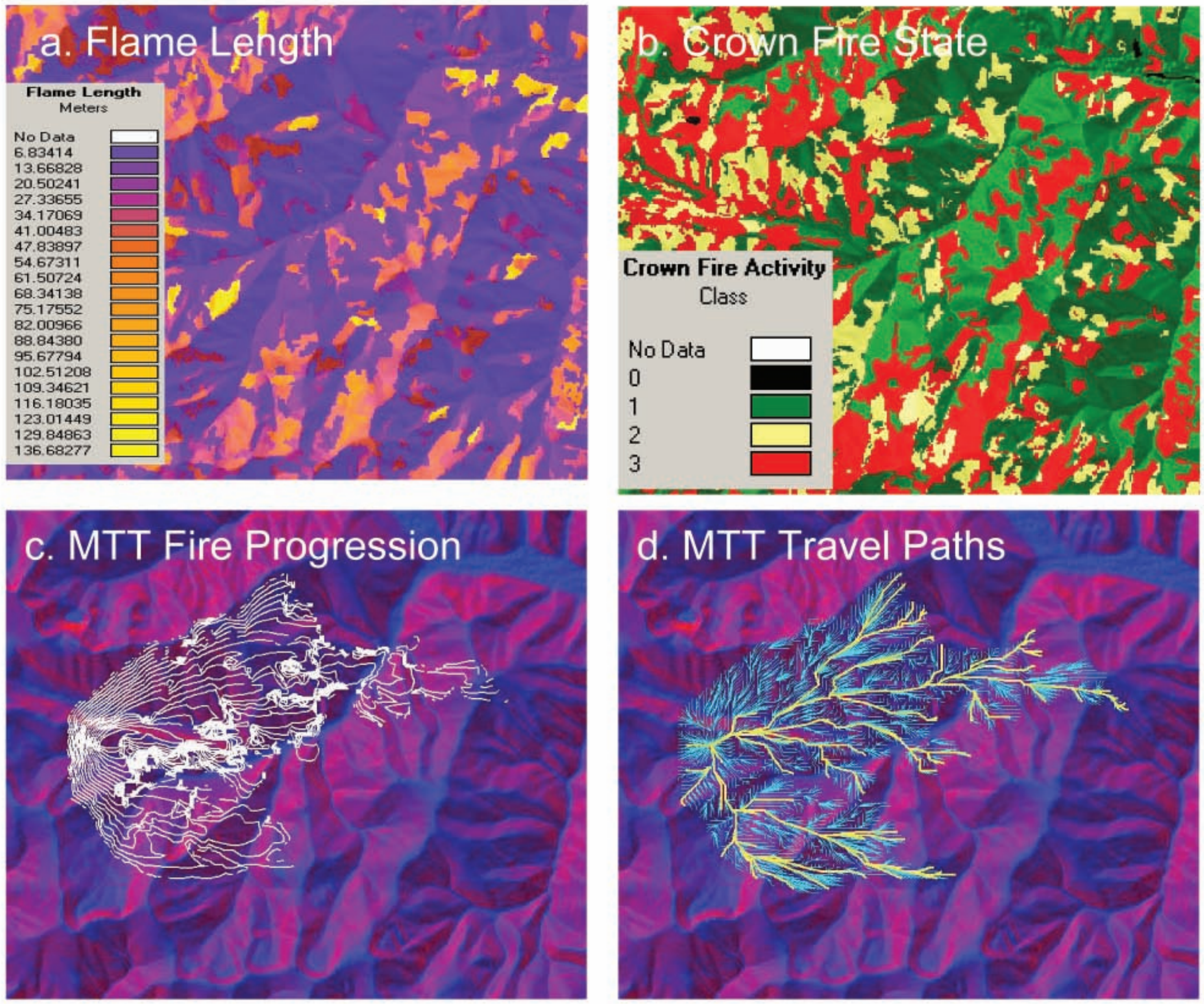

Figure 2—Example outputs from FlamMap for (a) fire spread rate, (b) crown fire activity (0=none, 1=surface fire, 2=torching trees or passive crown fire, and 3=active crown fire), (c) fire progression (white perimeters) simulated using the Minimum Travel Time (MTT) method, and (d) the fire travel paths produced by MTT (bold yellow lines distinguish major paths from all paths in light blue).

A different suite of outputs is generated from the MTT calculations than for the basic FlamMap products (Table 2). These outputs are produced only for the area within the spreading fire and are affected by the direction of fire movement, revealing heading, flanking, and backing spread. They will, therefore, be different from the values that are generated for outputs listed in Table 1. All fire growth calculations across the landscape are performed assuming independence of fire behavior among neighboring cells (e.g. the travel time across a cell does not depend on the behavior in adjacent cells). If random ignitions are selected, then the only output will be a burn probability map (0.0-1.0). These probabilities are properly interpreted as conditional probabilities, since they are conditional upon large fires occurring.

Table 2—Fire behavior outputs from the Minimum Travel Time feature of FlamMap.

Fire Behavior Value	Output Type	Units
Rate of Spread	Raster	m min^{-1} or ft min^{-1} or ch hr^{-1}
Influence Grid	Raster	Index (logarithm of nodes burned after this node)
Arrival Time Grid	Raster	minutes
Fireline Intensity Grid	Raster	kW m^{-1} or BTU ft^{-1} sec^{-1}
Flow Paths	Vector	
Major Paths	Vector	
Arrival Time Contour	Vector	Interval 1/10th range
Burn Probabilities	Raster	0.0-1.0

Fuel Treatment Optimization

Fuel treatment optimization is accomplished using an algorithm that attempts to block the major MTT pathways with fuel treatments that are designed to slow large fires (Finney 2004). Several major assumptions must be met before this process can be attempted:

1. The specific objective of the optimization is to find fuel treatment locations that retard the growth rate of large fires. There are many objectives for fuel treatment, some of which are to provide local benefits only to the area treated. However, the major assumption here is that reduction in large fire growth is obtainable through the collective effect of many units occurring on the landscape (Finney 2001).
2. Wildfires are larger than the fuel treatment units – this allows the analysis to focus on the directions fires move rather than their start locations.
3. Treatments are targeted to perform under a specific set of weather conditions – target conditions must be specified to contrast fire behavior between the current landscape and the ideal landscape. These are often taken from the extreme weather and fuel moisture conditions associated with historic large fire events for which fire suppression is ineffective.

The treatment optimization model (TOM) process requires the user to provide several sets of input data besides the target weather conditions:

1. Ignition location – this is generally a line fire or large ignition source at the upwind edge of the landscape. This ignition configuration allows fire movement to be calculated through the entire landscape for identifying major travel routes.
2. An ideal landscape is required that identifies the fuel conditions everywhere on the landscape where fuel treatments are possible. The changes to the five fuel layers of the LCP file (Figure 1) can vary across the landscape depending on the appropriateness of the treatment prescription. Areas where treatments are not possible remain the same as the current landscape.
3. The resolution of the calculations has the same effect on treatment optimization as on the execution of the minimum travel time algorithm. Finer resolutions require more computations but permit greater detail in identifying treatment unit locations.

4. The maximum treatment dimension is the maximum length dimension that the treatment can be, although multiple treatments may be located adjacent to one-another and form a combined area with a longer dimension than this constraint. Practically, this value should be set no finer than 5 or 6 times the resolution of the calculations (i.e. #3 above) in order to allow the treatment unit to be delineated with several cell widths.
5. The maximum fraction of the landscape that can be treated.

The process begins by dividing the landscape into parallel strips beginning with the upwind edge. Fire growth is calculated using MTT to identify the major fire movement routes and then identifies intersections with areas of the landscape where the treatments change fire behavior favorable to slowing the fire. If such intersections are found, an iterative procedure identifies the collection of grid cells that efficiently blocks each fire travel route (Finney 2004) subject to the constraint on treatment size and total area treated.

The outputs from TOM are similar to those from MTT (Table 2) with the addition of the treatment opportunities grid, which shows the areas where treatments spread faster, slower, or the same as the untreated landscape (values of -1, 0, or 1, respectively), and the final treatment grid which indicates the cells which were selected for treatment (flagged as 0 for untreated and 1 for treated).

Discussion

The basic fire behavior calculations in FlamMap are intended for characterizing fuel hazard in fire management planning. Data on fire spread rate, crown fire activity, and flame length can be quickly calculated and displayed to spatially compare fire behaviors under given weather conditions. FlamMap was used near Flagstaff, Arizona (http://forestera.nau.edu/tools_firemodeling.htm) and in the Sierra Nevada Mountains of California (http://ssgic.cr.usgs.gov/Pages/mapping_nj.htm) for this purpose.

Fire behavior calculations are at the heart of risk assessment as well because risk assessment requires an assessment of probability of fire behavior occurring. Approaches to quantitative risk assessment have incorporated fire behavior from FlamMap for ranges of weather conditions. Examples of such uses include the Florida Risk Assessment (http://www.fl-dof.com/wildfire/wf_fras.html), and the CRAFT risk assessment process (http://www.fs.fed.us/psw/topics/fire_science/craft/craft/introduction.htm).

FlamMap is also useful in the verification process of spatial data. The fire behavior calculations can easily be compared with expected behaviors for the particular fire environment at each cell (i.e. fuels, weather, topography). Display of the landscape, and wind vectors, and various outputs in two- and three-dimensions is often helpful for evaluating reasonableness of the fire behavior calculations.

For fuel treatment analysis the MTT and TOM calculations allow effects of treatment on fire movement to be analyzed. These capabilities are relatively new, however, and have only recently been applied beyond the research phase. However, the basic calculations in FlamMap for comparing effects of fuel treatments on fire behavior have been used to illustrate the stand-level fire behavior changes resulting from treatment (Stratton 2004).

Summary

Version 3.0 of FlamMap has capabilities of 1) calculating surface and crown fire behaviors and moisture of fine dead fuels over an entire landscape, 2) simulating fire growth for constant conditions using a minimum travel time (MTT) algorithm, and 3) fuel treatment optimization modeling (TOM) for delaying the growth of large fires. The basic features are useful for characterizing fuel hazard or potential behavior under specified environmental conditions. New features of MTT and TOM have potential for analyzing fire movement and fuel treatment interactions.

Acknowledgments

Development of FlamMap (available at http://fire.org) has been funded by grants from Joint Fire Sciences and from the Bureau of Land Management. Programming of the graphic interface of FlamMap was accomplished by Stuart Brittain of Systems for Environmental Management. The help system was developed by Rob Seli (U.S. Forest Service). Rick Stratton provided Invaluable testing and feedback on FlamMap features during development.

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Using Landscape-Based Decision Rules to Prioritize Locations of Fuel Treatments in the Boreal Mixedwood of Western Canada

Marc-André Parisien[1], Dave R. Junor[2], and Victor G. Kafka[3]

Abstract—*This study used a rule-based approach to prioritize locations of fuel treatments in the boreal mixedwood forest of western Canada. The burn probability (BP) in and around Prince Albert National Park in Saskatchewan was mapped using the Burn-P3 (Probability, Prediction, and Planning) model. Fuel treatment locations were determined according to three scenarios and five fuel treatment intensities. Fuel treatments were located according to jurisdictional boundaries and BP; BP only; and nonflammable landscape features, BP, and fuel treatment orientation. First, a baseline BP map was created from the original fuel grid. Fuel treatments were then added to the grid and BP maps produced for each combination of scenario and treatment intensity. BP values for the treated landscapes were compared with those of the baseline BP map. Results varied substantially among scenarios and treatment intensities. Locating fuel treatments as a function of the jurisdictional boundaries and BP yielded the lowest reduction in BP. Results suggest that clumping fuel treatments within a limited area or using landscape features to maximize the large-scale spatial benefits of the fuel treatments can significantly reduce landscape-level BP. Although these two strategies may produce similar overall reductions in BP, their appropriateness and utility depend on management objectives.*

Introduction

A fuel treatment consists of a stand-level modification of flammable vegetation aimed at reducing specific aspects of fire behavior, such as rate of spread, fire intensity, and fire severity (for example, crown involvement) (Agee and others 2000). This strategy is receiving increasing attention from land managers and scientists in North America, especially since the catastrophic wildland–urban interface incidents of 2003 in Kelowna, BC, and San Diego, CA. Furthermore, the alarming rate of expansion of the wildland–urban interface (Radeloff and others 2005) is forcing managers and policy-makers to find ways of mitigating the negative impacts of large wildfires (Stephens and Ruth 2005).

There is a growing body of evidence on fire behavior responses to fuels modifications from empirical (Pollet and Omi 2002; Finney and others 2005) and simulation (van Wagtendonk 1996; Stephens 1998; Stratton 2004) studies. Although much remains to be learned about fire behavior in fuel-treated areas, a substantial fuel modification will always translate into a change in physical fire processes (Agee and Skinner 2005). For instance, a heavy reduction in crown and ladder fuel load (for example, by reducing

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tree density or pruning trees) will reduce fuel consumption and hence fire intensity. Similarly, conversion of a flammable coniferous fuel type to a less flammable deciduous fuel type can significantly reduce fire behavior severity and fire size (Hirsch and others 2004). At present, most of the research on fuel treatments in North America is based on stand-level information. However, the spread of large fires is also influenced by landscape-level factors that promote or interrupt fire spread (Mermoz and others 2005), and these factors should be taken into account for fuel treatment design and evaluation.

To this end, equations were developed to determine the optimal shape and size of fuel treatments (Finney 2001). This technique, known as strategically placed areas of treatments (SPLATs), represents the first known spatial extension of this concept and is gaining popularity with managers working in the fire-dominated biomes of North America. Although assessments of effectiveness remain fragmentary, SPLATs reduced fire behavior in two large, high-intensity Arizona fires (Finney and others 2005). The SPLAT design represents an advancement in the science of fuels management, but it does not address such critical landscape-level aspects as the placement of fuel treatments or the most suitable treatment fraction (treatment intensity).

Spatial modeling studies have shown that the connectivity of flammable fuels affects the size of fires (Miller and Urban 2000; Duncan and Schmalzer 2004). From a fuel treatment viewpoint, an increase in the relative proportion, as well as aggregation, of less-flammable fuels reduces the spread of fire (Bevers and others 2004; Loehle 2004), but this approach is often unrealistic on a real landscape. First, a large fraction of the landscape (usually more than 50 percent) must be treated to achieve an appreciable reduction of fire spread; second, the random placement of treatments implies inefficiency (Finney 2003); and third, the shape of these aggregates may be suboptimal and they may therefore provide only a small reduction in area burned.

Despite some preliminary data, the best placement of fuel treatments on the landscape remains a crucial but largely unanswered question. This information is particularly important in the Canadian boreal forest, where fuel treatments may be necessary to reduce the spread of large fires burning at intensities that preclude direct fire suppression. Because financial resources to create fuel treatments are limited, land managers need to quantify fire risk and apply fuel treatments where they are most needed and can meet management objectives (Sanchez-Guisandez and others 2002). A scarcity of spatially explicit tools for long-term strategic planning in fire management has inhibited significant progress, but the recent development of approaches for mapping burn probability (BP), such as Burn-P3 (Probability, Prediction, and Planning) (Parisien and others 2005), represents an opportunity. Reliable estimates of BP are necessary to examine the combined effects of altering the type and spatial configuration of forest fuels.

The goal of this study was to develop and assess a rule-based approach to prioritizing the placement and level of fuel treatments in a boreal mixedwood forest. Our working hypothesis was that incorporating landscape-level features would enhance the effectiveness of fuel treatments. In this article, we explore landscape "recipes" for fuel modifications using the Burn-P3 simulation model. Our specific objectives were (1) to create a BP map for the study area, (2) to identify areas where the effectiveness of fuel treatment could be maximized, and (3) to assess the relative benefit of increasing treatment intensity (that is, total area treated). The results are discussed in the context of current land management objectives for the study area.

Study Area

The study area, which encompasses Prince Albert National Park (PANP), is located in central Saskatchewan (Fig. 1) and covers 1 653 467 ha. The area has long, cold winters and short, warm summers. The average monthly temperature of the Prince Albert weather station, located in the southern part of the study area, ranges from –19.1°C in January to 17.5°C in July. Mean annual precipitation is 424 mm, most of it falling between May and August (Environment Canada 2005).

The study area can be described as a flat to rolling plain, a large proportion of which is covered by lakes and wetlands. It is characterized by coniferous, deciduous, and mixedwood stands of various sizes. The main conifers of the study area are white spruce (*Picea glauca* (Moench) Voss), black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), and tamarack (*Larix laricina* (Du Roi) K. Koch.). The deciduous component is mainly represented by trembling aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.), and white birch (*Betula papyrifera* Marshall).

The fire regime of the study area — one of the most active in Canada — is dominated by infrequent large and intense fires, more than 80 percent of which occur between May and August (Parisien and others 2004). Although lightning-ignited wildfires are frequent and are responsible for most of the

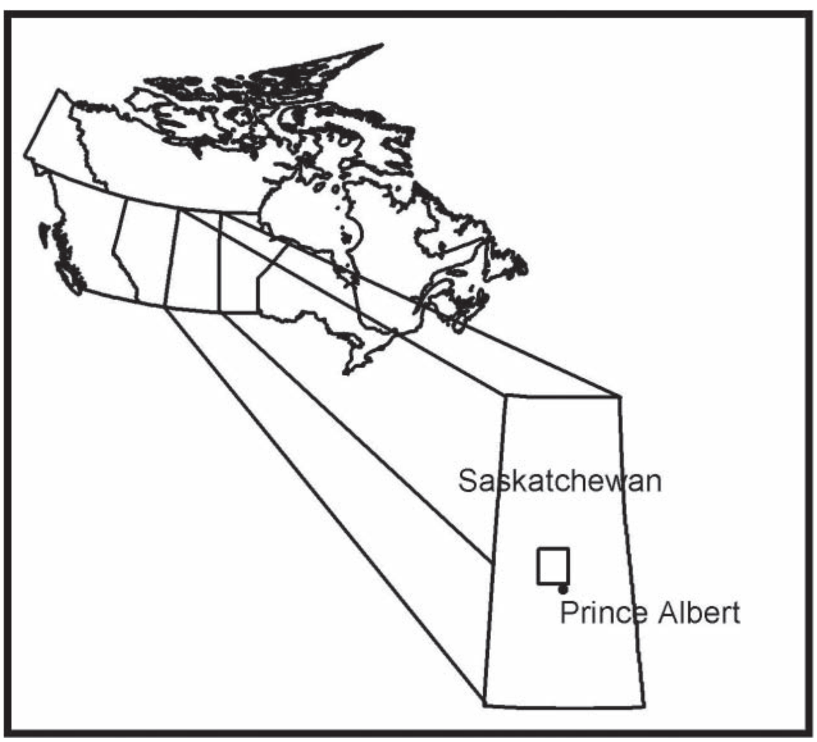

Figure 1—The study area in central Saskatchewan covering Prince Albert National Park and its surroundings.

area burned, humans ignite most fires and have had a marked impact on the fire regime since colonization (Weir and Johnson 1998). The main fire management policy in the area consists of aggressive initial attack of small fires and fire suppression operations aimed at limiting fire spread. However, in recent years Parks Canada has committed to restoring the fire regime in PANP (Weir and Pidwerbeski 2000) to achieve a level of burning similar to that of historical fire cycles and thereby maintain ecological integrity (Weir and others 2000).

Methods

Data Types

Three types of data were required as inputs for the Burn-P3 analysis: records of historical large fires, daily fire weather conditions, and fuel types.

Historical Large-Fire Database—The Canadian Forest Service Large Fire Database (Stocks and others 2003), which consists of points of ignition for all reported fires of 200 ha or more in the period 1959 to 2003, was used to determine the historical number of large fires in the study area. A database of daily progression of 130 large fires that occurred in Saskatchewan between 1991 and 2000 was used to determine the average number of days of significant fire spread or the number of spread event days (4 percent or more of the final fire size) per fire.

Daily Fire Weather—Daily noon observations of temperature, relative humidity, wind speed, wind direction, and 24-h precipitation, as well as the associated fuel moisture codes and fire behavior indices (from the Fire Weather Index System [Van Wagner 1987]), were obtained for 8 weather stations in and around the study area for the period 1990 to 2001. To integrate fire weather into the Burn-P3 model, only daily records for days with fire weather conditions conducive to significant fire spread, defined here as having an Initial Spread Index of 8.6 or more (Parisien and others 2005), were extracted from the database.

Fuel Types—The fuels were represented as a grid of fuel types of the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group 1992). The FBP System categorizes vegetation into 16 fuel types; here, however, fuels were grouped into 5 main types: coniferous, deciduous, mixedwood, grasses, and slash. The coniferous fuel type produces more severe fire behavior than the deciduous fuel type, whereas the flammability of the Boreal Mixedwood fuel type lies between the two. Slash is also highly flammable, but it is uncommon in the study area. The deciduous and mixedwood fuel types are more flammable in the spring, before the deciduous trees leaf out. A map of the fuel groups used in the study is presented in Figure 2, and percent cover is presented in table 1.

Fuel Treatment Dimensions

Fuel treatment dimensions were determined according to the SPLAT design (Finney 2001). In brief, this design consists of multiple treatment units (blocks) that are less flammable than the surrounding forest. The aim of a SPLAT is to slow down the fire front and promote flanking, thereby reducing

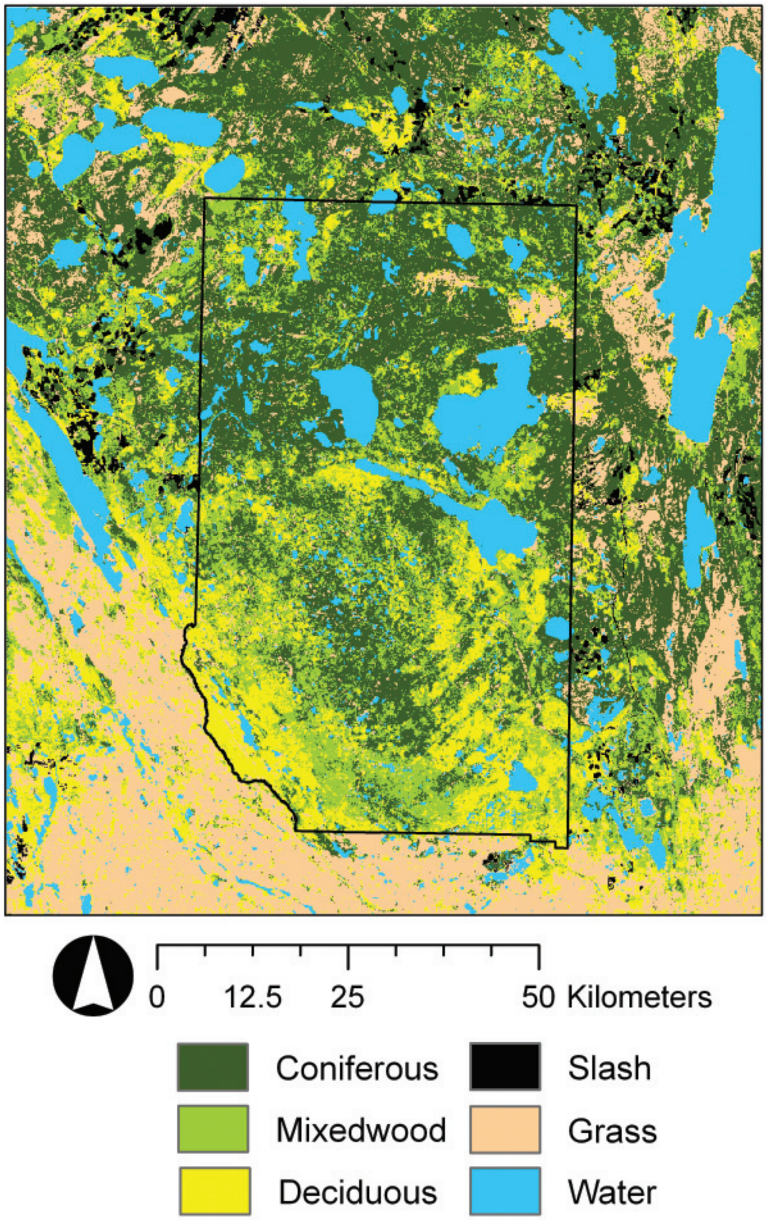

Figure 2—Major fuel groups of the study area.

Table 1—Area and percentage of each fuel group and water within the study area.

Fuel type	Area (ha)	Proportion (%)
Coniferous	511 478	30.9
Mixedwood	268 527	16.2
Deciduous	222 400	13.5
Grass	411 424	24.9
Other fuels	39 847	2.4
Water	199 791	12.1

forward spread of the fire. The width (*W*) and length (*L*) of the treatment units are based on estimates of typical forward fire spread (*D*) (the distance between the point of ignition and the fire front), the distance between rows of treatment units (*S*), the overlap between units (*O*), and the angle at which the units are slanted (Fig. 3) (see Finney 2001 for details). The dimensions of the treatment units are arbitrary as long as their spatial configurations are adjusted according to the SPLAT design equations; however, the units must be large or numerous enough to significantly reduce fire spread.

The fuel treatments in this study consisted of 3 rows of treatment units for deciduous fuels (Fig. 3b). The SPLAT dimensions were calculated for high-intensity wind-driven fires (10 000 kW/m and 90th percentile winds) in coniferous forests, which represent the threshold conditions above which direct fire suppression is impossible. We used a consistent SPLAT design so that our analysis of treatment location and intensity would not be obscured by design factors. We opted for a conversion to the deciduous fuel type as a treatment because it provides a realistic yet effective way to reduce fire spread in the boreal mixedwood (Hirsch and others 2004) and its fire behavior characteristics are well known. In addition, we selected treatment unit dimensions similar to those for typical cutblocks in the boreal forest, where *W* = 300 m and *L* = 900 m (total area = 27 ha). The separation (*S*) between unit rows was set at 200 m and the units were angled at 20°. These dimensions were consistent throughout the study, but the overall length of the area with multiple fuel treatments varied according to location on the landscape, as dictated by the scenarios.

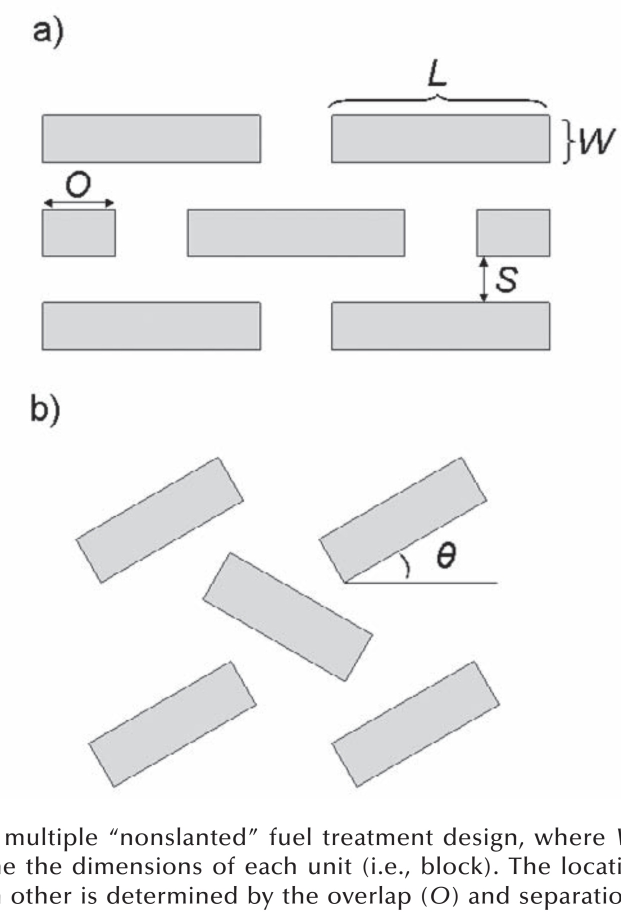

Figure 3—(a) A multiple "nonslanted" fuel treatment design, where *W* (width) and *L* (length) define the dimensions of each unit (i.e., block). The location of units in relation to each other is determined by the overlap (*O*) and separation distance (*S*) between unit rows. (b) Slanted units, as used in this study, are inclined at an angle (θ) to block openings through the pattern. Both fuel treatments consist of three rows, or superimposed layers of treatment units. This figure was modified from Finney 2001.

Modeling Scenarios

We developed three modeling scenarios from different sets of decision rules for SPLAT placement and tested each of them according to 5 treatment intensities: 1500, 3000, 4500, 6000, and 7500 ha. A baseline BP map was produced from the original fuel grid to guide placement of the fuel treatments. In all scenarios, the deciduous fuel treatments had to be embedded in areas dominated by coniferous or mixedwood fuels.

In the first (boundary) scenario, fuel treatments were positioned exclusively around the periphery of PANP. The 7500-ha treatment intensity covered the entire periphery of PANP where it was dominated by coniferous and mixedwood forest (Fig. 4a). The second rule specified that SPLATs for the other treatment intensities would be positioned as a function of the highest value of BP in the baseline BP map.

In the second (BP-only) scenario, SPLATS were located solely as a function of BP. To identify the areas of highest BP, the values of the baseline BP map were "contoured" by intervals of 0.5 percent. The 1500-ha area class was thus associated with the highest BP region, the 3000-ha with the highest and second-highest BP regions, and so on. To entirely cover the areas of high BP, the 3-row fuel treatments were stacked in a clustered, rather than linear layout. As a result, the SPLATs for the 7500-ha area class corresponded to 3 very large areas of high BP and several smaller localized areas (Fig. 4b).

Unlike the first two scenarios, the third (lake-linking) scenario located SPLATs according to a hierarchal set of rules based on the linkage of nonflammable landscape features (lakes), the highest BP values, and the most suitable orientation of fuel treatments. Fuel treatments were used to connect large lakes that were no more than 20 km apart, an arbitrary maximum distance that is realistic for landscape-level fuel treatments in the area. The minimum lake size to be considered was determined by classifying areas of the BP map as having either above-average or below-average BP and calculating the

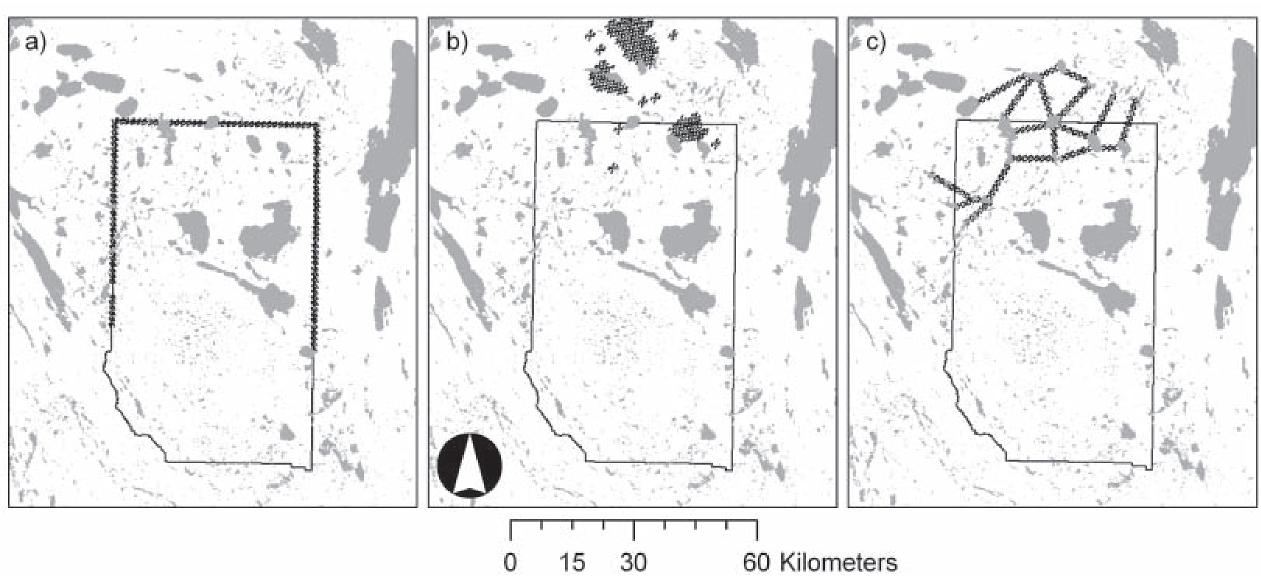

Figure 4—The fuel treatments (in black) for the boundary scenario (a), BP-only scenario (b), and lake-linking scenario (c) for the 7500-ha treatment intensity. The black outline represents the boundary of Prince Albert National Park; lakes are shown in gray. BP = burn probability.

frequency of lakes of different sizes (in 50-ha classes) that were adjacent to below-average BP areas. Using this method, we determined that lakes of 350 ha represented the smallest size class in which all lakes were adjacent to areas with below-average BP. Among all possible links between lakes, prioritization occurred as a function of BP, as in the BP-only scenario, except that in the lake-linking scenario the fuel treatments were not stacked (Fig. 4c). The final rule was that if multiple fuel treatments were identified for a BP contour, priority was given to the fuel treatments that had an angle of 45° (that is, spanning the northeast–southwest axis), the orientation perpendicular to the most likely direction of large fire spread (Parisien and others 2004).

The SPLATs for each combination of scenario and treatment intensity were added to the original fuel grid in a geographic information system to create a total of 15 modified fuel grids. When the SPLATs were added, cells in the grid that were classified as water, nonfuel, or already deciduous were not replaced. Because it was nearly impossible to obtain exactly the targeted treatment area (for example, 7500 ha), we allowed a variation of 100 ha for each treatment intensity.

The Burn-P3 Simulation Model

The Burn-P3 simulation model evaluates BP of large fire-prone areas by simulating the growth of a very large number of fires (Parisien and others 2005). Burn-P3 models only large fires because these fires are responsible for virtually all of the area burned in Canada (Stocks and others 2003). Individual fires are simulated deterministically for one fire season using the Prometheus fire growth model, and this process is repeated for a large number of iterations (for example, 1000). The Prometheus model calculates the elliptical growth of each fire through complex fuels and terrain according to the FBP System (Forestry Canada Fire Danger Group 1992) and fire spread mechanisms (Richards 1995). Fires are recorded in Burn-P3 only if they reach 200 ha. All other components in Burn-P3 are stochastic: the number of fires per iteration, the location of fire starts, the burning conditions, and the burning period.

The number of fires per iteration was input as a frequency distribution of the number of fires of at least 200 ha per year (mean 1.06 fires/year), stratified by two seasons: spring (April 1 to May 31) and summer (June 1 to August 31). The locations of fire starts were random, but lighting-caused and human-caused fires were distinguished, to prevent lightning ignitions in deciduous fuels. No fire starts were allowed in the grass fuel type, most of which is farmland, where very few large fires occur (P. Maczek, personal communication). The duration of the burning period for each fire was input as an exponential frequency distribution, on the basis of the average number of spread event days from the daily fire progression database (mean 3.8 days). Burning conditions were randomly drawn from a database of daily fire weather conditions conducive to fire growth for each spread event day.

In a Burn-P3 run, fires are simulated according to a given set of landscape (fuels and topography, although the latter was not used in this study because of the relatively flat terrain of the study area), fire, and weather inputs for an iteration and recorded in a grid. This process is repeated for each iteration, and the grids of all iterations are compiled in a cumulative grid of area burned. Several internal Burn-P3 settings (for example, daily hours of burning, curing of grass fuels) were heuristically adjusted to produce a fire size distribution similar to the historical distribution (compare with Parisien and others 2005).

The BP in a given cell i is calculated as follows:

$$BP_i = \frac{b_i}{N} \times 100 \quad [1]$$

where b_i is the number of iterations that resulted in cell i being burned and N is the total number of iterations. BP_i, expressed as a percentage, represents the likelihood of cell i being burned in a single fire season.

Analysis

Burn-P3 was used to produce 1000-iteration BP maps for the original grid with unmodified fuels (the baseline BP map) and for each combination of scenario and treatment intensity. A 10-km buffer was added to the study area and subsequently removed from the BP maps to prevent an edge effect.

The results for each combination of scenario and treatment intensity were compared with those of the same areas in the baseline BP map. The comparison areas consisted of the SPLATs and 2-km buffers around them. The buffer distance was selected through comparison of the BP response at several buffer distances. The mathematical comparison of the treatment BP maps with the baseline BP map was a step-wise process. In the equations below, the scenarios are denoted as j, where scenarios 1, 2, and 3 are expressed as $j = \{1,2,3\}$, respectively, and the treatment intensities are denoted as k, where the $k = 0$ treatment intensity refers to the baseline BP map, and the baseline and 1500, 3000, 4500, 6000, and 7500 ha treatment intensities are expressed as $k = \{0,1,2,3,4,5\}$, respectively.

First, the mean BP, $\overline{BP}_{jk}$, for each buffered area was defined as follows:

$$\overline{BP}_{jk} = \sum_{i=1}^{n} \frac{b_{ijk}}{n_{jk}} \quad [2]$$

where b_{ijk} is the value of BP for any given cell i for the scenario j and the treatment intensity k, and n_{jk} is the total number of cells in the buffered area for each combination of j and k.

The calculated values of $\overline{BP}_{jk}$ were then standardized as follows:

$$\overline{BP}(s)_{jk} = \frac{\overline{BP}_{jk}}{\overline{BP}(t)_{jk}} \quad [3]$$

where $\overline{BP}(s)_{jk}$ represents the standardized $\overline{BP}_{jk}$ for each combination of j and k, and $\overline{BP}(t)_{jk}$ is the mean BP of the total of all cells in the baseline BP grid of j and k. The purpose of standardization was to account for background variability in $\overline{BP}_{jk}$ among BP grids. Although this variability is usually minimal, it can partially obscure the patterns of reduction in BP observed between treatment and baseline BP.

Finally, the relative difference (i.e., reduction) in $\overline{BP}_{jk}$, ΔBP_{jk}, expressed as a percentage, was calculated using the following equation:

$$\Delta BP_{jk} = \frac{\overline{BP}(s)_{jk} - \overline{BP}(s,u)_{jk}}{\overline{BP}(s,u)_{jk}} \times 100 \quad [4]$$

where $\overline{BP}(s,u)_{jk}$ is the mean BP calculated for the area corresponding to each combination of j and k in the baseline BP map.

In an additional analysis, the values of ΔBP_{jk} were adjusted for area in terms of an arbitrary comparison area (50 000 ha) to assess the spatial "coverage" of the different fuel treatment layouts. The area A_{jk} (in ha) was obtained for each buffered fuel treatment of scenario j and treatment intensity k. Then, an area factor, $F(A)_{jk}$, was calculated as follows:

$$F(A)_{jk} = \frac{A_{jk}}{5 \times 10^4\, ha} \qquad [5]$$

The area-adjusted mean change in BP (ΔBP_{jk}), $\Delta BP(a)_{jk}$, was obtained for each j and k:

$$\Delta BP(a)_{jk} = \Delta BP_{jk} \times F(A)_{jk} \qquad [6]$$

The resulting ΔBP_{jk} and $\Delta BP(a)_{jk}$ were plotted as a function of treatment intensity for each scenario.

Results and Discussion

The baseline BP map had localized areas of high and low BP (Fig. 5). High-BP values were usually found in conifer-dominated areas. The relative reduction in BP for treated landscapes varied substantially by scenario and by treatment intensity (Fig. 6a). At all treatment intensities, the boundary scenario yielded the lowest reduction in BP. A larger relative reduction in BP was

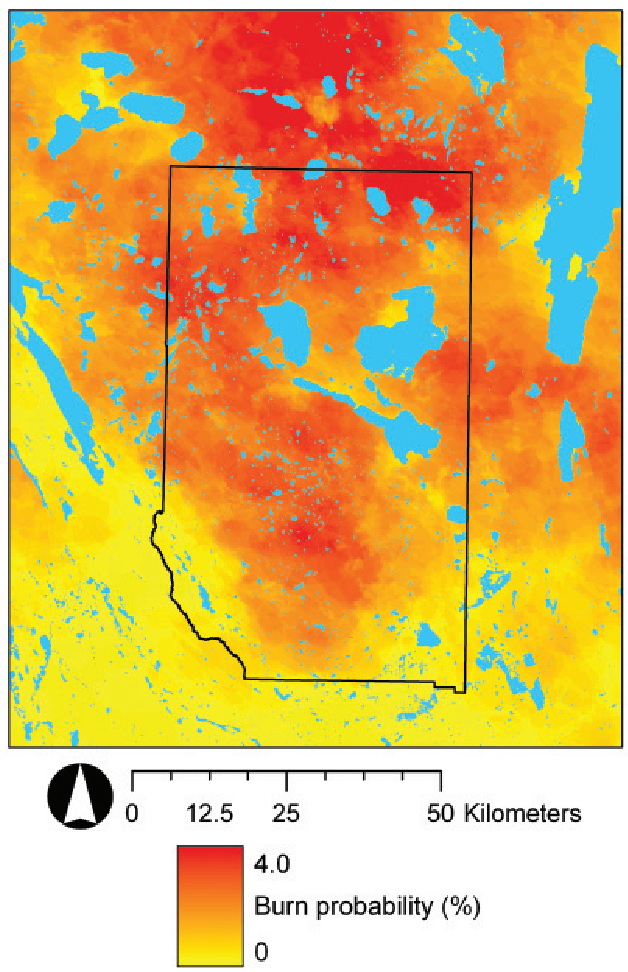

Figure 5—Baseline (i.e., untreated) burn probability in the study area. The black outline represents the boundary of Prince Albert National Park.

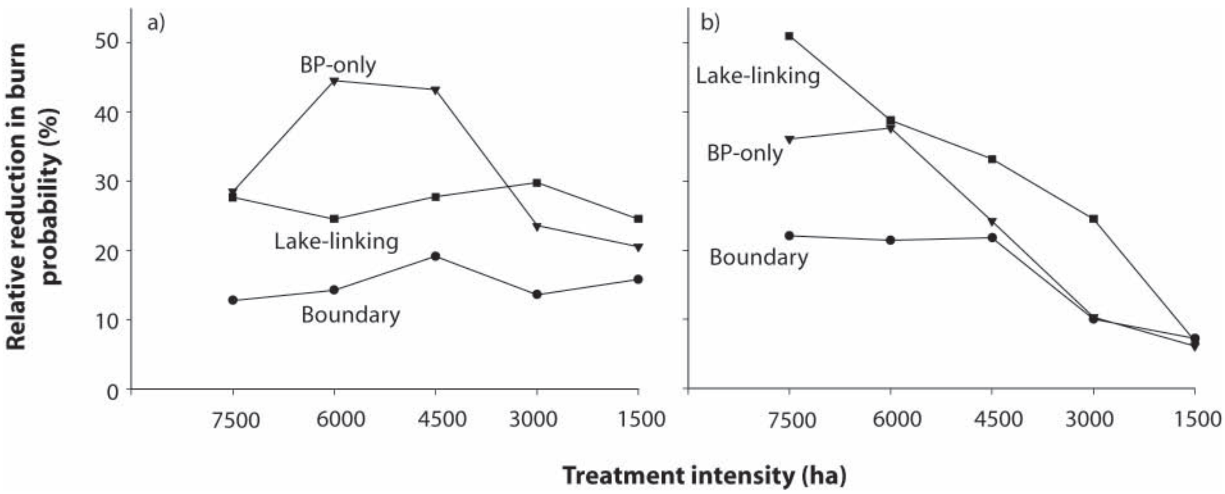

Figure 6—The relative reduction in burn probability as a function of decreasing treatment intensity by scenario without (a) and with (b) an area adjustment to 50 000 ha.

expected at the lower treatment intensities because the minimum treatments were linked to areas where fuel treatments would be most needed (high BP). That this was not borne out for the boundary and BP-only scenarios suggests that there are optimal treatment intensities for large-scale effectiveness of SPLATs. The SPLATs in some locations did not always yield an important reduction in BP (not shown), especially for the boundary scenario. Some of the treated areas at the PANP boundary were virtually unaffected by the fuel treatments, which suggests that locating linear SPLATs as a function of jurisdictional boundaries and BP represents a poor option. This outcome may be due to a number of factors, notably the ineffectiveness of SPLATs that are oriented parallel to an oncoming fire (Finney 2001) and the critically low portion of the landscape treated (Bevers and others 2004; Leohle 2004).

Without adjustment for area, the 6000-ha and 4500-ha treatment intensities for the BP-only scenario performed the best, with a BP reduction of more than 40 percent (Fig. 6a). The 7500-ha treatment intensity did not yield as high a reduction in BP because the small, isolated clumps of fuel treatments (Fig. 4b), which were not retained with the smaller treatment intensities, were unsuccessful in reducing BP. Large fires presumably wrapped around these clumps readily. In contrast, bigger clumps were highly effective at reducing BP, which suggests that stacking fuel treatments is effective in reducing BP. These stacked SPLATs not only represented greater impediments to fire spread, but also were more versatile in terms of reducing the spread of fires burning from a range of directions.

The observed reduction in BP in the lake-linking scenario was fairly constant among treatment intensities, but this scenario was more effective at the 3000-ha and 1500-ha treatment intensities than the other two scenarios (Fig. 6a), which suggests that this set of decision rules would be superior to the others when only a small area can be treated. The reduction in BP with the lake-linking scenario would also be much higher if the BP reduction around the lakes to which the fuel treatments were linked had been considered in the calculation of the buffered fuel treatment area. Furthermore, the compound effect of closely spaced fuel treatments on BP reduction in this scenario (Fig. 7) suggests a synergistic effect of adjacent placement of fuel treatments. However, to maximize the treated area,

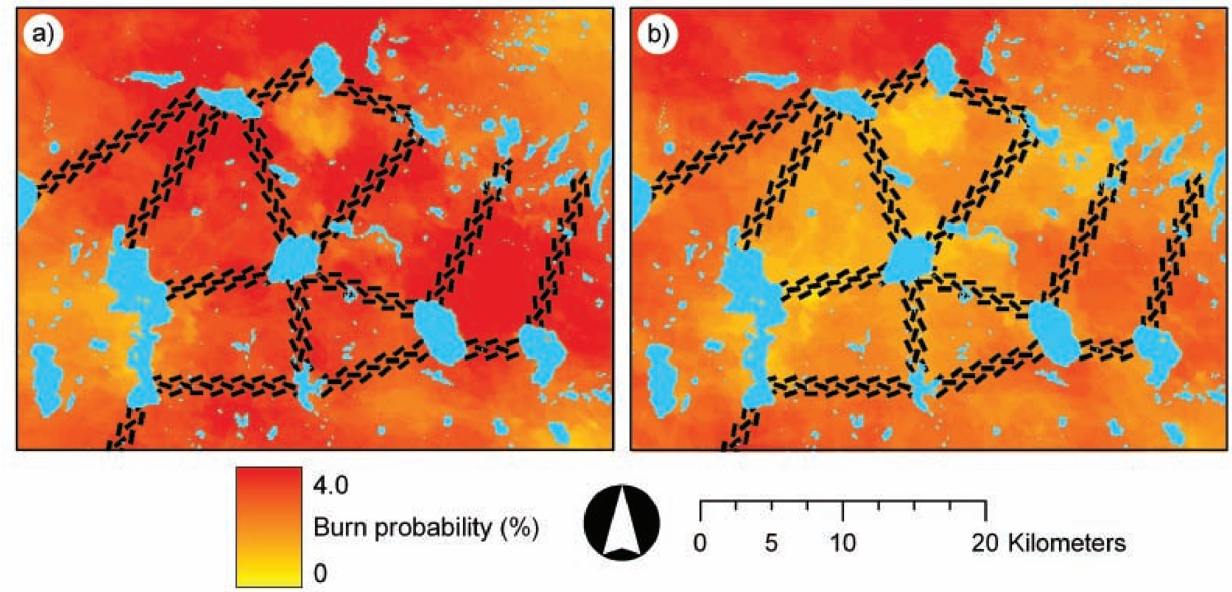

Figure 7—Part of the burn probability map of the baseline (i.e., untreated) landscape (a) and the same part of the burn probability map of the treated landscape with the lake-linking scenario (b) for the 7500-ha treatment intensity. The overlaid fuel treatments are shown in black.

managers should avoid placing too many treatments in the same locations. There is thus a need to evaluate the optimal proximity of neighboring fuel treatments.

The high effectiveness of the lake-linking scenario supports previous suggestions that one of the most effective layouts of fuel treatments is one that compartmentalizes areas of high wildfire susceptibility (Agee and others 2000; Hirsch and others 2004). One way to determine the most suitable compartments is to take into account the spatial effects of SPLATs on BP reduction (Fig. 7). The 2-km buffer proved appropriate for the analysis and was consistent with a field study reporting a marked decrease in fire frequency within a 2-km radius around large lakes in the boreal forest of Quebec (Cyr and others 2005). However, the reduction in BP may extend far beyond the 2-km buffer, depending on several spatial features of the landscape (Parisien and others 2003). Consideration of the scale of BP reduction would certainly have favored the lake-linking scenario in this analysis.

The potential benefits of fuel treatments are explicitly linked to their area of influence or spatial coverage, which is far greater for the buffered area of the boundary and lake-linking scenarios than for the BP-only scenario (85 794, 91 917, and 63 290 ha, respectively), where the fuel treatment buffers are "shared" among rows of treatments because they are stacked. High spatial coverage thus extends the effects of the treated areas to a larger proportion of the landscape. If an area adjustment is taken into account in the BP reduction, the lake-linking scenario performed the best in terms of BP reduction for all but the 1500-ha treatment intensity (Fig. 6b), where all three scenarios performed equally.

Implications for Land Management

The classic definition of wildfire risk considers two components, BP and potential impacts (Finney and others 2005). At present, the main challenge in estimating wildfire risk is that few approaches provide a quantitative estimate of landscape-level BP. However, according to Finney (2005), without this measure "it is not possible to estimate the cost-effectiveness of management activities that may be proposed for mitigating potential fire impacts." In this respect, BP modeling represents an important advance in assessing wildfire risk. The strength of this approach is that it allows us to directly measure the change in BP that results from landscape modifications, such as fuel treatments, prescribed burns or wildfires, and changes in land use.

Given the costs of implementing SPLATs over a large area, a tool such as Burn-P3 can provide valuable new information to land managers. A BP map is very useful in itself, but is perhaps most helpful when used in "what if" scenarios of landscape change (Miller 2003), as showcased in this study. In the PANP area, where fire and land management policies differ substantially within and outside the park, strategic management planning can be challenging, especially given the high numbers of large fires. Our results strongly suggest that simple decision rules based on in-depth knowledge of an area and its fire environment provide a robust framework for SPLAT placement and that the straightforward nature of this approach makes it simple to explore and implement. However, we acknowledge that much could be learned by combining these methods with more sophisticated ones, such as spatial optimization (Zuuring and others 2000) and succession modeling of fuels (He and others 2004).

Even at the 7500-ha treatment intensity the overall treated area was small relative to the entire study area. Converting 7500 ha of coniferous and mixedwood forest to deciduous forest appears to represent a massive effort, but in most of the commercial forest of western Canada it could easily be achieved, given the extensive harvesting and site preparation associated with forestry operations. In fact, Stratton (2004) suggested that fuel treatment units could be shaped like forest patches without significantly affecting the benefits of fuel treatments. Where there are no forestry operations, as in PANP, fuel conversion could be an alternative in strategic areas because it requires minimal maintenance. However, the use of prescribed burns as a fuel treatment, either alone or combined with deciduous conversion, is preferred, because it also contributes to restoring the historical fire regime.

Ideally, the effectiveness of fuel treatments should be measured not only by their effect on BP but also by the reduction in fire behavior potential. Although the decision rules of the BP-only and lake-linking scenarios produced appreciable reductions in BP (more than 40 percent in some cases), in reality fires would rarely burn freely: some level of fire suppression, even minimal, would be undertaken. In fact, the purpose of fuel treatments in PANP is largely to enhance fire suppression operations (Weir and Pidwerbeski 2000). If the rate of spread and fire intensity can be markedly reduced by fuel treatments, fire suppression is more likely to succeed. Furthermore, the treated areas can be used for indirect attack to contain burnout operations, a technique that is widely used by boreal fire management agencies.

Our results emphasize the importance of identifying the appropriate spatial scale for decision-making regarding fuel treatments (Finney and Cohen 2003). At a local landscape scale, it appears that the clumping of fuel treatments is the most effective way to reduce BP. In fact, at an even smaller scale (for example, in a single community) it is often feasible to concentrate fuel management efforts and reduce the BP to almost zero, effectively creating a "fuel break." By contrast, at a larger spatial scale it is not always possible or even desirable (for example, ecologically) to treat a sizeable portion of the landscape. If resources are finite, it is preferable to spread out the potential benefits of fuel treatments by using strategic decision rules. Moreover, at a large spatial scale, a decision scheme like that of the BP-only scenario may position fuel treatments where they are not needed, whereas the lake-linking scenario not only extends the spatial coverage of the treatment but also is more flexible in terms of identifying adequate fuel treatment locations. Comparison of the observed BP reduction among scenarios also suggests that the use of nonflammable landscape features in our decision rules is highly profitable, which further exemplifies the importance of using spatial data in decision-making for placement of fuel treatments.

Acknowledgments

This study was made possible by the Prince Albert Model Forest Science and Technology Fund. We are grateful to Jen Beverly, Paul Maczek, Diana Stralberg, Nicole Vaillant, and Jeff Weir for their ideas and comments. Alan Frank and Dave Wieder provided geographic information system data, and Daniel Poirier and Richard Carr provided weather data. We thank Cordy Tymstra for his project-long assistance with Prometheus and Peter Englefield for helping with the geographic information system analysis.

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Fuel Characterization and Mapping

Fuels Products of the LANDFIRE Project

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Abstract*—The LANDFIRE project is a collaborative interagency effort designed to provide seamless, nationally consistent, locally relevant geographic information systems (GIS) data layers depicting wildland fuels, vegetation and fire regime characteristics. The LANDFIRE project is the first of its kind and offers new opportunity for fire management and research activities. Here we introduce the LANDFIRE wildland fuels data layers including fire behavior fuel models, canopy bulk density, canopy base height, canopy cover, canopy height and new Fuel Loading Models. Specifically, we focus on the methods and data used to create these layers and present preliminary assessments. These key fuels layers will support fuels and smoke management and fire behavior modeling in addition to providing essential information for evaluating and managing wildland fires, seamlessly and consistently.*

Introduction

Wildland fuels are critical elements in wildland fire planning and management activities. Wildland fuels are needed to parameterize consumption models, for example First Order Fire Effects Model (FOFEM) and fire behavior models such as NEXUS (Scott 1999), BehavePlus (Andrews 2003) and FARSITE (Finney 1998). These models can be used for two basic but critically important purposes; prioritizing fuel treatments and assessing fire behavior and effects in wildland fire suppression activities. Data to drive these models are lacking for most federal lands. These issues led the Wildland Fire Leadership Council, a group of senior administration executives representing all land management agencies in the country, to charter the LANDFIRE Project. The LANDFIRE project is currently mapping or developing geospatial data to meet the need for continuous, consistent, unbiased and scientifically produced fuels layers. In particular, LANDFIRE produces the fuels layers needed to run FARSITE including fire behavior fuel models, both the Anderson (1982) models (13 fire behavior fuel models) and the relatively newer Scott and Burgan (2005) set, canopy cover, canopy height, canopy bulk density and canopy base height. For fire effects analysis, a new set of Fuel Loading Models is being developed that focus on providing the necessary inputs to run FOFEM spatially. This paper explains methods and tools employed by LANDFIRE to map each of these fuel products.

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Methods

Upstream Products

The fuels layers rely on previously produced LANDFIRE layers and ancillary data (fig. 1) including existing vegetation type (EVT), canopy cover (CC), canopy height (CH), environmental site potential (ESP), Enhanced Thematic Mapper (ETM) imagery, digital elevation model (DEM) and associated derivatives and biophysical gradients. A brief explanation of these data is required so that the fuels mapping process can be discussed and understood with clarity.

Reference Database—The LANDFIRE reference database forms the foundation for nearly all LANDFIRE deliverables. It is used for developing training sites for imagery classification; validating and testing simulation models; developing vegetation classifications; creating empirical models; determining and archiving data layer attributes and; assessing the accuracy of maps and models (Caratti 2006). The reference database stores all relevant plot level information and provides the means to generate, test, and validate predictive models and LANDFIRE deliverables. Data have been received from a variety of sources in various forms, though the United States Forest Service has been the largest contributor with approximately 56,000 plots (~40% of the total). Roughly 140,000 plots have been archived in the

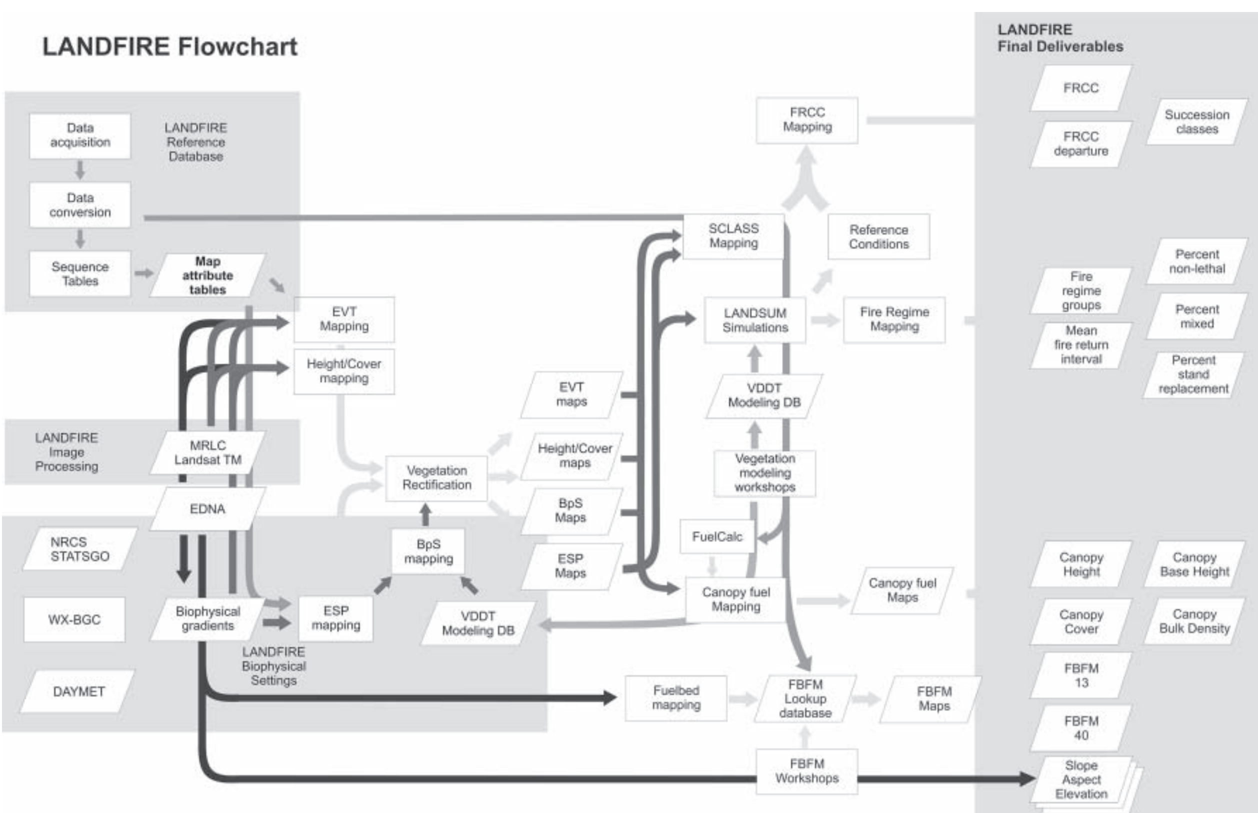

Figure 1—Flow of data, data processing and final products of the LANDFIRE project. Note the dependency of the fuels products on upstream LANDFIRE layers.

reference database for the first 16 mapping zones (fig. 2). Once each plot is converted to a common format, it is keyed to an existing vegetation type (EVT) and environmental site potential (ESP) using sequence table classifiers based solely on floristic composition. A main feature of the reference database for fuels mapping is the inclusion of a suite of predictor variables. These predictor variables form the basis for the landscape prediction models developed for mapping canopy fuels.

Predictor variables fall into one of four categories including; 1) imagery, 2) DEM and associated derivatives, 3) biophysical gradients, and 4) other LANDFIRE layers.

The LANDFIRE program uses the satellite imagery from the Multi-Resolution Land Characterization (MRLC) 2001 project (Homer and others 2004). This system divides the nation into separate mapping zones (fig. 2). There are two key elements resulting from this study that are used by LANDFIRE. First, the LANDFIRE project uses the same mapping zones as those created in the MRLC 2001 project. Second, LANDFIRE uses the satellite imagery that was painstakingly mosaicked for each zone for the conterminous U.S. The essential characteristics of this satellite imagery database are; 1) image dates (time of acquisition) range from 1999 – 2003; 2) imagery is supplied by the ETM sensor, and 3) each mapping zone has three sets of associated imagery including leaf-on, spring and leaf-off. A full description of these data is available in Zhu and others (2006).

The biophysical gradients are derived from WXBGC (Keane and others 2002), a modified version of the ecosystem simulation model, BiomeBGC (Running and Gower 1991; Thornton and others 2002). The meteorological data used to drive WXBGC come from the DAYMET meteorological database, which comprises interpolated surfaces of daily meteorology observations (Thornton and others 2002). In addition to these gradients, a suite of terrain variables such as DEM, slope and aspect are used.

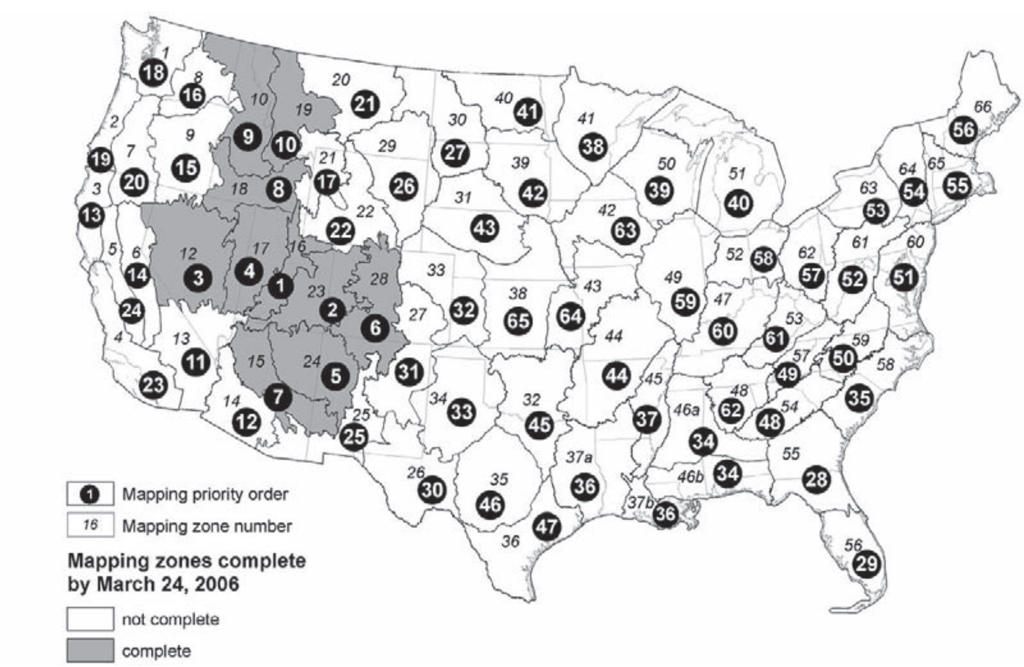

Figure 2—Multi-Resolution Land Characterization (MRLC) mapping zones used by LANDFIRE. Numbers in bold circles represent zones completed as of 5 April, 2006.

Other LANDFIRE Layers—The fuels mapping process relies extensively upon EVT, existing vegetation cover, height and, to a lesser degree, ESP. The EVT and associated structural attributes are produced by Earth Resources Observation Systems (EROS), a United States Geological Survey LANDFIRE partner, while ESP is created at the Missoula Fire Sciences Laboratory.

The EVT depicts the dominant Ecological System (Comer and others 2003) currently present at each 30 m pixel. Each field plot is assigned a life-form and ecological system class, and this information is then used to train decision tree models (Quinlan 1993) using imagery, topographic, and biophysical data (Zhu and others 2006).

Existing vegetation canopy cover, as defined in the LANDFIRE project, represents the average percentage of dominant life-form, non-overlapping canopy cover for each 30 m pixel. A life-form stratification is used to develop independent canopy cover for tree, shrub, and herbaceous life-forms. Canopy cover for the shrub and herbaceous life-forms is developed through use of field plot information in the reference database combined with imagery, topographic, and biophysical data to train regression tree models (Quinlan 1993), while tree canopy cover is developed by procedures employed for the National Land Cover Dataset (NLCD) effort (Homer and others 2004). The final existing vegetation cover dataset is comprised of nine, 10 percent incremental classes ranging from 10 to 100 percent.

Existing vegetation height represents the average height of the dominant life-form for each 30 m pixel. Field plot height measurements, in addition to Landsat imagery, topographic, and biophysical spatial data, are used to train decision tree models that predict existing vegetation height. Continuous tree, shrub, and herbaceous height field data are grouped into 3 to 5 discrete classes, depending on plot height ranges and data availability, prior to being modeled. Prior to dissemination on the National Map (http://nationalmap.gov [last visited 24 March, 2006]) as fuels layers, existing vegetation height and cover are converted to the canopy height (CH) and canopy cover (CC) products. These differ from the existing vegetation height and cover products because the thematic classes are converted to ordinal, biologically meaningful values so that they can be used directly in a fire behavior processor (Finney 1998; Scott 1999). In addition, the CH and CC products only represent cover and height of forested systems, as all herbaceous and shrub areas are coded as 0.

The environmental site potential (ESP) represents the vegetation that could be supported at a site based on the biophysical environment. Map units are named according to NatureServe's Ecological Systems classification (Comer and others 2003). As used in LANDFIRE, map unit names represent the natural plant communities that would become established at late or climax stages of successional development in the absence of disturbance. The ESP is similar in concept to other potential vegetation classifications in the western United States, including habitat types (for example, Daubenmire 1968; Pfister and others 1977).

Fuels Mapping

Fire Behavior Fuel Models—Prior to creating maps of fire behavior fuel models (here referred to as FBFM), LANDFIRE fuelbeds are created using the spatial intersection of EVT/CC/CH/ESP. Every unique combination identified during this process is assigned a fire behavior fuel model. Use of these four variables for identifying fuelbeds is appropriate because it enables maps of fire behavior fuel models to be inferred from vegetation. Existing vegetation type yields information about the type of litter and ultimately, the vegetation that will most likely carry the fire. Canopy cover permits inference of the nature of the understory. For example, in more open canopy situations a greater preponderance of understory vegetation, such as shrubs and herbs is expected. Canopy height can further help the distinction between FBFM's. For example, a grass existing vegetation type will probably burn more like a fire behavior model 1 (Anderson 1982) if it is short, whereas if the grass is tall and dense, for example ≥ 1 m, it will likely be categorized as a FBFM 3 (Anderson 1982). The environmental site potential is infrequently used to distinguish relatively more xeric fuelbeds from those that are relatively more mesic.

Using this information, rules can be created that divide these ranges of possibilities into several categories for each EVT based on expected fire behavior. For example, the assumption can be made that there are two general kinds of fire behavior typically observed in a Great Basin pinyon-juniper environment. The first is a creeping fire with low flame length and rate of spread. This situation often occurs on relatively more dense stands with high canopy cover and low fuel moistures. The other type of fire behavior is more active, with higher rates of spread and flame lengths. This type of behavior is typically observed in relatively more open stands, in high winds, where herbaceous species are denser and shrubs such as sagebrush are interspersed with the larger pinyon pine and juniper.

With this logic, several rulesets can be derived from our example stand of pinyon-juniper (table 1). Each ruleset is subsequently assigned two fire behavior fuel models; one from Anderson (1982) and one from Scott and Burgan (2005). After these preliminary assignments are made they are refined and reviewed by local fire and fuel managers during fire behavior fuel model assignment workshops. After fuelbeds are reviewed, they are linked to a layer in a GIS and fuel model maps are created. After each fuel model map is created it goes through a separate cycle of review by local fire and fuel specialists with revision as appropriate. This second revision process differs from the assignment workshops because it focuses on the spatial expression of the rulesets created by experts during the assignment process. These workshops are a critical part of the LANDFIRE process because they permit collaboration between specialists, with knowledge about their area, and LANDFIRE scientists.

Canopy Base Height and Bulk Density—Canopy base height (CBH) is defined as the lowest point in the canopy at which there is sufficient available fuel for propagating the fire vertically, while canopy bulk density (CBD)

Table 1—Example LANDFIRE fuelbed assignments from a Great Basin Pinyon-Juniper Existing Vegetation Type. ESP is Environmental Site Potential.

Fuelbed #	Cover (%)	Height (m)	ESP	FBFM13[1]	FBFM40
1	0 - 50	Any	Xeric	6	SH1
2	0 - 50	Any	Mesic	2	GS2
3	50 - 100	≥ 3	Any	8	TL1
4	50 - 100	≤ 3	Any	6	SH1

[1]FBFM13 and FBFM40 are fire behavior fuel models from Anderson (1982) and Scott and Burgan (2005) respectively.

refers to the mass of available canopy fuel per unit canopy volume (Scott and Reinhardt 2001). These canopy characteristics are most often used to determine expected crown fire activity for a stand or larger landscape.

The canopy fuels mapping process begins by attributing each plot with estimates of CBH and CBD. These canopy characteristics are computed using FuelCalc (Reinhardt and others 2006, this proceedings). The inputs required by FuelCalc include species, diameter at breast height (d.b.h), canopy height, height to live crown, crown class and trees per acre. These tree lists used as input to FuelCalc are simple attributes to collect but not often recorded in the field with the exception of the Forest Inventory and Analysis (FIA) program. Indeed, 84% of all plots used thus far in the LANDFIRE fuels mapping effort come from FIA data. The FIA data used for this effort range in date from 1978 to 2005, and therefore were obtained using different field methods and plot designs (Bechtold and Scott 2005).

These tree lists are ingested by FuelCalc and canopy biomass is computed by linking d.b.h. with total canopy biomass using species allometric equations. Using these equations, total crown biomass is computed and crown fuel is estimated to be that portion of the crown biomass that may be consumed by the flaming front of a passing fire (≤ 0.6 cm. [¼ in.] dia.). This fuel biomass is apportioned through the canopy of the stand according to the nature of the stand being investigated. From this CBD profile the maximum value is chosen to represent the stand. Likewise, the CBH is defined as the lowest layer in the canopy at which the CBD is ≥ 0.012 kg m^{-3} (0.0007 lb ft^{-3}).

The goal of the canopy fuels mapping effort is to predict CBH and CBD across each LANDFIRE mapping zone by relating these attributes to the plethora of predictor variables available for each zone. These predictions derived in this manner are referred to as the FuelCalc — derived estimates of canopy characteristics. This distinction is significant to later discussions.

The statistical models used to spatially predict CBD and CBH are formulated using the commercially available regression tree, machine-learning algorithm, Cubist (© Rulequest Research 2004) (Quinlan 1993; Rulequest Research 2006). Cubist offers a fast, efficient and relatively accurate approach for building regression tree models that can be applied to large areas (Huang and others 2001; Xian and others 2002). Other salient features of Cubist are discussed in Zhu and others (2006) and Keane and others (2006).

The CBH and CBD regression tree models are evaluated using a 10-fold cross validation procedure (Shao 1993). Different combinations of variables are tested until a consistently low cross validation error rate is observed. Once a suitable regression tree model has been formulated, it is applied spatially using a suite of tools developed in support of the NLCD project (Homer and others 2004; Vogelman and others 2001). These tools were specifically designed to integrate and interpret regression trees formulated using Cubist with the ERDAS Imagine image processing system (Erdas Imagine 2006) (© ERDAS, Inc. 2001).

The landscape predictions of CBH and CBD are then subsequently qualitatively and quantitatively evaluated. Quantitative evaluations include comparisons of CBD with the LANDFIRE canopy cover and satellite imagery. Canopy bulk density is strongly related to canopy cover (fig. 3). Thus, logical relationships between canopy bulk density and canopy cover should be observed in the LANDFIRE products. To evaluate these relationships, zonal statistics are performed such that the mean CBD is computed for each canopy cover class. In a similar manner CBH is evaluated against canopy height for each mapping zone.

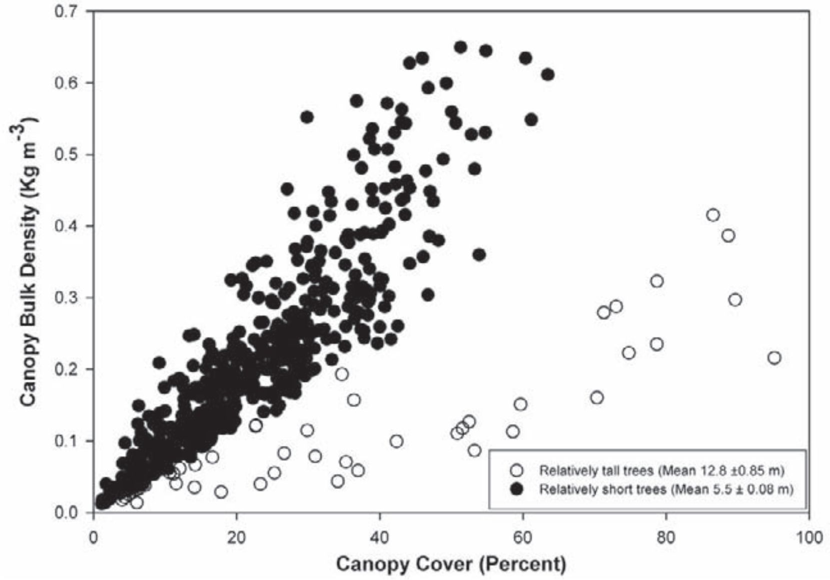

Figure 3—Relationship between estimated canopy bulk density (kg m^{-3}) and canopy cover (percent) from FuelCalc for Mapping Zone 12. Black dots represent relatively short trees (average of 5.5 m with standard error of ± 0.08 m) (usually *Juniperus* spp.), while open circles represent relatively taller trees (average of 12.8 m with standard error of ± 0.85 m).

Other quantitative methods of evaluating the canopy fuel products include comparisons between the frequency of CBH and CBD from the plot data with that of the predicted values in each layer. One might expect a consistent pattern in the numerical distribution between plot and image data, provided that the field plots sufficiently cover the range of variability observed in a mapping zone. For example, if 50 percent of the field plots fell below a bulk density 0.12 kg m^{-3}, then a similar finding in the predicted values for a mapping zone would be expected.

These quantitative methods are combined with extensive visual inspections for obvious errors. While not statistically rigorous, these methods yield valuable guidance and insight as to the appropriate predictor variables and subsequent regression tree formulations that should be used. As a result of these processes, a predictive regression tree model may undergo significant revision for a mapping zone prior to completion of the final product.

Identifying and Filling Areas of Snow, Cloud and Shadow—Although the MRLC project carefully selected scenes of imagery to eliminate clouds, there are still a few small areas where it was not possible to get a totally cloud free scene. Areas contaminated by snow, cloud and shadow are identified in each mapping zone using maximum likelihood supervised classification techniques implemented in Erdas Imagine. Any pixel in a mapping zone dominated by snow, clouds or shadow will be filled using one of two values. These "fill" values are generated using plot data by computing mean CBH and CBD for each EVT/ESP (Stage 1) and EVT (Stage 2) combination. The "filling" process occurs in two stages. Stage 1 filling draws from the database of mean CBH and CBD for each EVT/ESP combination. Use of Stage 1 filling is preferable because it maintains more spatial heterogeneity than the stage 2 filling. However, it is not always possible to use Stage 1 filling because not every EVT/ESP combination on the landscape has plot data with which to compute a mean CBH or CBD. In these instances, the simpler, mean CBH or CBD by EVT is used. Finally, if there is an EVT found in a mapping zone for which there are no plot data to compute a mean CBH or CBD, then the prediction is not altered from its original state (as computed using regression tree formulae) regardless of the error associated with that prediction.

Obtaining Canopy Base Height From an Expert System—Canopy base height is used to aid in predicting surface to crown fire transition. Thus, it is a critical parameter for accurate simulation of crown fire activity. For maximum effectiveness, however, canopy fuels should not be developed independently of surface fuels or illogical combinations might occur (Keane and others 2001). In recognition of the need to convolve CBH estimates with each LANDFIRE fuelbed, an expert system was developed to crosswalk these entities to permit crown fire simulation.

To accomplish this task a series of fire behavior and fire management experts were asked to estimate conditions under which each appropriate LANDFIRE fuelbed would transition from a surface to a crown fire. The expert panel was shown a picture and a description of each fuelbed and then asked to identify specific environmental criteria under which, in their experience, they had observed transitions from surface to crown fire. These fuelbeds combined with the environmental criteria obtained from the experts were fed into a spreadsheet analysis system with the appropriate functions from FARSITE (Finney 1998) programmed into it. The necessary CBH to permit passive crown fire was computed from this analytical spreadsheet. This dataset is separate from the FuelCalc — derived estimates of CBH described above. Indeed, these expert system canopy base height estimates are specifically designed to be used with LANDFIRE data in fire behavior processors and should not be construed as biologically relevant predictions of CBH across the landscape. Instead, this CBH layer simply represents a model parameter that is estimated in the context of each LANDFIRE fuelbed.

Fuel Loading Models—The Fuel Loading Models (FLM) represent a unique surface fuels classification that incorporates the variability of fuel loading within and across fuel components. The model classification uses surface components including fine and coarse woody debris (FWD ≤ 7.62 cm [3 in.] and CWD ≥ 7.62 cm respectively), duff and litter. Fuel loading models were created using four generalized steps: 1) collection of fuels data, 2) compute fire effects from fuels data, 3) cluster fire effects predictions into "Effects Groups" (EG), and 4) classify effects groups to create FLM's. Roughly 4,000 plots were used to create these FLM's spanning a large geographic range.

Using these plots, fire effects were estimated using the First Order Fire Effects Model (FOFEM) (Keane and others 1994; Reinhardt and others 1997). Each fuels plot was subsequently clustered into one of ten effects groups based on total $PM_{2.5}$ emissions and maximum surface soil heating (fig. 4). Classification tree analysis was then used to build a rule set to predict each of these effects groups based on FWD, CWD and duff and litter. These FLM's will eventually be spatially mapped through vicarious linkages with vegetation and fuels attributes from the LANDFIRE project. These mapped FLM's will contain the necessary data to parameterize fire effects models such as FOFEM in a spatial manner.

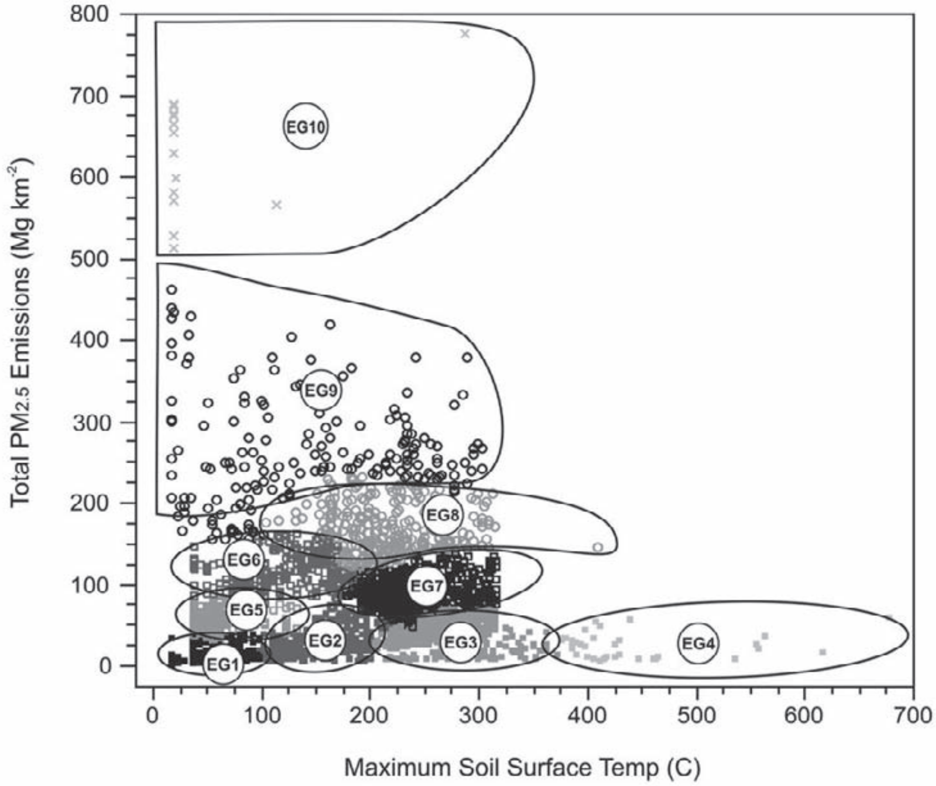

Figure 4—Ten effects groups ordinated by $PM_{2.5}$ (Mg km^{-3}) emissions and maximum soil surface temperature (C).

Discussion

Fire Behavior Fuel Models

Approximately 130 fire behavior and fuels specialists have participated in the LANDFIRE fire behavior fuel model assignment and calibration workshops. This has greatly increased the efficacy of the FBFM layers. For example, a common problem identified with the LANDFIRE FBFM layers is the lack of grass models resulting from invasion by *Bromus* spp. (for example, cheatgrass). As a result, we implemented a procedure, which resulted in millions of acres being updated to grass models due to the preponderance of *Bromus* spp. These and other changes have updated LANDFIRE layers to represent local conditions as near as possible given the constraints of mapping consistency and objectivity. It is notable that the LANDFIRE EVT mapping process is not refined enough to detect stands that have been minimally thinned, which result in accumulation of slash. Thus, it is rare to observe any of the slash models in LANDFIRE data, with one exception. Slash models have been assigned to some LANDFIRE fuelbeds in the southwestern United States. Some stands in this region are late successional decedent stands of *Abies concolor* (white fir) where very high fuel loads (> 60 tons acre^{-1}) of coarse woody debris are observed and blowdown can be several meters thick. The fire and fuel specialists in these areas felt that the fire behavior under these conditions could only be described by slash models, but these situations are relatively rare.

Canopy Base Height and Bulk Density—Examples of the relationships developed during the canopy fuels regression tree analysis are shown in figures 5 and 6. Figures 5 and 6 indicate CBD estimates above 0.4 and CBH estimates above approximately 6 meters are probably not reliable. In general there are not enough plots with large values of CBD or CBH to make a reliable and stable regression tree above these values.

There is an inverse relationship between canopy cover and bulk density in some mapping zones but only in areas of extremely high CC. This non-linear relationship typically only occurs in stands with relatively high CH. This follows the pattern observed in the plot level estimates of CBD and CC (fig. 3). Figure 3 clearly shows two distinct relationships between CBD and CC; one for tall trees and one for short trees.

In comparison to CBD, CBH is more difficult to interpret, map and identify using field based reconnaissance. This is because CBH is more abstract and is not a definitively measurable feature of a stand. Thus, few techniques exist that can be used to asses the true accuracy of these estimates in LANDFIRE data. This is one primary reason for creating the expert system derived CBH estimates. Examples of these expert system estimates are shown in table 2.

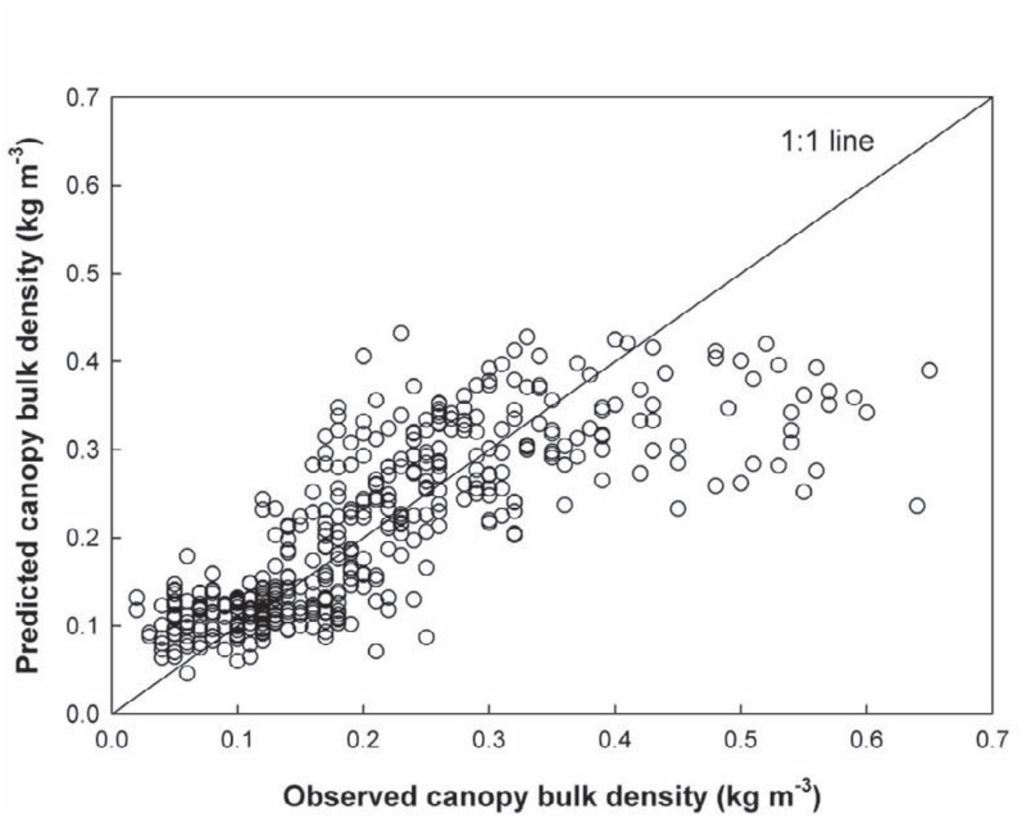

Figure 5—Predicted and observed canopy bulk density (kg m^{-3}) resulting from a regression tree analysis for Mapping Zone 12. Note the asymptotic feature beginning at approximately 0.4 kg m^{-3}.

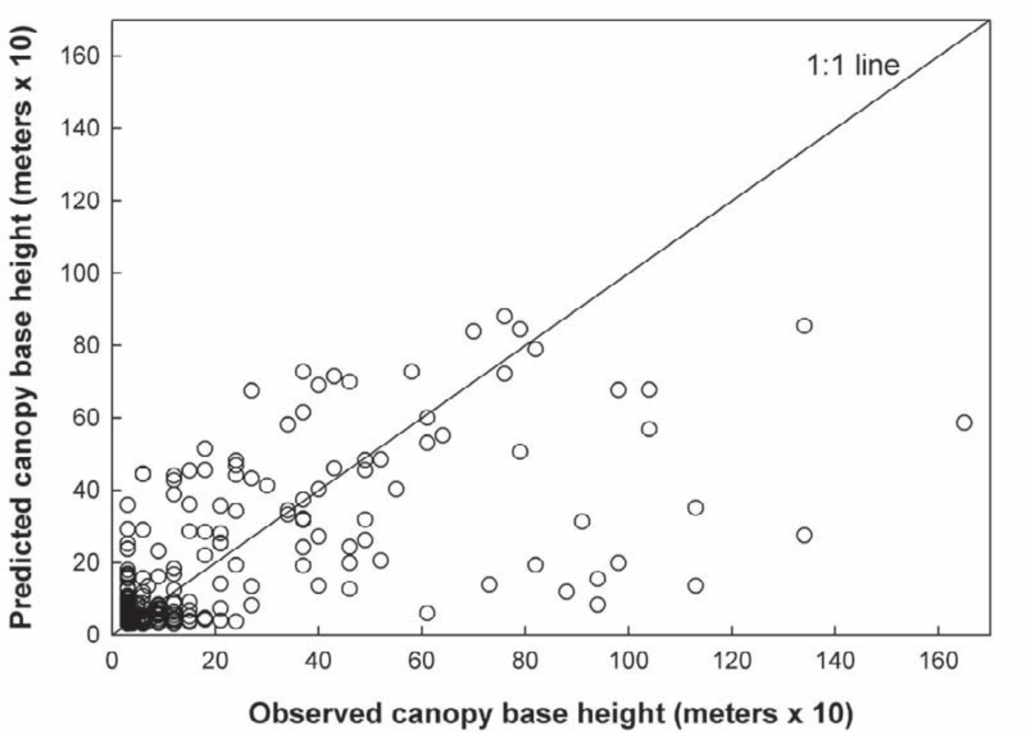

Figure 6—Predicted and observed canopy base height (m) resulting from a regression tree analysis for Mapping Zone 23. Predictions above approximately 6.0 meters are unreliable.

Table 2—Canopy base heights computed using an analytical spreadsheet informed through an expert system. Note that each fuelbed has both Anderson (1982) (FBFM13) and Scott and Burgan (2005) (FBFM40) fuel models. The environmental criteria for this analysis are as follows: fine dead fuel moistures (1,10 and 100 hr time lag fuels) are 4,5 and 6% moisture content respectively; 20 ft. wind speed was estimated as 20 mph.

EVT	Cover	Ht	ESP[1]	FBFM13	FBFM40	CBH13[2]	CBH40[3]
	(%)	*(m)*				- - - - - - *(m)*	- - - - - -
Northern Rocky Mountain Ponderosa Pine Woodland and Savannah							
	≥50	≥ 5	Any	9	TU5	0.29	.71
	< 50	≥ 5	Any	2	TU3	0.075	2.33
	Any	< 5	Any	6	GS2	N/A	N/A
Rocky Mountain Subalpine Mesic Spruce-Fir Forest and Woodland							
	≥ 50	≥ 5	Any	10	TU5	0.34	1
	30 - 49	≥ 5	Any	8	TU1	0.25	0.23
	< 30	< 5	Any	5	SH4	N/A	N/A

[1] ESP is Environmental Site Potential.
[2] Canopy base heights formulated using the Anderson (1982) fuel model.
[3] Canopy base heights formulated using the Scott and Burgan (2005) fuel model.

Use and Limitations of LANDFIRE Fuels Data

The LANDFIRE fuels data layers can be used for applications at varying scales, including project level planning (for example, < 5000 acres), particularly when higher resolution data are lacking. These data are particularly well suited for comparative analyses within and between regions. Thus, it is the responsibility of the user to determine the appropriate scale and usefulness of LANDFIRE fuels data. These fuels layers span all ownerships, a trait not likely to be found in other fuels data sets. These layers are expected to form the baseline data for interagency planning, while local datasets, which cost more and take longer to produce can be used in place of, or in addition to, LANDFIRE data. However, because of their objective and comprehensive nature LANDFIRE data can be used efficiently for such activities as strategic fuels reduction plans, tactical fire behavior assessment and estimating fire effects. These fuels data are the first of their kind because they will seamlessly cover the nation. Any project with this scope will have tradeoffs between quantity and quality. As a result, there is a need for further research for improving the quality of these layers and for assessing their true efficacy. To meet this need we recommend cohesive, scientific, interagency assessments of LANDFIRE fuels data.

Summary

This paper provides a general overview of the LANDFIRE fuels mapping procedures and highlights their interdependency on multiple data sources including other LANDFIRE layers. Fire behavior fuel models are linked with vegetation type and structural attributes based on rulesets devised by local fire and fuel experts. In turn, the spatial expression of these rulesets is evaluated and critiqued in a series of local calibration efforts. Canopy fuels are mapped using predictive landscape modeling by relating a multitude of predictor variables to CBH and CBD in regression trees. These regression trees are subsequently applied across the landscape. Given the nebulous nature of CBH and the dependence on this variable by fire behavior processors, we have devised a strategy to map canopy base height across the landscape using an expert system approach. At national and regional scales LANDFIRE will provide valuable insight for modelers, fire scientists and managers. Finally, we recognize the need for cohesive efforts to assess the efficacy of all LANDFIRE fuels data and hope to initiate this process in the future.

Acknowledgments

We acknowledge Robert E. Keane, Mark A. Finney, Charles McHugh, and Joe Scott for their thoughtful contributions to LANDFIRE methods. A large national project could not succeed without a business management team. We therefore also acknowledge Henry Bastian, Daniel Crittenden, Bruce Jeske, and Timothy Melchert for their professional business support. Finally, we wish to thank the participants of the various fuels workshops. Their local expertise has dramatically improved the LANDFIRE fuels layers.

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FUEL3-D: A Spatially Explicit Fractal Fuel Distribution Model

Russell A. Parsons[1]

Abstract—*Efforts to quantitatively evaluate the effectiveness of fuels treatments are hampered by inconsistencies between the spatial scale at which fuel treatments are implemented and the spatial scale, and detail, with which we model fire and fuel interactions. Central to this scale inconsistency is the resolution at which variability within the fuel bed is considered. Crown fuels are characterized by clumps of fuel separated by gaps between needles, between branches, and between trees. A growing body of evidence suggests that this variability plays an important role in how fire spreads. A new system currently in development for representing fuels with higher detail, called FUEL3-D, is presented. FUEL3-D is designed to both facilitate fundamental fuel and fire science research and to provide detailed guidance to managers in the design and evaluation of fuel treatments. Unlike existing fuel models that do not deal with spatial structure or variability within the fuelbed, FUEL3-D represents fuels with spatially explicit detail; individual branches on individual trees are resolved and quantified using fractal geometry and allometric relationships. Fuels can be summarized to 3-D pixels, at any scale, as input to advanced physical numerical fire behavior models such as FIRETEC and WFDS. FUEL3-D can thus be used to represent fuels before and after treatment with much greater detail than has been possible before. Model development, preliminary validation against destructively-sampled crown fuels data sets, and current research inquiries are discussed.*

Background

Current fire management practices and policy emphasize implementation of fuel treatments, such as thinning and prescribed burning, that seek to modify future fire behavior by reducing or altering the fuel bed in some way. A common objective of many fuels treatments is to reduce the likelihood of a fire spreading from surface fuels, such as litter and fine woody debris, to the forest canopy. Fuel treatments must generally be implemented at one time, and actually tested (by a wildfire passing through or near them) at a different time. As substantial resources must be committed to carry out fuel treatments, and conditions at the time the treated area burns are unknown, fuel treatment assessments rely heavily on predictions from computer models. The accuracy of predictions from such models is dependent on the detail with which they represent the main components of the problem, namely, wildland fuels and their interactions with fire.

Spatially explicit models of trees and shrubs have been developed with different levels of detail. The most common applications of such models are light dynamics and plant growth models (see Brunner 1998 and Busing and Mailly 2004 for reviews of several such models, respectively). A common

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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approach is to represent trees and shrubs crowns as simple geometric forms, such as cylinders, cones or ellipsoids (e.g., Canham et al. 1999, Kuuluvainen and Pukkala 1987, Pukkala et al. 1993). Such representations are limited to particular scales because detail within the tree crown is not modeled. A much more accurate approach represents plants as fractal objects (Mandelbrot 1983, Godin 2000) and model plant architecture in detail, sometimes extending as far as individual branches, twigs and leaves (Berezovskava et al. 1997, Ozier-Lafontaine et al. 1999, Richardson and Dohna 2003, Godin et al. 2004). Such approaches are particularly relevant to representation of canopy fuels because they successfully capture the natural pattern of clumps of fuel separated by gaps, such as those between needles and between branches.

The clumped nature of wildland fuels is important to fire behavior because propagation of fire is a fundamentally fine scale, spatial process, dependent on the size, shape, composition and arrangement of fuel particles (Burrows 2001) and, particularly, distance between fuel particles (Fons 1946, Vogel and Williams 1970, Weber 1990, Bradstock and Gill 1993). Current management tools used to predict fire behavior, such as BehavePlus (Andrews 2003) and FARSITE (Finney 1998) do not deal with spatial relationships within the fuel bed and cannot be used to reliably assess transitional fire behaviors, such as the change from surface fire to crown fire, or fire-atmosphere interactions that strongly influence the initiation of rapid and intense "blow-up" behaviors which may pose great threats to fire fighter safety (Rothermel 1991, Potter 2002). Fuel treatments can only be assessed with such models as a comparison of average conditions (e.g., Van Wagtendonk 1996). This is problematic because the complex and dynamic nature of fire-fuel and fire-atmosphere interactions may result in cases in which the average conditions either do not actually occur (such as mean crown base height in a two storied tree stand) or do not result in average fire behavior.

In recent years more advanced physics-based, numerical fire behavior models have emerged, such as FIRETEC (Linn et al. 2002, Linn and Cunningham 2005), and WFDS (Mell et al. 2005) that consider spatial variability within the fuel bed, fire-fuel interactions and fire-atmosphere interactions. The detail with which these models address fundamental drivers of fire behavior, as well as the underlying physics basis of the models, facilitates robust prediction of fire behavior and related analyses of fuel treatments at multiple scales.

One of the key limitations in the application of these models is that they require fine scale spatially explicit fuels inputs that are difficult to directly measure in the field, such as 3-D cells describing the distribution of fuel density within a tree. While the fire behavior models are very sophisticated in their treatment of the physics of fire spread and heat transfer, fuels information for wildland fuels of commensurate detail is extremely rare or non-existent. At present no procedures exist by which fuels data measured in the field can be used to develop these inputs or test the accuracy with which fuels are represented. Perhaps even more importantly, no tool exists by which the fundamental properties of wildland fuels can be assessed, quantified and evaluated as to their importance across a range of spatial scales. Wildland fire science will not be able to take full advantage of the advancements that have been made in fire modeling until these knowledge gaps are addressed.

One component of fuel treatment assessments that has not received much attention is the change in microclimate resulting from the treatment. The size, density and geometry of plants affects solar radiation at the forest floor (Reifsnyder and Lull 1965, North 1996, Govaerts and Verstraete 1998) and the interception of rain by the canopy (Helvey and Patric 1965), which both influence fuel moisture (Fosberg and Deeming 1971, Nelson 2002). The canopy structure also influences winds within a stand (Jensen 1983, Oke 1978, Brandle 1980). Fuel treatments may thus result in significant feedback relationships with the microclimate, which may alter the future behavior of fire within a stand in unexpected ways. At present we are greatly limited in our ability to assess the nature and magnitude of these effects.

Objectives

In this paper I introduce a spatially explicit fuel model called FUEL3-D, which can be used to represent fuels in great detail, both as discrete branches and as 3-D cells. This model represents a new concept in fuel modeling, in which fuel beds are described as a collection of discrete elements such as individual trees and branches within trees. FUEL3-D can be used to provide inputs to detailed numerical fire behavior models that account for spatial relationships within the fuel bed and are thus more sensitive to fuel treatments than current operational fire models.

I describe preliminary parameterization for ponderosa pine crown fuels based on destructively sampled crown fuels data and present results of preliminary validation analyses of biomass quantities against independent validation data. I then demonstrate two ways in which fine scale representations of fuels might provide insights relevant to fuel treatment assessments. First, I demonstrate how spatial relationships within the fuel bed influence fire behavior using a three-dimensional physical fire behavior model, WFDS (Mell et al. 2005). Second, using ray-tracing procedures I demonstrate how the spatially resolved structure of wildland fuels can be used to simulate the influence of the forest canopy on light dynamics at the forest floor, an important component of surface fuel moisture dynamics as well as vegetative response to fuel treatments. I conclude with discussion of how modeling fuels at fine scales fits into the larger picture of fire management.

Methods

Parameterization of the FUEL3-D Model for Ponderosa Pine

As the precise number, size and positions of individual branches composing the crown of an individual tree will generally never be known, it is necessary to simulate this structure. This is done on the basis of relationships identified from field data describing biomass quantities and geometry within the crown.

Field Data and Analysis—Detailed crown fuels data were collected through a destructive sampling crown fuels study in five locations in the western United States in 2000 and 2002 (Scott and Reinhardt 2002). In each study location, field crews systematically measured, removed, dissected and weighed individual branches for each tree in five stands destructively sampled between 2000 and 2002 (Scott and Reinhardt 2002). Tree level measurements included height, height to crown base, health status, canopy class (dominant, codominant etc.), coordinates of the tree stem and diameter at breast height (1.35 m, DBH). Branch level measurements included branch basal diameter, height on bole, angle from vertical, total length, width, and weight, separated out by component (woody vs. foliage, live or dead, etc.).

Woody fuels were separated and weighed by fuel moisture lag time size classes, i.e. 1 hour, 10 hour (Fosberg and Deeming 1970). I used tree and branch data measured for ponderosa pine (*Pinus ponderosa*) trees in a dense, single storied stand at the Flagstaff, Arizona field site in this initial development and testing of the FUEL3-D model. Of the original 85 trees, 7 trees with no individual branches, such as broken snags, were excluded from analysis, resulting in a data set of 78 trees and a total of 2207 individually measured branches. The trees were mostly codominant and intermediate trees with diameters ranging from 2.6 to 38.4 cm (mean 17.2 cm) (Figure 1). The majority (80%, 62 trees) of this data was randomly selected for model-building (to develop empirical relationships used in the model), and the remainder (20%, 16 trees) was withheld for validation. An additional 16 ponderosa pine trees measured at the Ninemile, Montana field site for the same study were used to assess how well relationships identified for the Flagstaff data could be applied to ponderosa pine trees sampled at other locations.

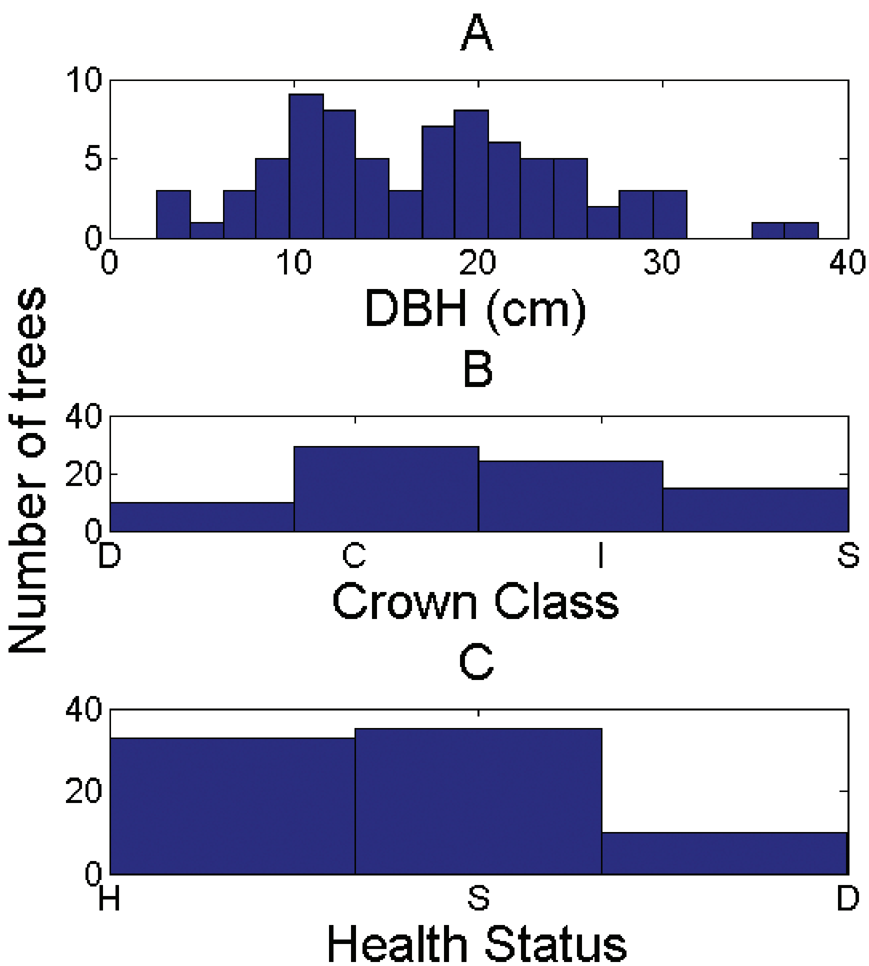

Figure 1—Three plots showing properties of data for the 78 ponderosa pine trees used in this study. All data used were from the Flagstaff field site: A) diameter distribution: B) Crown class distribution: D=Dominant, C=Codominant, I=Intermed, S=Suppressed. C) Health Status: H=Healthy,S=Sick,D=Dying

I supplemented this main data set with additional data collected in 2004 and 2006 in Montana. These data sets included measurements of angles between sub-branches, lengths and diameters of sub-branches as proportion of parent branches, and weights and dimensions of individual clumps of needles. This data in combination with the more extensive crown fuels study data described above provided information adequate for modeling sub-branches and distribution of biomass within a branch.

Using the model-building data I used non-linear regression procedures to predict the total branch biomass, and total foliar biomass for a branch as a function of basal branch diameter. I then used maximum likelihood estimation procedures to fit theoretical Weibull probability density functions (Grissino-Mayer 1999) describing the branch size class distribution of individual branches as a proportion of tree diameter at breast height (DBH) (Figure 2). The Weibull distribution is a flexible continuous positively skewed distribution described by the probability density function

$$f(y) = (cy^{(c-1)} / b^c) e^{(-(y/b)^c)} \qquad [1]$$

for the range $0 <= y < \infty$, scale parameter, b and shape parameter, c. I assessed model fit for branch size distributions with the Komologorov-Smirnov (K-S) test. Additional analyses (not presented here for the sake of brevity) assessed relationships between the position and orientation of the base of a branch along the tree stem and set upper limits for the total length and width of each branch, all on the basis of branch basal diameter. A summary of parameters used to describe and model ponderosa pine is presented in Table 1.

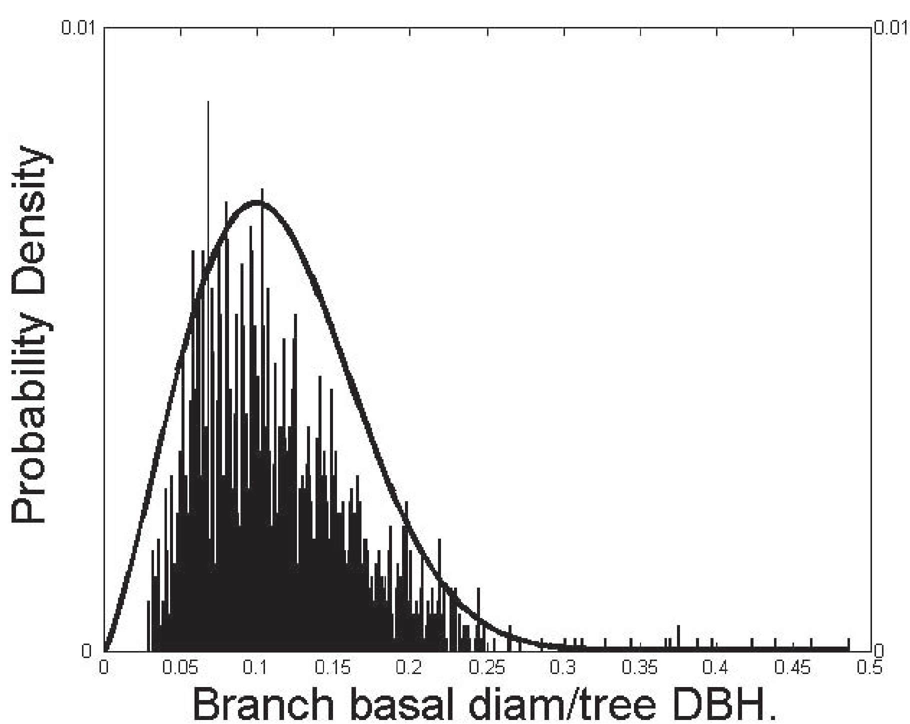

Figure 2—Distribution of branch basal diameters, as proportion of tree diameter at breast height, for 62 ponderosa pine trees destructively sampled near Flagstaff, Arizona. Smooth line shows theoretical distribution fitted on this data.

Table 1—Empirical relationships and parameters used to model ponderosa pine crowns.

Dep. var. (abbrev), units	Indep. var. (abbrev), units	Function type	Equation	Fit
Allometries				
Branch diameter size class distribution[a]		Weibull pdf.	$f(y) = (cy^{(c-1)} / b^c)\, e^{(-(y/b)^c)}$ b = 0.128 c = 2.285	K-S 0.06 p-value 0.0002
Total branch biomass(TB), g	Branch basal diameter(BD),cm	Power $Y = ax^b$	$TB = 27.17 * BD^{2.77}$	$R^2 = 0.96$
Branch foliar biomass (FB), g	Branch basal diameter(BD),cm	Power $Y = ax^b$	$FB = 11.15 * BD^{2.36}$	$R^2 = 0.92$
Geometry				
Total branch width (BW), m	Total branch length (BL,m)	Linear Y = ax	BW = 0.50 * BL	$R^2 = 0.69$
Total branch length (BL), m	Branch basal diameter(BD),cm	Power $Y = ax^b$	$BL = 0.47*BD^{0.99}$	$R^2 = 0.77$
Angle between branches, degrees	NA	Random, normal pdf.	Mean = 77 stdev = 9	

[a] Branch diameter distribution modeled as a proportion of tree diameter, so y = Branch basal diameter / tree d.b.h. This accounts for the increase in branch diameters as trees get larger.

Simulation of Tree Crowns—Simulation of a tree begins with a measurement of DBH. This is used to predict the size class distribution of branch basal diameters on the basis of analysis described above. Individual branch basal diameters are then sampled from this distribution until the sum of the cross sectional areas of the branches equal the tree cross sectional area. This relationship, first observed by Leonardo da Vinci and later applied in the pipe model theory (Shinosaki et al. 1964), has been shown to be true for a wide range of tree species and is a common basis in fractal models of plant structure (Berezovskava et al. 1997, Ozier-Lafontaine et al. 1999, Enquist 2002). For each branch basal diameter total branch biomass and foliar biomass quantities are then predicted using empirical functions described above. At this point each branch is defined in general terms but has no structure of sub branches.

The structure of sub branches which comprises the total branch is modeled as a series of frustums of a right circular cone, described by two vertices defining the position of the end points, and the radii at each end perpendicular to the line connecting the vertices (Figure 3). The branching structure is assembled using a static fractal model approach (e.g., Ozier-Lafontaine et al. 1999), described only briefly here. An initial segment is defined which represents the first part of a branch up to the point where sub branches form. The dimensions of this branch, along with geometric parameters describing the number of child branches and angles between them are used as the "seed" in a recursive function, common to numerous fractal tree models (Berezovskava et al. 1997, Niklas 1986). The effect of the recursive function is to continue

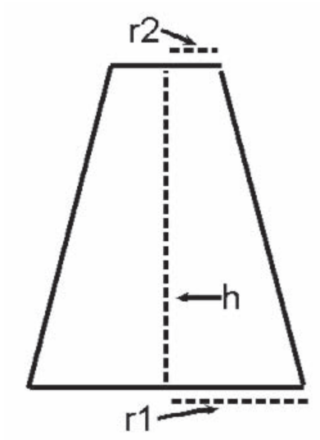

Figure 3—Planar view of a frustum of a cone, defined by length h, large radius R, and small radius r. The frustum of a cone is the basic building block for branches within the FUEL3-D spatial fuel model.

branching until some predefined end condition is met. In this manner each branch extends itself, splits into smaller branches, which themselves split into smaller branches, and so on (Figure 4). The position of each segment in 3-D space, dimensions and orientation and other attributes are written to a list for future use. In this initial configuration of the model branching was stopped when the distal radius of the segment was small enough to be considered a terminal, which represents a clump of needles. A terminal is defined in space as a frustum of a cone but also has additional attributes describing the total number of needles, surface area, foliar biomass etc. For extremely detailed simulations (typically only within a small area) it is possible to replace each terminal with a series of smaller objects. In this manner it is possible to represent detail down to the level of individual needles if desired.

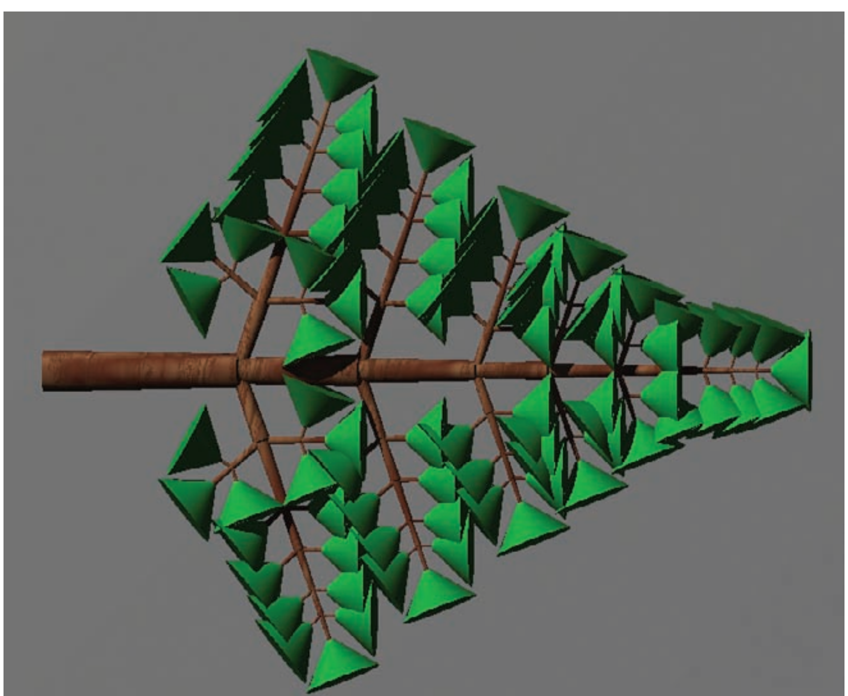

Figure 4—A simulated branch with sub-branches generated with FUEL3-D.

Summarization to 3-D cells—In order to use the fuels data defined as discrete objects in the numerical fire behavior models it is necessary to convert the data to values associated with three-dimensional grid cells (Figure 5). This is accomplished by slicing each branch segment, perpendicular to its main axis into a number of circular cross sections. Each circle is "clipped" along the line of intersection between the plane within which it lies and each of the applicable planes which constitute the limits of the 3-D cell. The area of the resulting, possibly irregular, polygon is stored off in a list. All of these areas are then numerically integrated to calculate the volume of that branch that lies within the particular cell. This procedure is repeated for each cell and for all branch segments. Parts of a branch segment that are cut out of one cell will be accounted for in an adjacent cell. In this manner the total quantities are preserved across whatever spatial scale is desired.

Comparison With Validation Data—Comprehensive validation of a complex model often requires a large number of tests; as the FUEL3-D model is still in active development validation efforts are ongoing. I compared the measured total crown biomass, for the two independent validation sets, against quantities simulated with FUEL3-D (Figure 6). The modeled relationships used in testing were all derived from the Flagstaff model building data set.

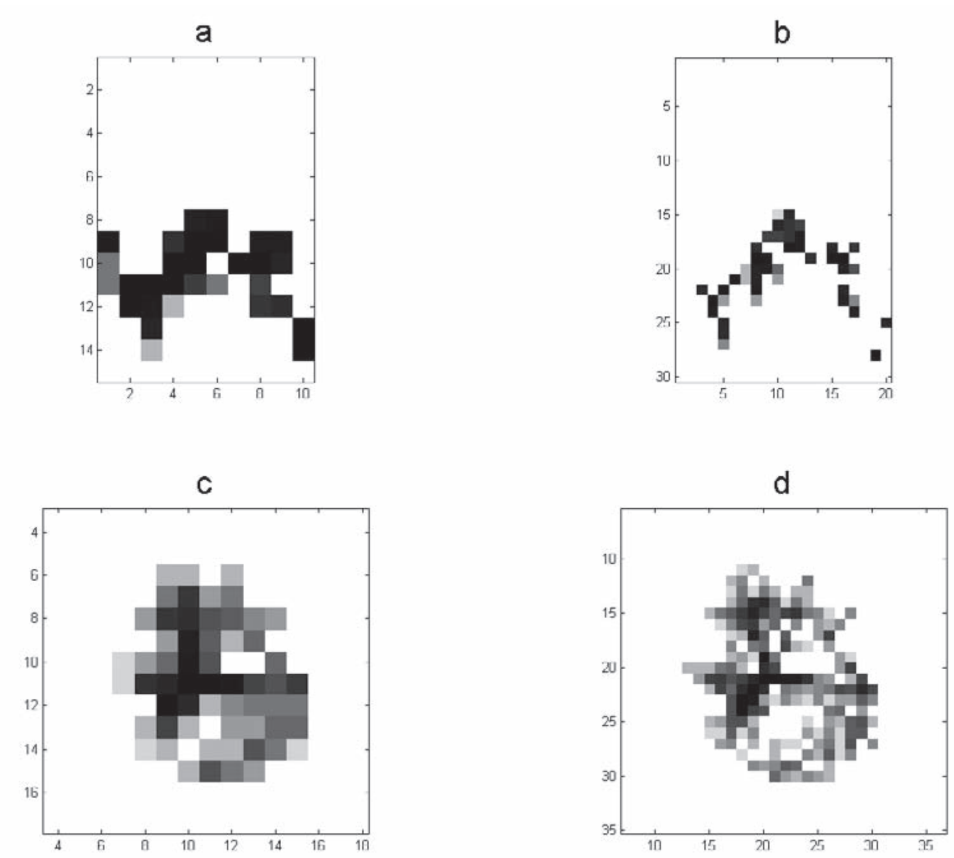

Figure 5—3-D cell representation of density within the crown of a small tree, for two resolutions (columns, left 10 cm cells, right, 5 cm cells) and two perspectives (rows, top, side view of vertical slice through volume, bottom, overhead view of horizontal slice through volume. Light colors are low values of density within a cell and dark cells are higher values. A) 10 cm cells, side view, vertical slice; B) 5 cm cells, side view, vertical slice; C) 10 cm cells, overhead view, horizontal slice; D) 5 cm cells, overhead view, horizontal slice.

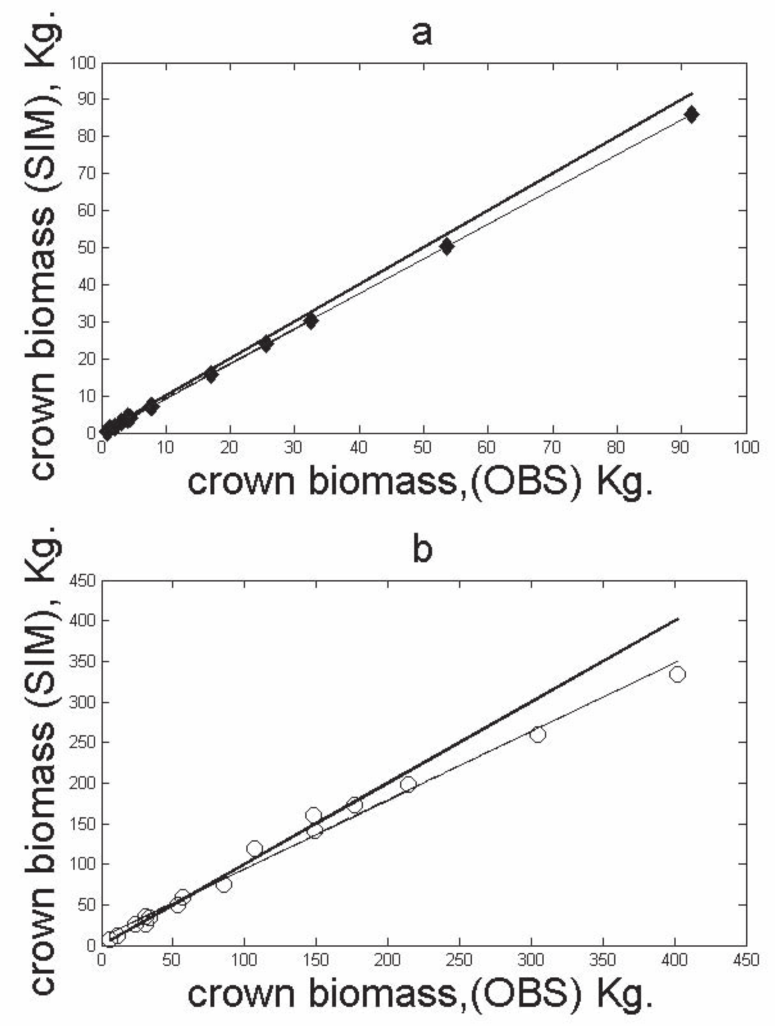

Figure 6—Comparison of measured total crown biomass (X axis) against crown biomass simulated with FUEL3-D (Y axis) for 16 trees used as independent "holdout" validation data from the Flagstaff site (a), and from the Ninemile site (b). Neither set of trees was used to construct modeled relationships. Solid lines in both figures represent the 1:1 line, while thinner lines are fit to the data. Correlations for fitted lines were 0.94 (a) and 0.98 (b), but slopes less than 1.0 show that modeled relationships underpredict biomass for larger trees in both sites.

Simulating Fire and Fuel Interactions—I demonstrate how detailed representations of fuel structure may provide insights to fire and fuel interactions with two related simulations using the physics-based fire model WFDS (Mell et al. 2005). The data used as inputs were similar to outputs from FUEL3-D, with values associated with individual 3-D cells, but were somewhat simplified as explicit connections between FUEL3-D and WFDS are still in development. The simulations were set up within a very small area similar to a wind tunnel in dimensions (8m long x 4 m wide x 4 m wide). For fire computations this area was divided into 64 x 32 x 32 cells, 0.125 m on a side. Within this small spatial domain I simulated a surface fuel bed 0.25 m in depth, 2 m wide and 6 m long, with fuel properties of excelsior (shredded aspen) and a constant moisture content of 6.3%. Three simulated trees were placed with the center of their stems at 2 m, 4.5 m and 6 m along the centerline of this fuel bed (Figure 7). WFDS represents trees and other

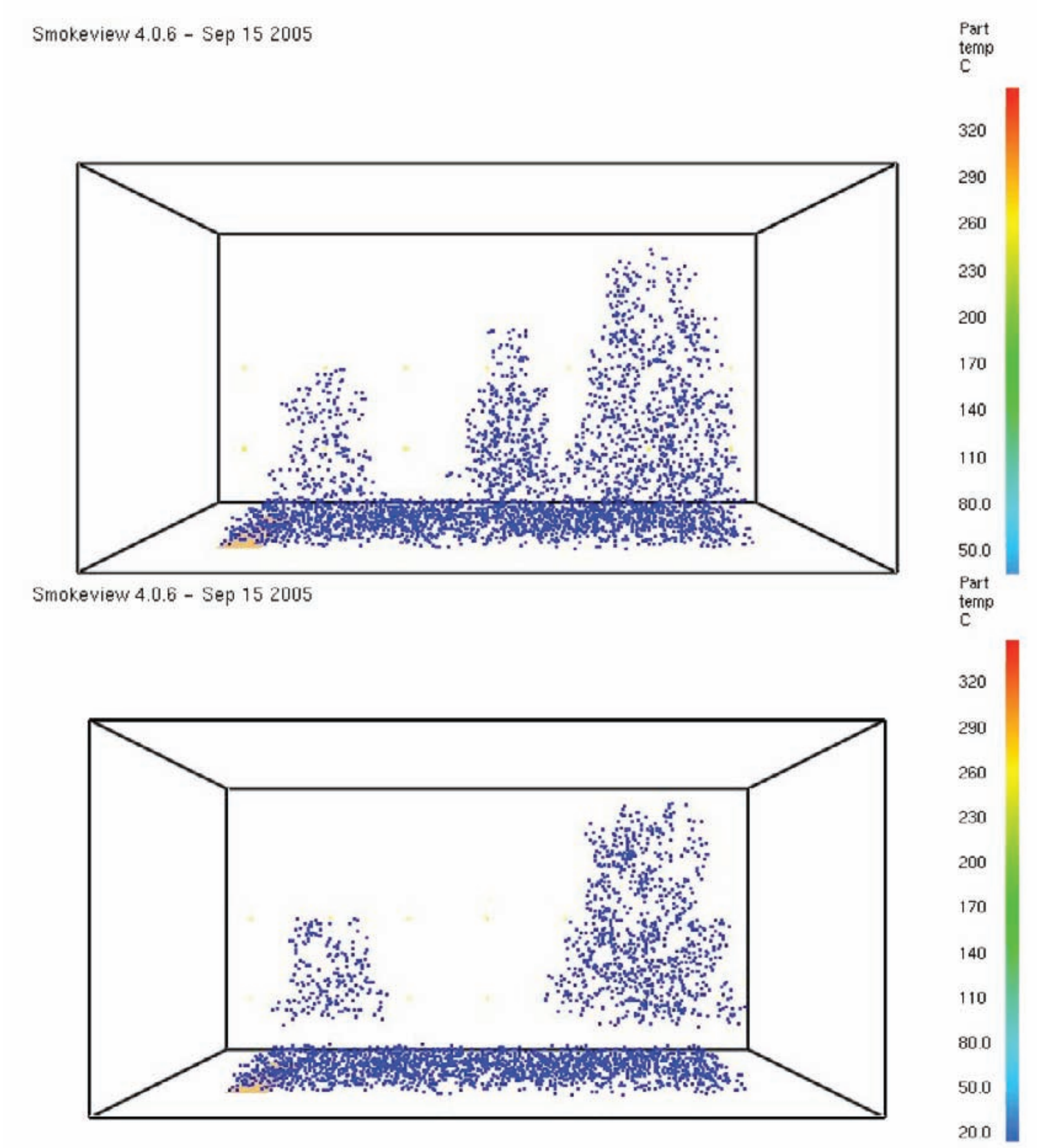

Figure 7—Comparison of two simulations with a numerical fire model, WFDS, and highly resolved at t = 0. Top figure shows "untreated" simulation with three small trees and a surface fuel bed in a wind tunnel. The outer trees are live, with high moistures and the middle tree is dead with low moisture, representing a recently bug-killed tree. Bottom figure shows the "treated" simulation in which the middle dead tree has been removed and lower branches have been pruned to 0.75 m.

elevated fuels as collections of thermally thin particles. Each tree was defined individually with a height, height to crown base, crown radius, and available fuel moisture content. To represent gaps within the crown, the crown for each tree was defined as frustum of a right circular cone. Within the volume of that cone, each cell was either assigned fuels or was empty depending on a random number. The first and third trees were parameterized as with more gaps, to represent more gappy, live trees while the middle tree was parameterized as less gappy and dead, with a much lower moisture content. An ignitor panel was simulated at the left edge of the fuel bed to start the fire. Winds were initialized at zero but were accelerated to a constant 1.5 m/s (3.4 mph) three seconds into the simulations. The first simulation used these fuels with no modifications and represents the "untreated" case. The second simulation represents an extremely simple fuel treatment, consisting of thinning (removal of the dead, middle tree) and branch pruning (removal of fuels in the two remaining trees below 0.75 m). Both simulations were run for a duration of 120 seconds. Graphical outputs from Smokeview, the companion software to WFDS used to visualize WFDS outputs for the two simulations for t = 0, 48, 60 and 72 seconds are shown in Figures 7-10. In these figures, the small particles represent the fuels, the lighter cloud-like structures represent flames (as isosurfaces of heat release rate per unit area, in KJ/m^2) and the darker cloud like structures represent soot density. These simulations were not intended to provide definitive scientific results, as the spatial domains are probably too small to eliminate artifacts arising from the proximity of the boundaries, but simply to illustrate potential applications of numerical fire behavior models in fuel treatment assessments.

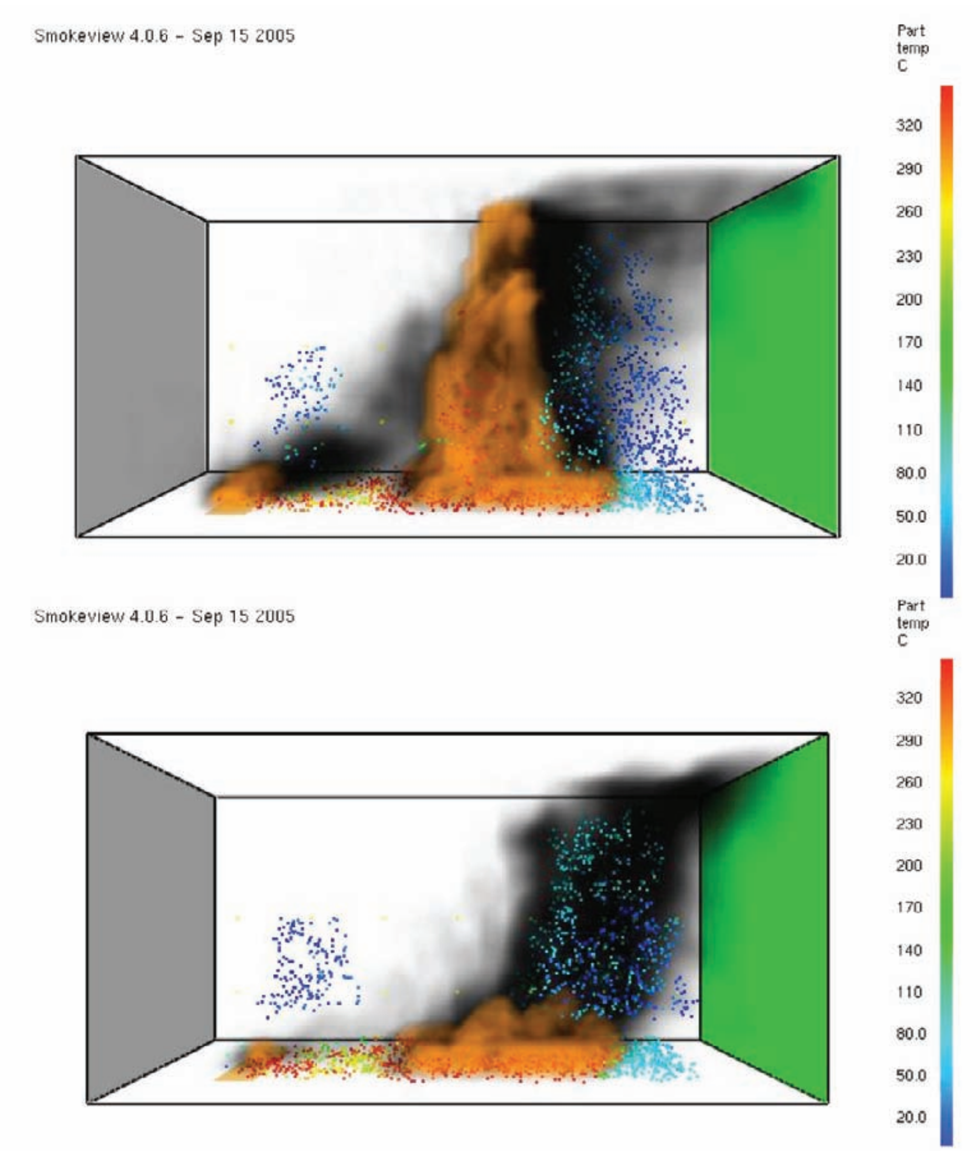

Figure 8—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 48 seconds. Surface fuels are burning in both simulations but the middle dead tree in the untreated simulation (top) is burning intensely.

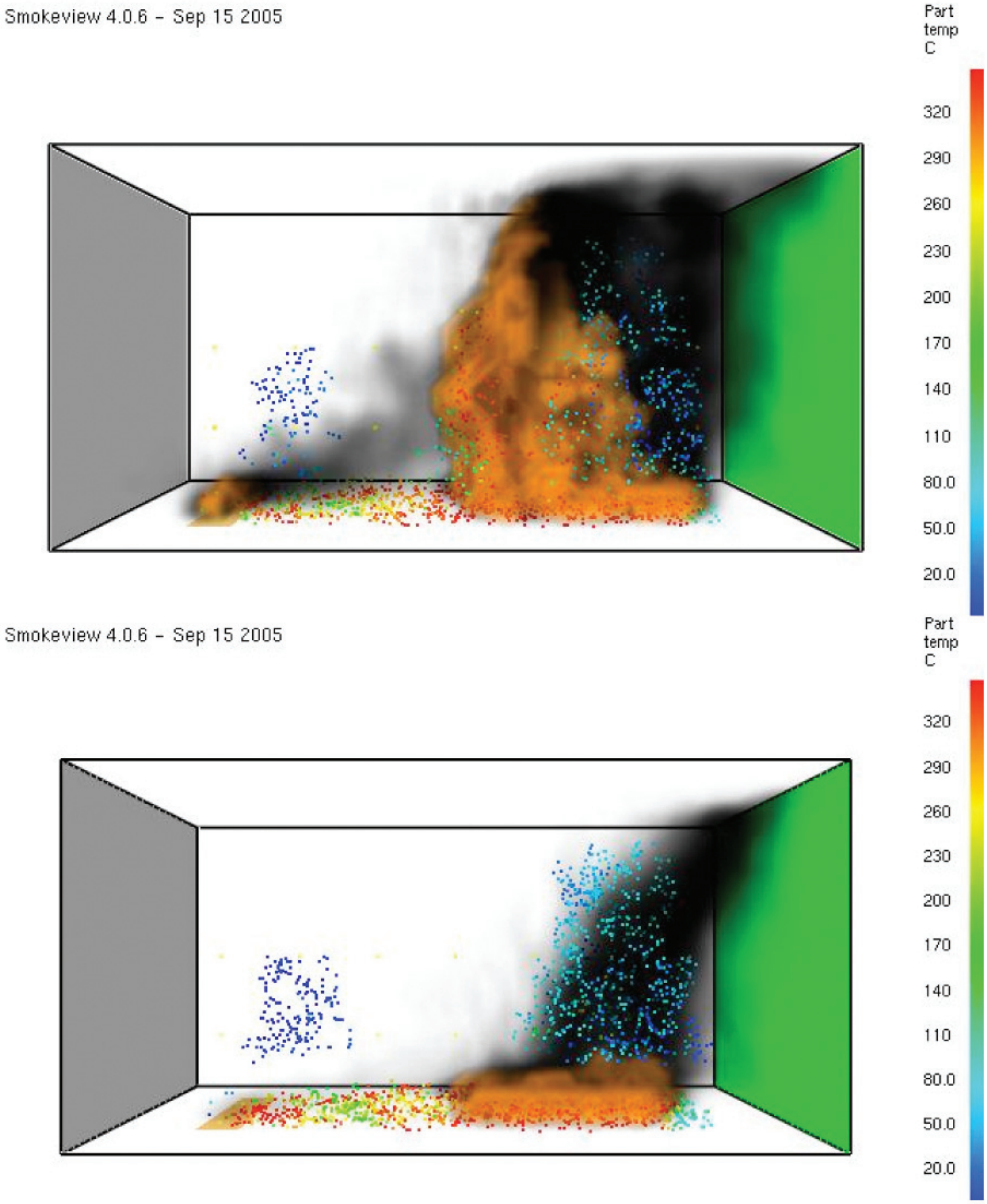

Figure 9—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 60 seconds. Surface fuels are burning in both simulations. Heat from the the middle dead tree in the untreated simulation (top), as well as from the surface fuels, has caused the tree at right to ignite. In the "treated" simulation (bottom) the tree at right is scorched from below but does not ignite.

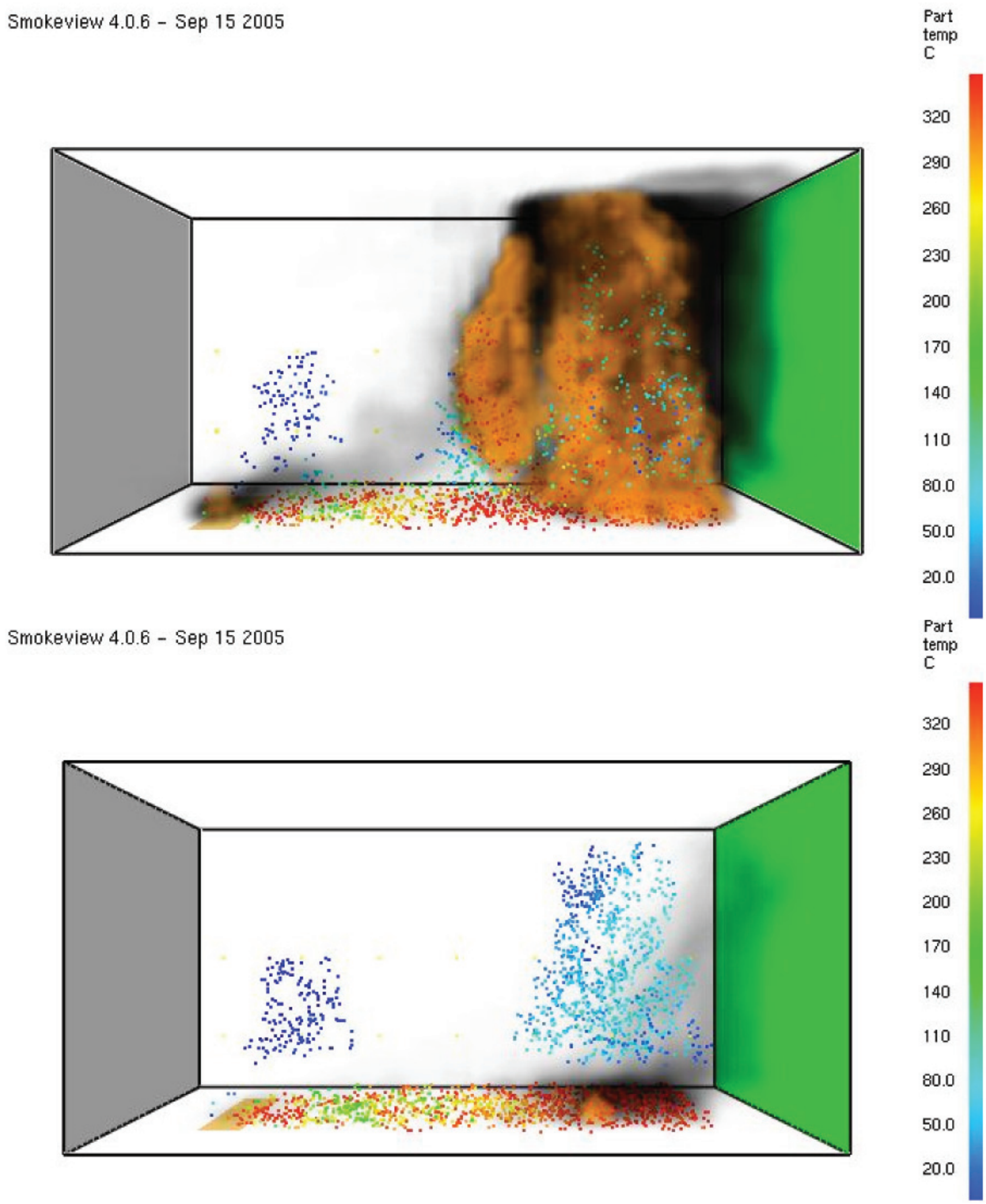

Figure 10—Demonstration of a numerical fire simulation with the Wildland Urban Interface Fire Dynamics Simulator (WFDS), and highly resolved fuels at t = 72 seconds. Surface fuels are burning in both simulations. Heat from the the middle dead tree in the untreated simulation (top), as well as from the surface fuels, has caused the tree at right to ignite, and it continues to burn intensely. In the "treated" simulation (bottom) the tree at right is scorched from below but does not ignite.

Simulating Canopy Shading—To demonstrate the application of fine scale spatial representation in assessing impacts to the microclimate I used ray tracing procedures (North 1996, Govaerts and Verstraete 1998, Brunner 1998) to simulate the shadows cast by a single tree modeled with FUEL3-D. The tree was parameterized with data from the Flagstaff field site but arbitrarily located in Missoula, Montana, at a point in space (Latitude 46.5 North, Longitude 114.0 degrees West, Missoula, Montana) and at two points in time 30 minutes apart (June 21, 2005, 14:20 and 14:50 local time) (Figures 11 and 12). Ray tracing is a spatially explicit approach for light modeling which samples beams of light between the light source (the sun) and a given object and thus is capable of representing shadows and other behaviors related to light with great detail, both in space and in time.

Figure 11—Visualization of a medium sized ponderosa pine tree modeled with FUEL3-D. The shadow of the tree, modeled with ray-tracing procedures, is shown at left.

Figure 12—Visualization of the same tree as in Figure 11 but 30 minutes later. The shadow of the tree, modeled with ray-tracing procedures, is shown at left, has moved slightly as the position of the sun changed.

Results

Field Data Analysis

Several relationships were identified from analysis of the field data (Table 1). Two sets of relationships are described: allometric relationships which relate easily measured quantities on a tree, such as DBH, to properties within the tree, such as the size class distribution of branches, and geometric relationships which describes properties and proportions. The size class distribution of individual branches on a tree, as a function of tree DBH, was positively skewed and fit well with the Weibull distribution as measured with the K-S statistic (Figure 2, Table 1). Branch biomass quantities were strongly related to branch basal diameter with power law relationships. These relationships provide the basis for the simulation of canopy structure of ponderosa pine trees.

Comparison/Validation

Biomass quantities simulated with FUEL3-D compared reasonably well with both validation data sets, with correlation coefficients of 0.94 for the independent holdout data for Flagstaff site and 0.98 for the Ninemile site data (Figure 6). Slopes of linear trend lines fit to the validation data were somewhat less than 1.0 (0.95 for Flagstaff and 0.86 for Ninemile), indicating that biomass quantities for larger trees might be underestimated. The Ninemile data consisted of generally larger trees, and a very different biophysical setting, so it is difficult to determine whether the underestimation observed for larger trees is purely a function of tree size or if it has some interaction with differences between sites.

Numerical Fire Simulations

The two simulations illustrate how spatial relationships within the fuel bed can result in differences in fire behavior. The two simulations had identical environmental conditions (wind speeds and fuel moistures) but removal of the center dead tree and elimination of lower branches on the remaining trees (Figure 7) resulted in differences in fire behavior between the two simulations. Figures 7-10 show the progression of the two simulations at t = 0, 48, 60 and 72 seconds, respectively. At t = 48 (Figure 8) the center tree in the untreated simulation (top) is engulfed in flame while in the treated simulation, the fire is confined to the surface fuels. At t = 60 (Figure 9), flames are moving into the crown of the large tree at right in the untreated simulation (top); at t = 72 that tree is actively flaming throughout the crown (Figure 10). At these points in time in the treated simulation the fire is burning underneath the crown of the rightmost tree but does not ascend into the crown.

Simulating Crown Shading—Visualizations at two points in time 30 minutes apart (Figures 11 and 12) show the detail with which individual trees and their shadows can be modeled. In full sun conditions, shadows from trees significantly reduce the direct solar radiation received at a shaded point on the ground. Direct solar radiation is a key driver of dead fine fuel moisture, raising the fuel temperature, heating the boundary layer and accelerating evaporation (Nelson 2002). Modeling shadows from individual trees may thus be applied to assess spatial variability in surface fuel moistures and changes in such patterns arising from fuel treatments.

Discussion

The models which form the basis of our current operational capacity to assess fuel treatments, namely, the fire behavior model BEHAVE (Rothermel 1972) and the stand growth model PROGNOSIS (Stage 1973), were developed at a time when many processes in combustion science and plant growth were poorly understood, and when both computational resources, and the data which could be used as inputs to predictive models were limited. Advances in computing resources, information technology and geospatial applications such as GPS, GIS and remote sensing change the nature of what is possible in assessing fuel treatments. New sensors such as LIDAR make it possible to measure individual tree stems and branch heights (Henning and Radtke 2006), individual crown diameters (Popescu et al. 2003) and estimate other stand characteristics (Nelson et al. 1988). The continuing development of such technologies suggests that detailed modeling of fire and fuels will only become more accessible to the wildland fire community as time goes on.

The FUEL3-D model is still in development and should be viewed as a work in progress. The same holds true, to a lesser degree, for the numerical fire models themselves which represent a rapidly advancing but still emerging field in fire science. Continuing development of the FUEL3-D model will provide avenues by which important knowledge gaps regarding wildland fuel properties, microclimate-fuel dynamics, fire-fuel interactions and fire effects can be addressed. Although the model is currently more appropriate for research use, a management appropriate configuration will be developed as soon as the underlying structure of the model is sufficiently mature.

The ability to represent the spatial structure of vegetation in detail across a range of scales will facilitate improvements in our understanding of fundamental fuels science. Fuel beds can be constructed describing any configuration of trees and shrubs of any size. By building fuel beds from individual trees and shrubs (and associated surface fuels), loss of relevant detail and scale-dependencies associated with fuel classifications is avoided (Sandberg et al. 2001). At present there is no way that fundamental wildland fuel properties, such as surface area to volume ratio, the size distribution of particles or distribution of mass within a tree crown, can be easily calculated. With FUEL3-D these quantities can be calculated from the simulated structure, tested and calibrated. The flexibility with which FUEL3-D can represent the architecture of trees and shrubs makes it possible to develop species-specific fuel models. Differences in crown architecture between species likely play key roles in how fire burns through a stand and how that stand responds to fuel treatment over time. This provides stronger linkages between silviculture, ecosystem function and fuel management such that fuel treatments can be considered not only in terms of their potential impacts on fire behavior but also on other ecosystem components.

Detailed modeling of wildland fuels in space improves in our ability to assess changes in microclimate arising from fuel treatments, as well as to better understand the complexities of natural stands. A large number of spatially explicit light models have been developed (see Brunner 1998) but the majority of these focus on plant growth and thus do not consider fluctuations in solar radiation at temporal scales finer than a few weeks, as this tends to be the limit at which plant growth can be modeled (Brunner 1998). In fire and fuels applications such time scales are likely too coarse to capture much of the important dynamics, particularly with respect to dead fine fuel moisture, which exhibit significant sensitivity to solar radiation over short time periods (Nelson 2002). Current FUEL3-D research inquiries in this arena are directed at linking a ray tracing procedure to a dynamic fuel moisture model (Nelson 2002) in space. This will enable spatially and temporally explicit modeling of surface fuel moisture dynamics which can be used to quantitatively compare fuel treatments. Such detailed modeling will also likely also be of use in modeling shrub and grass growth response over time, a factor important to the effective duration of fuel treatments.

By quantitatively describing fuels at higher detail, FUEL3-D will promote an improved understanding of fire and fuels interactions. In conjunction with numerical fire behavior models such as FIRETEC or WFDS it will be possible to more precisely study transitions from surface to crown fire and develop species-specific thinning spacing guidelines. Analyses across scales will help to systematically identify conditions when greater complexity in modeling is required, and simpler conditions in which it is not. Correlative relationships observed through more intense numerical studies may be used to refine existing operational models. One advantage of FUEL3-D is its independence from any specific fire behavior model and its assumptions and limitations. At present the model is being designed to work with two numerical fire models, FIRETEC (Linn et al. 2002) and WFDS (Mell et al. 2005). As other models appear or as these models change FUEL3-D will be able to provide the needed inputs. The independence of the fuel model from particular fire behavior models provides flexibility and facilitates comparisons between models.

Finally, modeling fuel-fire interactions at fine scales will aid in a tighter coupling between fire behavior and fire effects. Most fire effects calculations are carried out as point calculations, where fuel consumption at a point or mortality of an individual tree are considered (Reinhardt et al. 2001). At present it is difficult to rectify the homogeneous stand-based fire behavior calculations from operational fire behavior models with point level fire effects predictions. Incorporation of finer detail in representation of fuels with FUEL3-D, and detailed spatially explicit fire behavior models will provide a basis for linkages between fire behavior, fuels and fire effects than has been possible before. This will improve our ability to define burn window prescriptions and anticipate the consequences of treatments or wildfire.

Acknowledgments

The author wishes to thank Elizabeth Reinhardt, Joe Scott, Jim Reardon, and Bob Keane for use of the crown fuels study data and their helpful insights into that remarkable study. Fire modelers Rod Linn, William Mell and Mark Finney provided much helpful discussion. Field crews at the Fire Sciences Lab in Missoula, Montana played a key role in gathering the data used in this project.

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FuelCalc: A Method for Estimating Fuel Characteristics

Elizabeth Reinhardt[1], Duncan Lutes[2], and Joe Scott[2]

Abstract*—This paper describes the FuelCalc computer program. FuelCalc is a tool to compute surface and canopy fuel loads and characteristics from inventory data, to support fuel treatment decisions by simulating effects of a wide range of silvicultural treatments on surface fuels and canopy fuels, and to provide linkages to stand visualization, fire behavior and fire effects programs that rely on estimates of fuel loads and qualities.*

Canopy fuel characteristics, including available fuel, canopy bulk density, canopy base height and canopy cover are estimated from a list of trees.

Key words*: canopy bulk density, canopy base height, wildland fuel, crown fire, fire behavior, biomass, stand table*

Introduction

Fuel treatment is mandated by the need to protect communities and municipal watersheds and manage ecosystems. Analysis to support fuel treatment decisions is required by the National Environmental Policy Act of 1969. In order to use the best available fire science in comparing fuel treatment alternatives, managers need access to high-quality fuel information, as well as the impact of fuel treatment alternatives on wildland fuels, fire behavior, fire effects, and fuel hazard. The most fundamental fuels information is, however, surprisingly hard to come by. We receive frequent requests for help from fuels managers who want to know simply: how can inventory data be converted to fuel quantities and qualities? Surface fuel loads, fire behavior fuel models, and canopy fuel characteristics are needed to model fire behavior, fire effects, smoke production, and to analyze fuel treatment alternatives. Managers need the ability to determine how these fuel quantities and qualities will change when treatments are applied to stands.

Site-specific, inventory-based data greatly strengthens the scientific foundation of fuel treatment decisions. Currently, although a variety of fuel analysis tools exist, it is quite daunting to perform these analyses with raw inventory data. There is a need for a simple, user-friendly, nationally applicable fuel analysis tool that accepts inventory data, allows users to simulate effects of silvicultural treatments on surface and canopy fuels, and provides linkages to other software for further analysis of fire behavior and fire effects in these fuels.

The FuelCalc computer program is a tool to meet these information needs. This tool, currently under development with support from the Joint Fire

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Science Program and the USDA Forest Service Rocky Mountain Research Station, will support fuel management decision-making directly and also provide input to a number of other analysis tools. This paper describes the sampling methods supported by FuelCalc, and the calculation procedures it uses to convert inventory data to estimates of fuel characteristics. It describes linkages and prescription development support provided by FuelCalc. Parts of FuelCalc, for example the canopy fuel calculations, are currently available in draft form, others are still in the design phase.

Fuel Strata in FuelCalc

Ground Fuels

Duff load information is critical in smoke management, soil heating, carbon balance, and site productivity applications. FuelCalc will include a method for estimating duff load based on a measurement of duff depth. Duff depth is multiplied by duff bulk density to estimate duff load. Duff bulk density can be entered or default values used based on cover type.

Surface Fuels

Surface fuel inventory may take a number of forms. FuelCalc will provide estimates from data collected using Brown's (1974) planar intercept method, Burgan and Rothermel's (1984) fuel sampling procedures, and Hardy's (1996) slash pile inventory method, as well as direct entry of fuel loads as estimated from photo-guides or other data sources. Crosswalks will be provided to standard fire behavior fuel models, and a first-cut custom fire behavior fuel model developed.

Planar intercept — Brown (1974) developed procedures for sampling down woody fuels by counting intercepts across a sampling plane by particles of different size classes. This is a well established method of inventorying woody fuels; FuelCalc contains procedures to convert this data to estimates of fuel loading.

Burgan and Rothermel — Burgan and Rothermel (1984) published a simple, effective method of inventorying surface fuel. The method relies on the relationship between fuel depth, load and bulk density. Field inventory requires estimates of depth and cover by life form, and the assignment of bulk density by comparison with photos. These inventory methods are supported in FuelCalc.

Hardy slash pile inventory — Hardy (1996) published guidelines for estimating biomass contained in slash piles. FuelCalc allows entry of pile shape and dimension, packing ratio and wood density, and uses these guidelines to estimate slash biomass.

Linkages to fire behavior fuel models — FuelCalc will provide a "best guess" standard fire behavior model (Scott and Burgan 2005) that seems to represent the sampled fuels.

Creation of custom fire behavior fuel models — FuelCalc will also provide a first cut custom fire behavior fuel model suitable for testing with BehavePlus (Andrews and Bevins 2003) or Nexus (Scott 1999).

Canopy Fuels

Van Wagner (1977) proposed a theoretical model suggesting that crown fire initiation is dependent on surface fire intensity and canopy base height, while sustained crown fire spread is dependent on crown fire rate of spread and canopy bulk density. His work has been further developed by Alexander (1988), Agee (1996), Scott and Reinhardt (2001), and Van Wagner (1993) and is incorporated in the Canadian Fire Behavior Prediction System (Forestry Canada 1992), FARSITE (Finney 1998), and NEXUS (Scott 1999).

Fire managers need estimates of canopy base height and canopy bulk density to use these fire models. The LANDFIRE program (Rollins, in prep.) has committed to mapping these variables at a 30 meter resolution for the continental U.S. In addition, land managers have a growing concern that crown fire activity may be increasing in some forest types due, in part, to fire suppression and resultant changes in stand structure. Assessing these changes in stand structure requires defining and consistently evaluating canopy fuel characteristics.

A rich body of literature exists quantifying tree crown and forest canopy characteristics for purposes other than fuel characterization. A number of studies exist that predict foliar and branch biomass from tree dimensions, typically diameter, sometimes in combination with height, crown ratio or sapwood thickness. Brown (1978) provides predictive equations for the common conifer tree species of the Inland West; Snell and Brown (1980), provide similar methods for Pacific Northwest conifers. A large number of allometric equations of this type from many research studies are summarized in the computer software BIOPAK (Means and others 1994). These equations, together with a list of trees representing a stand, may be used to estimate total foliar biomass, as well as biomass of branchwood of various sizes.

Canopy bulk density is the weight of available canopy fuel per unit volume of canopy space. It is a bulk property of the stand, not an individual tree. Estimates of total canopy biomass can be divided by canopy volume to estimate canopy bulk density. This method carries the implicit assumption that canopy biomass is distributed uniformly within the stand canopy. This assumption is unlikely to be true even in stands with very simple structures; multi-storied stands are likely even more poorly represented by this procedure.

Even canopy base height, a simple characteristic to measure on a single tree, is not well defined or easy to estimate for a stand. Neither the lowest crown base height in a stand nor the average crown base height is likely to be representative of the stand as a whole. In terms of its consequences to crown fire initiation, canopy base height can be defined as the lowest height above the ground at which there is sufficient canopy fuel to propagate fire vertically through the canopy. Using this definition, ladder fuels such as lichen, moss and dead branches can be incorporated. Sando and Wick (1972) suggested describing the canopy fuels by plotting the vertical distribution of available canopy fuel in thin (1-foot) vertical layers (figure 1). Canopy base height can then be computed as the height above the ground at which some critical bulk density is reached. Their method could also be used to define effective canopy bulk density. Scott and Reinhardt (2001) used the Sando and Wick approach in combination with Brown's (1978) equations to estimate canopy base height and canopy bulk density. Canopy base height was defined as the lowest height above which at least 100 lbs/acre/vertical foot of available canopy fuels was present. Canopy bulk density was defined as the maximum of a 15-foot deep running mean of canopy bulk density for one-foot deep vertical layers. This method has been incorporated into the Fire and Fuels

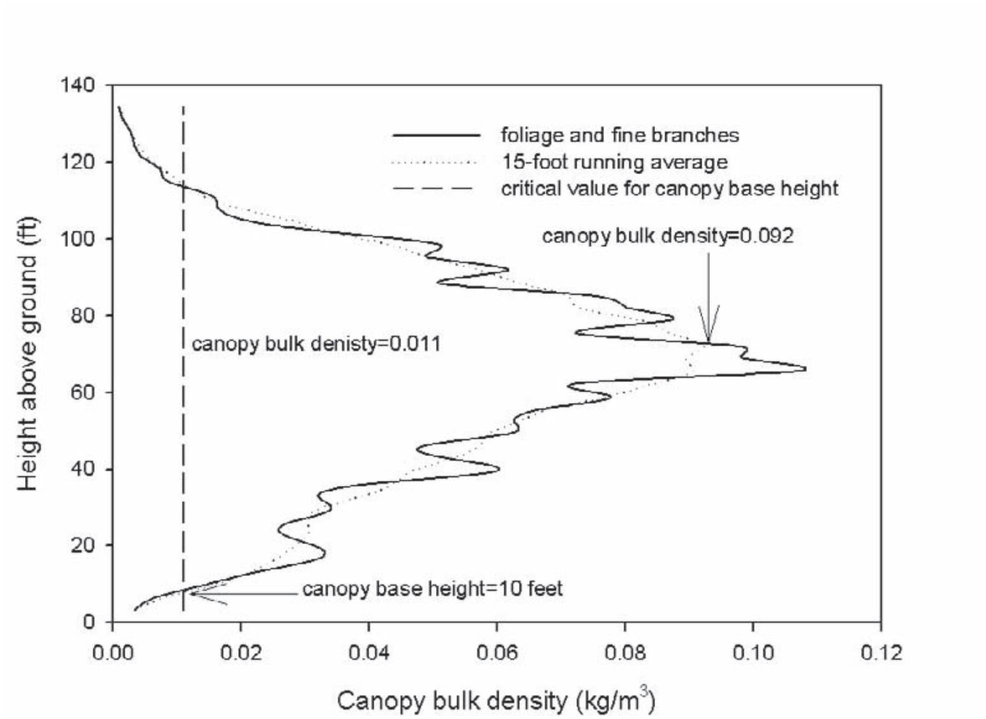

Figure 1—Vertical distribution of available canopy fuel as computed from a tree list using FuelCalc methods. Canopy bulk density is the maximum of the running mean. Canopy base height is the lowest point at which the running mean exceeds 0.012 kg/m^3, while stand height is the highest such point.

Extension to the Forest Vegetation Simulator (FFE-FVS, Reinhardt and Crookston 2003) and was validated by destructive sampling of forest canopies in five interior west conifer stands (Reinhardt and others, in prep.).

In FuelCalc we use this approach for computing canopy base height and canopy bulk density from a stand table or tree list. These methods have several advantages: 1. They do not require visual judgment calls or extensive interpretation that might result in inconsistent or subjective estimation, 2. They were developed with the underlying fire behavior models in mind, so the computed values are relevant in the context in which they will be used, 3. Because they are computed directly from a stand table or tree list they are derived using detailed information on stand structure, unlike methods based on image interpretation, 4. They can be performed quickly, using data sources that are widely available, so that values can easily be generated for thousands of stands.

Available canopy fuel load —Available canopy fuel load is assumed to be all the foliage and one-half of the 0-.25" branch material in the stand. We use Brown's (1978) equations for estimating the weight of foliage and small (0-1/4") branchwood for each tree from species and diameter. For some species no estimates of these components are available. In that case we use other published equations for total foliage biomass or crown biomass, if available, and crosswalk the proportions to Brown's equations. If no foliage or crown biomass equations of any kind are available, we crosswalk the species to a similar species that has published biomass relationships. These estimates are further adjusted to account for crown class (dominant, co-dominant, intermediate, suppressed) using adjustment factors developed in our canopy fuels field study (Gray and Reinhardt 2003). Trees less than 6 feet tall are excluded from the analysis, however, trees over 6 feet tall can contribute crown weight from branches less than 6 feet off the ground.

Canopy bulk density — Canopy base height is calculated by distributing the available crown fuel from each tree between its crown base and its top. The fuel is distributed vertically using regression equations developed from our destructively sampled data from 600 trees. These equations vary by species, but more biomass occurs higher in the crown. Fuel is summed in 1 foot height increments for all the trees in the stand. We smooth this profile with a 15-foot deep running mean, and define canopy bulk density as the maximum of this running mean.

Canopy base height — Canopy base height is computed in FuelCalc as the lowest point at which the running mean exceeds .012 kg/m^3 (33 lbs/acre/foot). This value, like Sando and Wick's 100 lbs/acre/foot, is arbitrary and not based on any kind of combustion physics, but it seems to perform well.

Stand height — Stand height is calculated in a way analogous to canopy base height, using the maximum height within the canopy at which canopy bulk density exceeds 0.012 kg/m^3.

Canopy cover — Canopy cover is estimated from the sum of the areas of individual tree crowns. Individual crown widths are computed from tree diameter (Moeur 1981). Following Crookston and Stage (1999), and assuming the crowns are randomly distributed within a stand, percent cover = $100(1-e^{-\text{totalcrownarea}/43560})$.

FuelCalc Linkages

FuelCalc is intended to make data management and analysis easy for managers by automating linkages to other software (figure 3).

FIREMON Database

For users who wish to store their data in a database, FuelCalc is linked to the FIREMON database (Lutes and others 2006). FIREMON provides a whole suite of statistical analysis tools. Similarly, FIREMON users will have the entire capability of FuelCalc available to them as an analysis tool, capable of reading data directly from the database.

SVS

The Stand Visualization System or SVS (McGaughey 1997) produces graphic representation of stands from tree list data (figure 2). These graphics are very helpful both for managers and even more importantly, for the public in assessing thinning treatments. FuelCalc will format data for use with SVS.

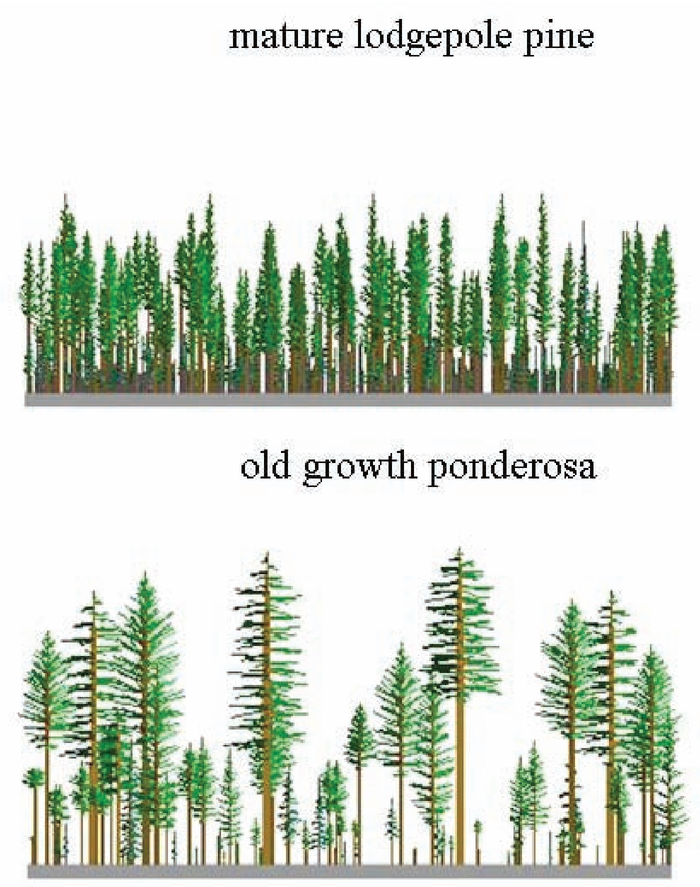

Figure 2—Examples of SVS (McGaughey, 1997) outputs.

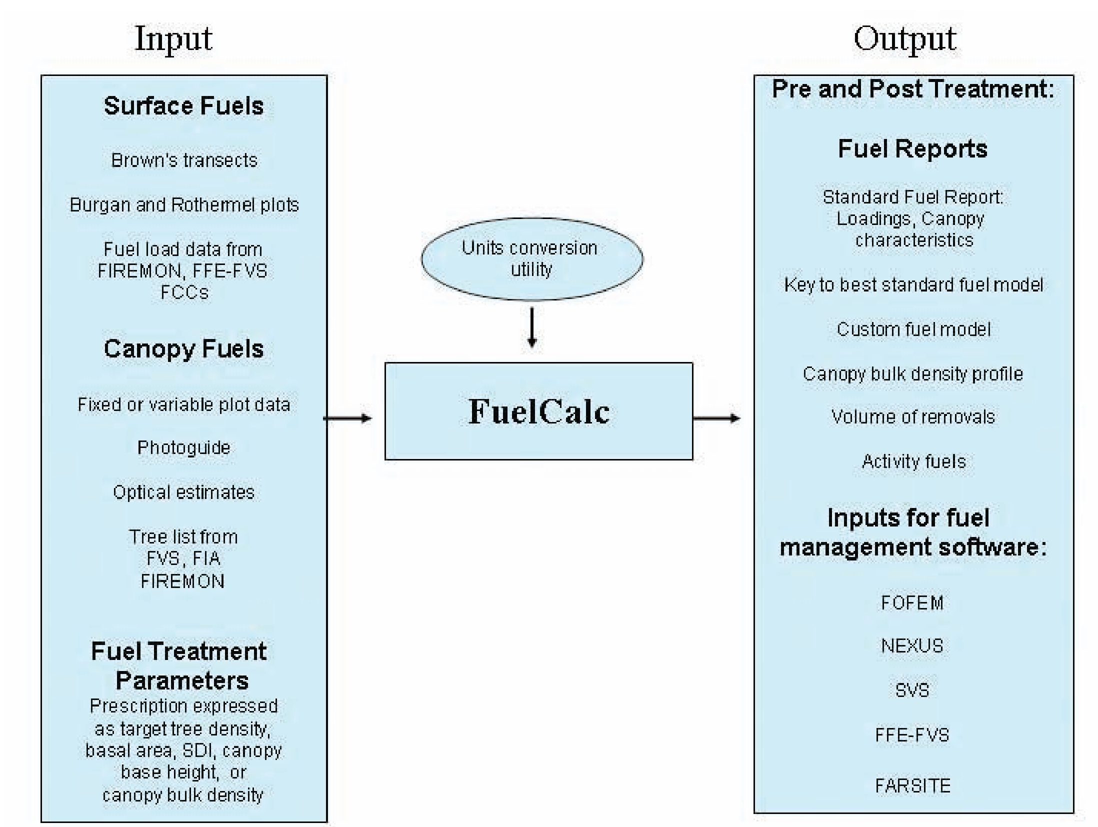

Figure 3—FuelCalc linkages.

FOFEM

FOFEM: a First Order Fire Effects Model (Reinhardt and others 1997, Reinhardt 2003) predicts tree mortality, fuel consumption, soil heating and smoke production from prescribed fire and wildfire. FOFEM requires as input exactly the kind of data that FuelCalc manages. FOFEM is widely used for NEPA documentation as well as smoke regulation. FOFEM will be fully integrated with FuelCalc so that as fuel treatment alternatives are developed within FuelCalc, FOFEM is invoked to assess impacts of those treatments on expected fire effects.

Nexus

Nexus (Scott 1999) is a fire behavior prediction system as well as a crown fire hazard assessment tool. It computes torching and crowning indices (Scott and Reinhardt 2001), as well as the full suite of fire behavior outputs including rate of spread, fireline intensity, and reaction intensity. Torching and crowning indices are windspeeds at which torching and active crowning can be expected to occur in a given fuel complex. Lower values indicate fuels that are more prone to crown fire behavior, i.e., crown fire can be expected at lower windspeeds. Torching and crowning indices vary as canopy and surface fuels are altered, thus they are useful indicators of crown fire hazard and of fuel treatment success. Nexus, like FOFEM, will be fully integrated with FuelCalc, so that as fuel treatment alternatives are developed in FuelCalc, expected changes in fire behavior and crown fire hazard can be assessed.

FFE-FVS

FuelCalc will convert data into files suitable for use with the Fire and Fuels Extension to the Forest Vegetation Simulator: FFE-FVS (Reinhardt and Crookston 2003). FFE-FVS can then be used to simulate treatment effects on fuels, potential fire behavior and stand structure over time.

National Volume Estimator Library

When thinning treatments are simulated, FuelCalc will use the National Volume Estimator Library of equations maintained by the USDA Forest Service Forest Management Service Center (USDA Forest Service 1993) in order to estimate the amount of potentially merchantable material that may be generated by thinning treatments.

FuelCalc Features

Prescription Design and Assessment

FuelCalc will provide analytical tools for prescription development. A user will be allowed to specify criteria such as: thin from below to a residual canopy bulk density of 0.05 kg/m^3, or thin from below to a residual basal area of 100 sq ft/acre, and FuelCalc will identify the number, volume, and characteristics of trees to be removed, as well as compute the activity fuels that would be generated by such a thinning. This analysis will combine the work of the JFSP-funded Canopy Fuels Study (Reinhardt and others 1999) with earlier work by Brown and Johnston (1976), and the National Volume Estimator Library (U.S. Forest Service 1993).

Batch Mode for Linking with GIS

FuelCalc is designed as a stand level tool, however, a batch mode will be provided to link with GIS and landscape level applications. We have successfully used this approach in developing FOFEM and Nexus. The LANDFIRE program has been using the batch FuelCalc program to process data from 1000s of plots.

Library of Code for Incorporation in Other Software

FuelCalc code will be provided on request to other software developers, hopefully resulting in more consistent use of inventory data across agencies and for a variety of applications.

Acknowledgments

FuelCalc is being developed with the support of the Joint Fire Sciences Program, the USFS Rocky Mountain Research Station, and Systems for Environmental Management. Thanks to Larry Gangi for computer programming, and Russ Parsons and Kathy Gray for manuscript reviews.

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Accuracy and Precision of Two Indirect Methods for Estimating Canopy Fuels

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Abstract*—We compared the accuracy and precision of digital hemispherical photography and the LI-COR LAI-2000 plant canopy analyzer as predictors of canopy fuels. We collected data on 12 plots in western Montana under a variety of lighting and sky conditions, and used a variety of processing methods to compute estimates. Repeated measurements from each method displayed considerable variability, but hemispherical photography proved to be the more precise method. To evaluate the accuracy of the different methods, we correlated measurements with allometrically derived estimates of canopy bulk density and available canopy fuel. Measurements from both methods were more highly correlated with available canopy fuel than canopy bulk density. Hemispherical photography emerged as the superior methodology, displaying greater precision and accuracy, at least when measurements must be collected under sub-par lighting conditions.*

In order to assess the potential risk of crown fires, accurate estimates of canopy fuel loads are needed. Direct met hods for measuring these loads are often difficult and time consuming, involving destructive sampling of the forest canopy or, alternatively, detailed allometric measurements on individual trees. As a result, indirect methods are being used increasingly to exploit the relationship between the amount of biomass in the forest canopy and the amount of light that gets transmitted to the forest floor. By measuring the relative amount of light reaching the forest floor, canopy fuels can be estimated indirectly.

This paper examines two indirect methods for measuring canopy fuels, the LI-COR LAI-2000 and hemispherical photography. Both of these methods have been used extensively to measure leaf area index (LAI), and are much less time consuming than direct methods (see Jonckheere and others 2004, or Chen and others 1997, for reviews of different methods for estimating LAI). Defined as the one sided leaf area per unit ground area, LAI is used frequently as a measure of canopy structure, and LAI has also been correlated with important metrics of canopy fuels loads, for example canopy bulk density (Keane and others, 2005). Thus these indirect methods could potentially provide an efficient method for estimating canopy fuel loads.

However, because these indirect methods rely on light transmittance, the resulting estimates can be highly sensitive to the ambient lighting conditions. Ideally measurements should be taken only at dawn or dusk with the sun below the horizon. Less ideally, data can also be collected under uniformly cloudy skies. In the former case, data collection is limited to only a few hours each day, while in the latter, data collection hinges on weather conditions. In practice these constraints may be too prohibitive, greatly limiting the time available for data collection. As a result they are often disregarded, and data are collected under a wide variety of lighting and sky conditions.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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In this paper, we evaluate the accuracy and precision of these two indirect methods with measurements taken under a variety of less than ideal lighting conditions. Using repeated measurements from 12 sites, we evaluate the precision of the estimates obtained using each method, and then compare these estimates with two allometrically derived metrics of canopy fuel loads: canopy bulk density (CBD) and available canopy fuel (ACF).

Background and Theory

Hemispherical photography and the LAI-2000 present different ways to measure the *gap fraction* in a stand: the proportion of sky visible under the canopy. With digital hemispherical photography, a digital camera with a fish eye lens is used to take a photograph of the canopy from which the gap fraction is computed. Usually this is accomplished by converting the color photograph to a black and white image: a threshold is chosen and all pixels darker than the threshold are declared to be not-sky and painted black, while all those brighter than the threshold are declared sky and painted white. The gap fraction is then equivalent to the proportion of white pixels in the image. Hemispherical photography requires little specialized equipment, simply a tripod, a digital camera, a fish eye lens, and software for processing the images.

The LAI-2000, on the other hand, is a specially produced piece of equipment for measuring LAI (LI-COR 1992). It consists of a light sensor mounted on a wand that is attached to an electronic control box. To compute gap fractions, the LAI-2000 needs to take two measurements of light intensity with the light sensor. The first measurement is taken above the forest canopy under open sky (usually in a clearing) while the second is taken below the canopy. The gap fraction is then computed by taking the ratio of these two measurements. Both measurements must be taken with the light sensor leveled and facing the same compass direction.

There is extensive theory detailing the relationship between gap fractions, leaf area index, and other canopy structure statistics (Welles and Norman 1991). Briefly, in an idealized homogenous full cover forest stand with small, randomly distributed foliage, the Beer Lambert law can be used to compute leaf are index, L, from gap fraction measurements as

$$L = 2\int_0^{\pi/2} -\ln(G(\theta))\cos\theta\sin\theta d\theta. \quad (1)$$

Here θ denotes zenith angle and $G(\theta)$ is the gap fraction as a function of the zenith angle. In practice, this integral is usually approximated by dividing the continuous range of zenith angles $(0,\frac{\pi}{2})$ into a number of concentric rings or sectors. The gap fraction is measured at specific zenith angles (or over a range of zenith angles) and then L is given by a weighted sum,

$$L = 2\sum_{i=1}^{n} -\ln(G(\theta_i))W_i, \quad (2)$$

Where n is the number of zenith angles (or number of rings) used, and W_i is the weighting term. The light sensor on the LAI-2000 has 5 rings centered at zenith angles of 7, 23, 38, 53, and 68 degrees. With hemispherical photography the number of rings and their locations can be controlled by the experimenter.

The LAI estimates derived from Hemi-photos and the LAI-2000 are very sensitive to lighting conditions. Both methods are best used under certain restricted light conditions: before sunrise, after sunset, or, less preferably, under uniformly cloudy skies (LI-COR 1992; Pepper 1998; Frazer 2001). Direct sunlight in a hemispherical photograph often leads to lens flare, and brightly lit foliage can be mistakenly classified as sky when hemispherical photographs are converted to black and white images for analysis. Similarly direct sunlight can lower resulting estimates from the LAI-2000 by up to 40% because of sunflects (Welles and Norman 1991). In practice appropriate lighting conditions can be difficult to obtain, greatly limiting the time available for data collection. As a result, these constraints are often neglected, or less data is collected. In this study, we examine how collecting data under sub-optimal lighting conditions affects the precision and accuracy of the measurements obtained.

Materials and Methods

Study Area and Sampling Methodology

The study area, located in Lolo National Forest in western Montana, consisted of 11 sample units, each 13m in radius. Each sample unit was either homogenously Douglas-fir (*Pseudotseuga menziessi*) or homogenously ponderosa pine (*Pinus ponderosa*). The tree densities varied substantially between plots (table 1). Nine of the plots were on south aspects, and 2 were on north aspects (plot codes DF-N and PP-N). Two of the Douglas-fir plots were open grown (DF-O-1 and DF-O-1) and located several miles from the others, in an area with thinner soil and higher winds.

Height, diameter and crown ratio measurements were collected on each tree in the study units, and then these tree lists were used to compute stand level canopy fuel load and bulk density, using methods described in Reinhardt and others (this proceedings).

Table 1—Fuel characteristics of the plots used in the study. Plots beginning with DF are homogenously Douglas fir, whereas those beginning with PP are homogenously ponderosa pine. All plots are circular with a radius of 13 m.

Plots					
Index	Plot Code	Canopy Bulk Density (Kg/m^3)	Available Canopy Fuel (Tons/Acre)	Canopy Cover (%)	Tree per acre
1	DF-2	0.0801	5.587	48.68	137
2	DF-3	0.1290	5.444	46.32	107
3	DF-4	0.2752	9.567	68.40	244
4	DF-N	0.0633	3.718	35.13	84
5	DF-0-1	0.0122	0.891	9.27	8
6	DF-0-2	0.0703	3.518	33.90	84
7	PP-1	0.0895	2.239	37.18	274
8	PP-2	0.0922	2.533	39.21	305
9	PP-3	0.0244	0.508	9.73	53
10	PP-4	0.1082	2.750	42.06	290
11	PP-N	0.0848	4.127	42.87	198

Hemispherical photographs and readings with the LI-COR LAI-2000 were collected in early September 2004. Data were collected under a variety of lighting and sky conditions, and in total measurements were taken 12 times with each instrument on each sample area.

A Nikon Coolpix 9000 digital camera with a fisheye lens was used for taking hemispherical photographs. The camera was attached to a leveled tripod and aligned so that the camera body pointed north. On each visit to a plot, two photographs were taken sequentially: one with proper exposure as determined by the camera's automatic metering and one underexposed by two f-stops. All photographs were taken using the highest resolution setting.

Two LICOR LAI-2000 units were used to obtain the above and below canopy measurements. The first unit was set up in a centrally located clearing, leveled, aligned to the North, and automatically logged above canopy readings every 30 seconds. The other unit was used to record the below canopy readings, and on each visit to a plot two below-canopy readings were taken immediately after the hemispherical photographs. The wand on the below canopy unit was leveled and aligned to the north for each measurement. Each LAI-2000 unit used a 90° view cap.

Data Processing

To compute gap fractions for the LAI-2000, we individually matched each below canopy reading with the above canopy reading that was closest in time, and computed gap fractions at each of the five zenith angles. Computing gap fractions for the hemispherical photographs was more complicated, as the color photographs first had to be converted to black and white images. Usually this is accomplished by choosing a threshold and coloring all pixels darker than the threshold black (vegetation) and all others white (sky). However, under uneven lighting conditions this approach can result in substantial misclassifications because foliage near the sun appears brighter than the sky far from the sun.

Instead, we used a two-stage supervised clustering algorithm to convert the color photographs to black and white images. The algorithm is an example of a commonly used iso-clustering algorithm from the image processing literature (Richards 1996), and was implemented in ARC-GIS. Briefly, the algorithm uses an automated procedure to assign each pixel in the image to one of a user-specified number of bins, based on the color and brightness attributes of the pixels in the image. In the first stage of processing, the photograph was divided into ten bins and the user was then prompted to classify each bin as not-sky (black), sky (white), or unknown (red). Often a single bin contained both vegetation and sky, and these bins were classified as unknown in the first stage. Any pixels classified as unknown during the first stage were then further subdivided into seven bins for a second stage of classification. The result was a black and white image with generally more fine detail than was obtainable using the traditional single threshold approach.

The resulting black and white images were then input into the commercial software HemiView for analysis. HemiView divides each image into a user-specified number of concentric circles (rings) of equal width, corresponding to different zenith angles, and then computes the average gap fraction in each ring. To facilitate comparison with estimates from the LAI-2000, five rings were used, centered at zenith angles of 9, 27, 45, 63, and 81 degrees. Note that the zenith angles from the two techniques are different, since the rings in the LAI-2000 are of unequal width.

There are potentially many ways to combine the individual gap fractions at each zenith angle into estimates of the overall LAI or fuel on a plot. The standard method is to compute LAI using all five zenith rings by taking a weighted sum of the logarithm of the gap fractions, i.e. equation 2. Not all rings need to be included in the sum however, and we also computed LAI values using different subsets of the zenith rings.

Moreover, it may be that the raw un-weighted gap fractions prove to be better indicators of canopy fuel loads. In this case the average gap fraction, $\bar{G}$, will be a useful statistic:

$$\bar{G} = \frac{1}{n}\sum_{i=1}^{n} G(\theta_i). \quad (3)$$

As with the LAI based statistics, this sum can be computed over different subsets of the zenith rings. In the following analysis, we utilized several different sets of zenith rings and computed predictions using both the raw gap fractions and the log transformed and weighted LAI as the predictive statistic (table 2).

Results

Comparing the Different Methods

We computed the mean, variance, and coefficient of variation (CV), for each method on each plot (table 3). The mean variance and CV per plot are both consistently larger for the LAI-2000 estimates than for the hemi-photo estimates. There is also a tendency for the CV and variance to increase as the number of rings used in the analysis is reduced. Note, however, that the estimates derived using only the 3rd ring do not conform to this pattern, suggesting that the number of rings is less important than the zenith angles of the rings used. Estimates derived using the smaller zenith angles exhibit more variation than do estimates derived from the larger angles.

Table 2—Factors in the analysis. Gap fractions were obtained with either the Licor unit or hemispherical photographs. Either the mean gap fraction or the log transformed and weighted leaf area index was used to derive predictions. The different analysis schemes used between and five zenith rings to derive predictions.

Methods	
Licor	LAI-2000 plant canopy analyzer
Hemi	Hemispherical photography
Statistics	
GF	Mean gap fraction (unweighted)
LAI	Leaf area index (weighted mean of the logarithm of individual gap fractions)
Analysis Scheme	
1	Only third zenith ring
2	Top two zenith rings
3	Top three zenith rings
5	All five zenith rings

Table 3—Summary statistics of the LAI estimates produced using different methods. The average variance and CV per plot represent the variance (CV) in measurements on each plot averaged across all the plots. Similarly the variance (CV) across plots denotes the variance (CV) in the mean value of the measurements for each plot. Note that these are the results using the LAI statistic.

Method	Mean	Average Variance Per Plot	Average CV Per Plot	Variance Across Plots	CV Across Plots
LAI-2000					
LAI-5	1.04	0.18	0.46	0.16	0.38
LAI-3	1.13	0.32	0.71	0.37	0.54
LAI-2	0.90	0.33	1.05	0.52	0.80
LAI-1	1.33	0.56	0.70	0.42	0.49
Hemi					
LAI-5	1.80	0.04	0.09	0.33	0.32
LAI-3	1.69	0.09	0.15	0.52	0.43
LAI-2	1.55	0.13	0.19	0.88	0.61
LAI-1	1.82	0.08	0.14	0.33	0.32

For the hemi-photos, the variance and CV across plots is substantially larger than the average variance and CV per plot, suggesting that the method can consistently distinguish between some of the plots. However, the LAI-2000 readings have roughly similar variances between and across plots, and the CV across plots is actually smaller than the average CV per plot. The mean estimates of LAI from the LAI-2000 are consistently lower than those from the hemi-photos for all of the different ring choices. Also, the mean estimated LAI values from the hemi-photos decrease as the rings with larger zenith angles are removed from the analysis.

To examine the correlation between the LAI-2000 estimates and the hemi-photo estimates, we computed simple correlation coefficients for each pair of estimates (table 4). The correlation between the LAI-2000 and hemi-photo estimates increases as the rings with the larger zenith angles are excluded from the analysis. Measurements were most correlated when only the top two zenith rings were used.

Table 4—Correlation coefficients between the hemi-photo and Licor LAI values.

	Licor LAI-2000			
Hemi-Photo	LAI-5	LAI-3	LAI-2	LAI-1
LAI-5	0.561	0.618	0.673	0.429
LAI-3	0.602	0.659	0.667	0.499
LAI-2	0.594	0.683	0.717	0.496
LAI-1	0.560	0.570	0.543	0.459

Relationship with Allometric Data

For all processing methods, we computed regressions using both available canopy fuel (ACF) and canopy bulk density (CBD) as computed from the stand data as response variables. We tested three different regression models. The simplest, the reduced model, used only the measured LAI or GF statistic as a predictor variable, but the other two regressions incorporated additional predictor variables. The second regression model introduced tree type (Douglas fir or Ponderosa pine) into the reduced model as a categorical predictor variable, including an interaction term. This approach is justified due to the homogenous nature of the stands in the study and the common use of species specific clumping factors for modifying LAI estimates (White and others 1998). Finally the third regression model further added canopy base height as an additional predictor variable. Canopy base height is defined as the average height within a stand from the ground to the canopy bottom. While more difficult to assess than tree type, canopy base height can be measured or estimated relatively easily.

To simply the presentation, we use R^2 values to measure goodness of fit (figure 1). For each of the two instruments there were two possible statistics (GF or LAI), four analysis schemes, two response variables, and three types of regression models, for a total of 2x2x4x2x3 = 96 different regression models.

Several clear patterns emerge from figure 1. The reduced regression model, using a single predictor, performs uniformly poorly for both instruments and both predictor variables. The third regression model, which includes canopy base height, performs substantially better than the other two, especially for hemispherical photography with CBD as the response variable. For all of the

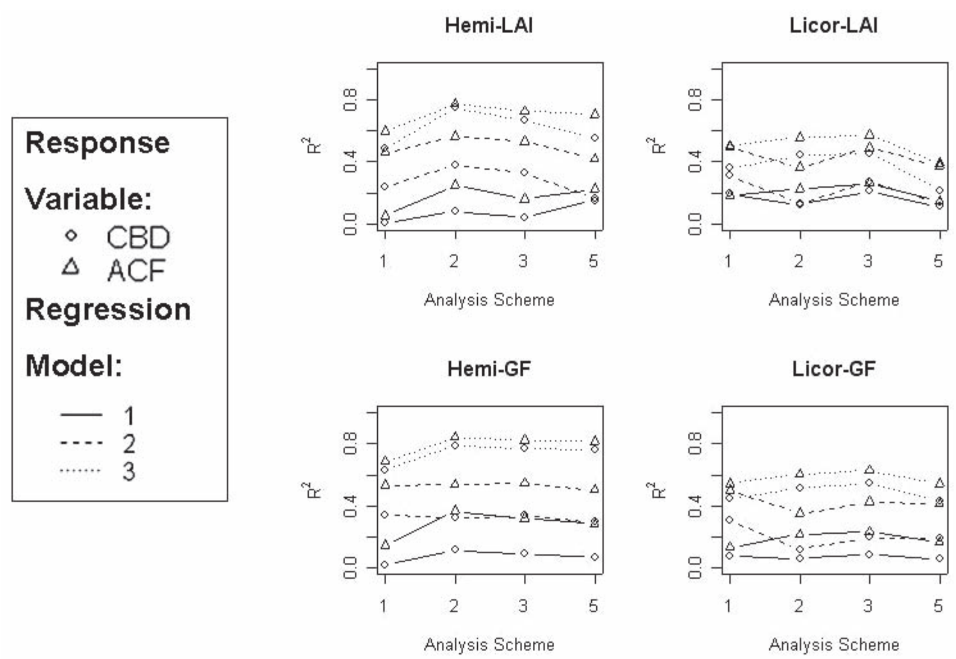

Figure 1—R^2 values from the different regressions. The x-axis shows the number of zenith rings used to derive predictions. Regression model 1 (solid lines) is the reduced model, model 2 (dashed lines) includes tree type as a predictor, and model 3 (dotted lines) also includes canopy base height. Results are shown with available canopy fuel (ACF) or canopy bulk density (CBD) as the response variable.

regression models, the fit was better using ACF as the response variable than it was with CBD as the response variable. The LAI-2000 estimates derived using only the third ring (analysis scheme 1), as well as those derived using the top 3 rings (analysis scheme 3), produced the best fits for both CBD and ACF. Conversely, the hemi-photo estimates derived using the top two rings consistently had the largest R^2 values, although only marginally larger than those derived using the top 3 rings. For the hemi-photos, correlations generally increase as the zenith angles increase, but for the LAI-2000 correlations appear to peak around the third zenith angle. Overall, there appears to be little overall difference in performance between the estimates produced using LAI and those produced using average GF.

With the simplest regression model, the hemi-photos and LAI-2000 both performed similarly. In the more complex regression models, however, the hemi-photo results were clearly dominant, with consistently larger R^2 values than the corresponding LAI-2000 based estimates. This suggests that hemi-photo based estimates of CBD and ACF are more accurate.

Discussion and Conclusions

As is clear from table 2, the hemi-photo measurements are more precise than the LAI-2000 measurements, with substantially smaller variances and CVs on each plot. The hemi-photos also provided more accurate measures of canopy fuels, as indicated by the R^2 values from the regressions against CBD and ACF.

The number of rings used in the analysis had a somewhat significant impact on the accuracy of the different estimates (table 4). The tendency towards increased accuracy with reduced zenith angles may be due to the relatively small size (13m radius) of the plots used. In any case, as the zenith angles used for analysis decreased, the CV of the measurements on each plot tended to increase. Taken together these results suggest that accuracy can be increased, at least on smaller plots, by only using the smaller zenith angles, but at the cost of decreasing the precision of the measurements.

The lower precision of the LAI-2000 estimates is not surprising: the LAI-2000 is not intended to derive estimates from individual measurements. Indeed, part of the attraction of using the LAI-2000 is the ease of taking repeated measurements on a single plot. Whereas repeated measures using hemi-photos require analyzing each photograph individually, the LAI-2000 can automatically combine repeated measures into a single estimate. Thus the lower precision of individual measurements is offset by the ease of repeating measurements. The large processing time needed to derive estimates from the hemi-photos, and the relative ease of incorporating multiple measurements into a single estimate using the LAI-2000, makes the LAI-2000 more competitive than the preceding analysis might suggest. Nonetheless, this analysis demonstrates that the hemi-photo method is preferable from the standpoint of both accuracy and precision. If the processing of the hemi-photos could be completely automated, the processing time would be more comparable for the two methods, and the hemi-photo methodology would be more clearly preferable.

Surprisingly the hemi-photos provided decent measures of canopy fuels despite the variety of less than ideal lighting and sky conditions under which the photographs were taken. In this study we used a very labor intensive processing methodology that allowed for more detailed black and white photographs even under poor lighting conditions such as direct sunlight. Apparently more labor intensive processing in the lab was able to compensate for less than ideal sampling conditions in the field. Hemispherical photography thus has the potential to reduce the labor, time, and environmental constraints in the field, in exchange for more time and labor spent in the lab.

Acknowledgments

This work was supported by the USDA Forest Service Rocky Mountain Research Station and Systems for Environmental Management. We appreciate Kathy Gray's assistance with estimation of canopy fuel characteristics.

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Mapping Fuels on the Okanogan and Wenatchee National Forests

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Abstract—*Resource managers need spatially explicit fuels data to manage fire hazard and evaluate the ecological effects of wildland fires and fuel treatments. For this study, fuels were mapped on the Okanogan and Wenatchee National Forests (OWNF) using a rule-based method and the Fuels Characteristic Classification System (FCCS). The FCCS classifies fuels based on their combustion properties, producing unique "fuel beds," each of which represents a distinct fire environment. Managers on the OWNF identified 187 fuel beds which were consolidated into 40 general fuel beds representing the major vegetation forms (forest vs. non-forest) and species groups. Fuel beds were assigned to each 25-m cell in the forest domain (27,353,425 cells) using decision rules based on a combination of spatial data layers. General fuel beds can then be subdivided into specific structural types using spatial data on canopy cover, quadratic mean diameter, and past disturbances (fires, insects, and management). This rule-based approach allows for the incorporation of more specific data if available or a more general classification if they are unavailable, and for reclassification when new data become available. Key uses of the fuels map include spatially explicit modeling of fire effects and assessment of spatial patterns of fire hazard under different management strategies.*

Introduction

Fuel mapping is a complex and often multi-disciplinary process, potentially involving remote sensing, ground-based validation, statistical modeling, and knowledge-based systems (Huff et al. 1995; Burgan et al. 1998; Keane et al. 2000, 2001; Rollins et al. 2004). There are strengths and weaknesses of each technique, and a combination of methods is often the best strategy (Keane et al. 2001). The scale and resolution of fuel mapping efforts depend both on objectives and availability of spatial data layers. For example, input layers for mechanistic fire behavior and effects models must have as high resolution (≤ 30 m) as possible (Keane and Finney 2003).

Because of the time and effort required for ground-based measurements and the intrinsic variability of fuel loads, even at fine scales, estimation of fuel loadings across broad extents must rely on indirect methods. For example, Ohmann and Gregory (2002) built stand-level models of vegetation, including fuel loads, from inventory plots, satellite imagery, and biophysical variables, and used nearest-neighbor imputation to assign them to unsampled plots (cells). Keane et al. (2000) used satellite imagery, terrain modeling, and simulation models to develop predictions of biophysical setting, vegetation cover, and structural stage, from which they assigned each cell a fire behavior fuel model (Anderson 1982). Both these efforts are *model-based* classifications.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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At broader scales, or where no ground data are available, fuel-mapping relies mainly on classifications of remotely sensed imagery and existing spatial data (for example, Burgan et al. 1998). *Knowledge-based* classifications (Schmoldt and Rauscher 1996) are often appropriate when there are multiple uncertainties associated with scaling predictive models (Rastetter et al. 1992, McKenzie et al. 1996). *Rule-based* classifications are knowledge-based methods that invoke a rule set: a collection of inferences that can be qualitative, or numerical, or both (Puccia and Levins 1985, Schmoldt and Rauscher 1996).

The choice between rule-based and model-based classifications involves trade-offs. Model-based methods provide quantitative estimates of variance and uncertainty whereas rule-based methods only provide qualitative estimates. A poor quantitative model is generally less useful than a qualitative model, (Puccia and Levins 1985, Schmoldt and Rauscher 1996, Schmoldt et al. 1999), so mapping efforts for which quantitative models perform poorly or cannot be validated are good candidates for rule-based methods.

Ecosystems are dynamic and fuel loadings change with succession, in response to climatic variability, or after disturbance. Quantitative fuel maps can become obsolete rather quickly. In order to keep fuel maps current so that they will retain their value for users, methods are needed to update fuel layers efficiently as landscapes change. An advantage to rule-based mapping is that new data layers can be incorporated efficiently because rules only need to be built for new attributes. In contrast, bringing updated data layers into model-based mapping requires entirely new models because relationships between response and predictor variables will change.

In this paper, we demonstrate the use of FCCS for fuel mapping on the Okanogan (ONF) and Wenatchee National Forests (WNF) at 25-m resolution. We focus on the process of assigning a unique *fuel bed* (Riccardi et al., in review) to each mapped cell in a spatial data layer and show how the classification scheme in FCCS, based on dominant vegetation, facilitates the use of existing GIS layers in developing classification rules and ongoing updates of fuel bed maps as new GIS layers become available. We briefly discuss how assigning actual fuel loads to cells can proceed. Finally, we discuss applications of FCCS-based fuel maps for both modeling and management.

Methods

Study Area

The Okanogan (690,400 ha.) and Wenatchee National Forests (890,000 ha.) are in north central Washington State extending from the crest of the Cascade Range eastward to savanna-steppe and agricultural lands. Near the crest topography is extremely rugged, with deep and steep-sided valleys. Climate is intermediate between the maritime climate west of the Cascade Crest and the continental climate east of the Rocky Mountains. The Okanogan highlands portion of the ONF lies further east and topography there differs from the western portion by having more moderate slopes and broad rounded summits. Conifer species dominate, notably subalpine fir (*Abies lasiocarpa*) and mountain hemlock (*Tsuga mertensiana*), at higher elevations and ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) at lower elevations.

Spatial Data Layers

We used GIS layers developed from a variety of sources and archived by the ONF and WNF. We selected the best available (highest level of local manager confidence) spatial data layers for each forest so techniques and methods differed based on the layers chosen. ArcGIS 9.0 (ESRI 2005) was used for all GIS computations.

For the WNF we used a 25-m raster layer (R6) and a photo-interpreted polygon layer (WenVeg) of cover type. The R6 layer comprises 6 cover types from a direct classification of LANDSAT TM imagery and 9 forested cover types from an interpretation of the cover classes in terms of potential natural vegetation (Lillybridge et al. 1995). The WenVeg layer distinguishes 26 forest types, each of which has one or more structural or age classes associated with it. WenVeg polygons were classified from aerial photos, and range in size from less than 1 ha to 28,000 ha, but with only 18 polygons larger than 4,000 ha. Many polygons were validated by site visits or expert local knowledge of ecologists on individual forest districts. The R6 layer was converted to polygons, then overlain with the WenVeg layer. We created a new coverage of the combined polygons whose attribute table retained the attributes of the original layers.

For the ONF we used a 30-m resolution raster layer of modeled hierarchical potential vegetation consisting of 10 vegetation zones (VZ) subdivided into 42 plant association groups (PAG), and a 25-m resolution raster layer of 36 cover types classified from LANDSAT TM imagery (USU 1997). Forest managers on the ONF conducted an accuracy assessment of the USU LANDSAT TM imagery and reclassifications were done when necessary (K. Davis, personal communication, 2006). The 30-m resolution PAG layer was resampled to 25-m and the resampled PAG layer and the USU layer were overlain and combined to create a new raster layer of all possible combinations of PAG and USU cover types.

Fuel Bed Development

Forest managers from the ONF and WNF collaboratively designed 187 fuel beds with distinct species composition, stand structure, and disturbance histories. We aggregated these into 35 general fuel beds based on forest composition, within which one or more structural or age classes could be distinguished (for example, table 1). Additional spatial data on disturbance history, canopy cover, and stand structure can be used to distinguish the 187 specific fuel beds (see Discussion).

Table 1—Sub-categories of a generic fuel bed (Douglas-fir, moist grand fir) on the Okanogan and Wenatchee National Forests based on structure, age class, and disturbance.

Fuel bed ID	Age range (yrs)	Structure	Change agent
OW020	0-30	Created opening	Wildfire
OW021	30-60	Seedlings & saplings	Pre-commercial thin
OW022	30-60	Seedlings & saplings, high density & load.	None
OW023	60-90	Poles	Selection cut and burn
OW024	60-90	Poles	None
OW025	90-200	Multi-layer	Selection cut & burn
OW026	90-200	Multi-layer, high density & load.	None
OW027	Over 200	Layered mature, medium density & load.	None
OW028	Over 200	Layered mature, high density & load.	None
OW029	Over 200	Open parkland, low density & load.	None
OW030	Over 200	Open parkland, medium density & load.	None

We used 1,490 plots from the USFS Pacific Northwest Region Current Vegetation Survey (CVS) on ONF and WNF to determine if the designated fuel beds adequately represented the likely species combinations. Some species and species combinations were poorly represented by the original 35 general fuel beds, so we added 5 general fuel beds. A limiting factor of using available spatial data is that some species are difficult to map due to the resolution of the data layers. For example, the initial list included fuel beds dominated by both whitebark pine (*Pinus albicaulis*) and subalpine larch (*Larix lyallii*), but the spatial layers lumped these species into one high-elevation parkland classification, so we added a corresponding high-elevation parkland fuel bed.

Fuel Bed Assignment

We assigned a fuel bed to each 25-m cell in the forest layers using a rule-based approach that incorporated the GIS layers for each national forest. The overarching criterion for the WNF was that the fuel bed assignment first had to be consistent with the WenVeg layer, because this was the one in whose accuracy local managers had the most confidence. Because WenVeg does not distinguish species composition as finely as the general fuel beds, however, we used the R6 layer to narrow possibilities for dominant species. For each R6 cell within each WenVeg polygon, the most likely fuel bed was assigned. Figure 1 illustrates the logic for three distinct fuel bed assignments within

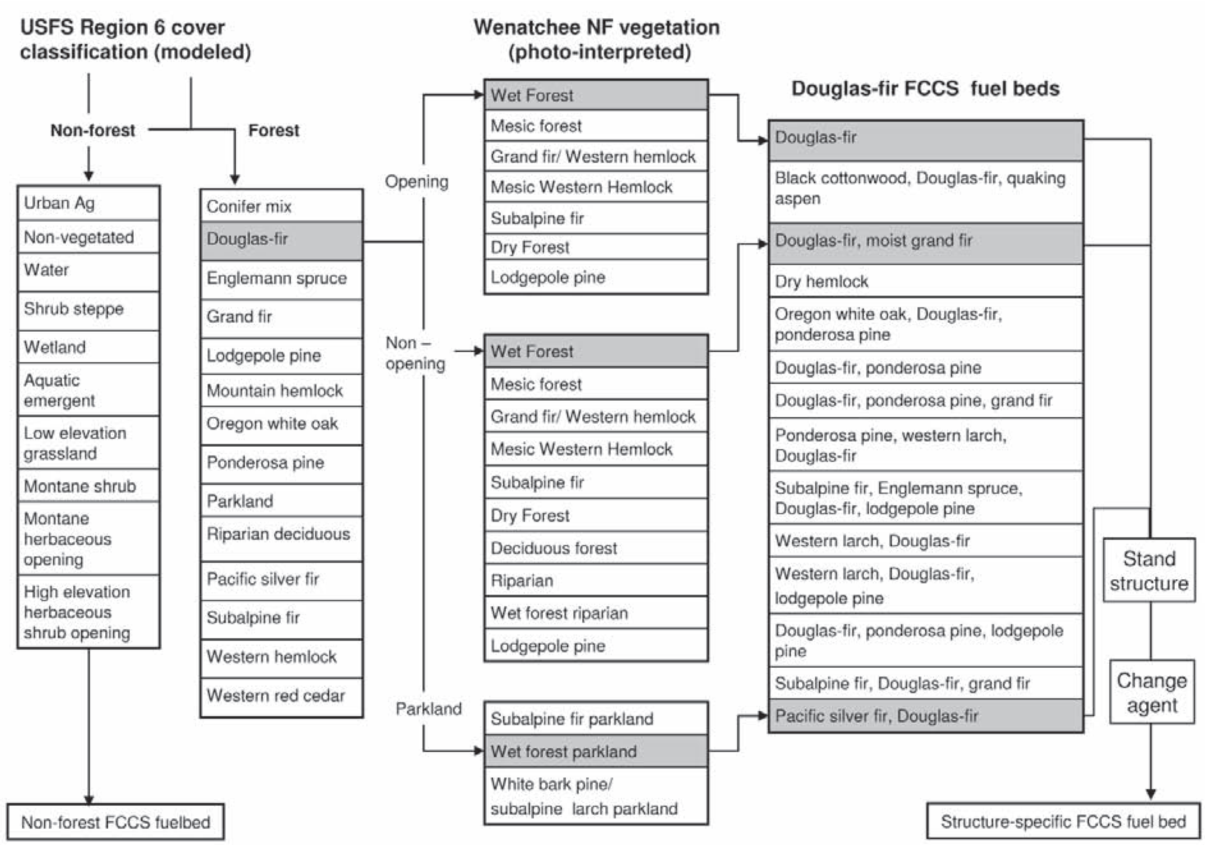

Figure 1—Example of logic for identifying a generic FCCS fuel bed for combinations of satellite-mapped vegetation and photo-interpreted vegetation on the Wenatchee National Forest.

the cover class "Douglas-fir" in the R6 layer, depending on the WenVeg polygon within which they fall. The LANDSAT-based cover type classification was the primary GIS layer used to assign fuel beds on the ONF because it was a measure of current vegetation for which an accuracy assessment was completed. If the cover type was not specific, it was further refined using the VZ, and if the cover type classification was common and coincided with many PAG, the PAG were also used to assign the most likely fuel bed. Figure 2 illustrates the logic for assigning fuel beds to the "Douglas-fir" LANDSAT-based cover type in the USU layer.

We used the CVS plots to validate the fuel bed assignments based on the remotely sensed data. The objective of this validation was to compare the frequency distribution of fuel beds represented in the spatial data layer with that of fuel beds represented by the CVS plots, not to match individual cells to individual plots. First we assigned a fuel bed to each of the CVS plots based on the relative tree species composition by basal area giving weight to the most dominant species and the presence of rare species. Each CVS plot is a cluster of five subplots in which trees were sampled in a 15.6 m radius circular plot (0.076 hectares). To compare fuel beds at a commensurate scale, only data from the center plot were used, which corresponded to one 25-m grid cell.

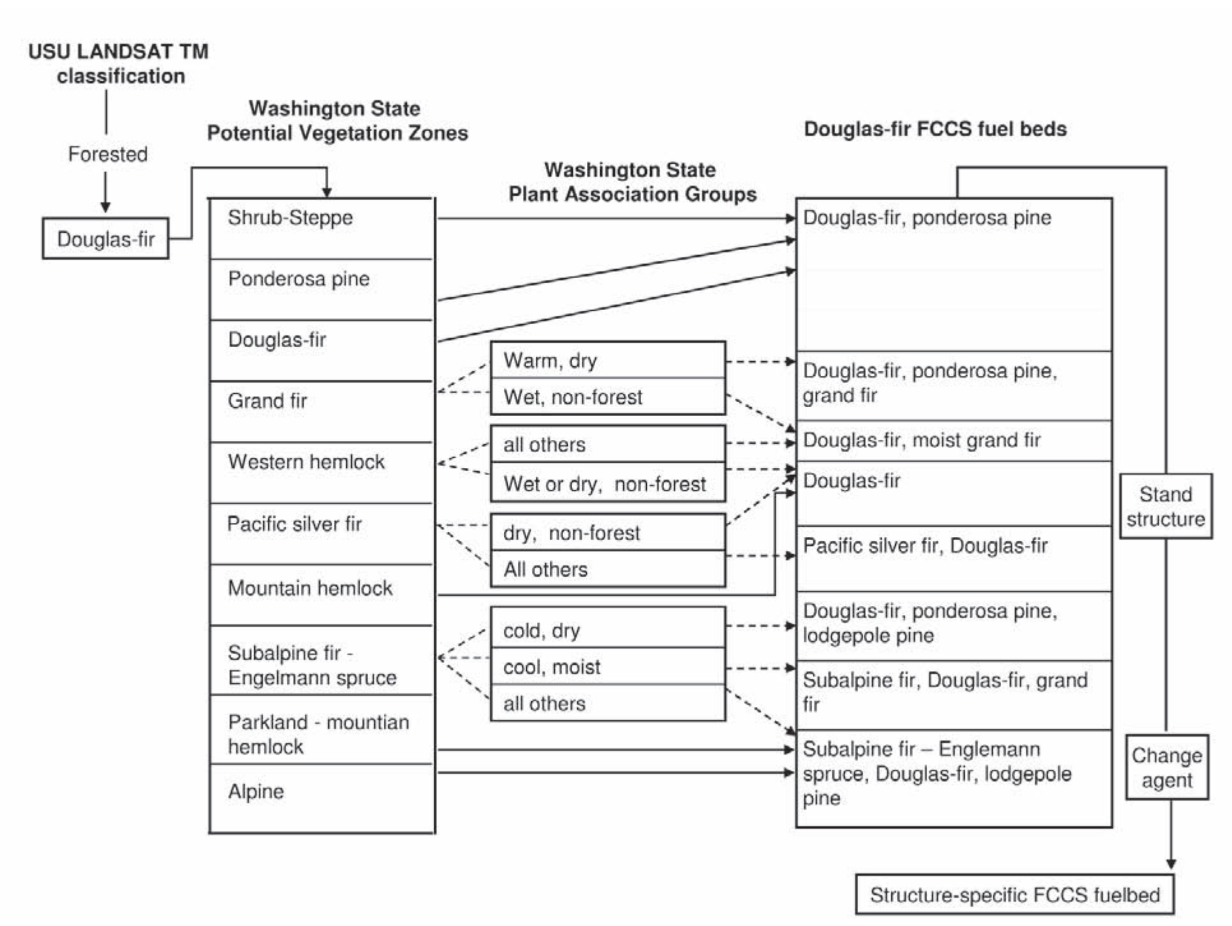

Figure 2—Example of logic for identifying a generic FCCS fuel bed for combinations of satellite-mapped vegetation and modeled potential vegetation on the Okanogan National Forest.

Results

The combination of 9 R6 modeled vegetation types and 6 LANDSAT-based cover types with 26 classes from the photo-interpreted WenVeg layer yielded 34 general fuel beds (figure 3) including 6 common (greater than 1,000,000 cells) and 5 rare (less than 10,000 cells) fuel beds (table 2). "Western hemlock, Pacific silver fir, mountain hemlock" was most prevalent, accounting for 14 percent of the mapped area (2,233,445 cells). The commonness reflects both the range of vegetation and the range of possible fuel bed choices. For example, fuel bed choices for the WNF included only two dominated by western hemlock and only one dominated by mountain hemlock, but five dominated by Douglas-fir. Five fuel beds with western larch or western white pine as a significant component were not mapped on the WNF due to the limited resolution of the original GIS layers. These species are problematic for the rule-based logic of assigning fuel beds on the WNF, because even when present, they rarely dominate stands or represent the climax species.

As would be expected, the rarest fuel beds reflect the species with more restricted ranges in the study area: Oregon white oak (*Quercus garryana*) and Engelmann spruce (*Picea Engelmannii*). The WNF map showed areas of greater homogeneity in the middle elevations on the west side of the forest where "Western hemlock, Pacific silver fir, mountain hemlock" and "Mountain hemlock, Pacific silver fir, subalpine fir" occur in large patches. In contrast, patterns in the lower elevations on the east side of the forest were more heterogeneous, a consequence of both more fuel bed options and a more patchy disturbance regime creating finer-scale spatial variability.

The combination of PAG and LANDSAT-based cover types yielded 36 fuel beds on the ONF (fig. 4)including 4 common (greater than 1,000,000 cells) and 6 rare (less than 10,000 cells) fuel beds (table 3). The most frequently occurring fuel bed was "Subalpine fir, Engelmann spruce, Douglas-fir, lodgepole pine" covering 16 percent of the area (1,776,623 cells). All fuel beds were mapped except the two Oregon white oak fuel beds because the area is beyond its range. The greater specificity of the LANDSAT-based cover type layer on the ONF better captured rare species such as Engelmann spruce, white bark pine, western larch, and western white pine. The greater frequency of these fuel beds reflects both the higher number of categories in the USU LANDSAT layer and the greater abundance of these species on the ONF. The pattern of fuel beds across the ONF domain distinguishes four general areas: (1) the western portion of the forest along the Cascade crest and west of the crest is dominated by the Mountain hemlock, silver fir, subalpine fir" fuel bed, (2) the north east is dominated my lodgepole pine fuel beds, (3) the south east is dominated by Douglas-fir and ponderosa pine fuel beds and (4) the Okanogan highlands is highly variable with the greatest fuel bed heterogeneity.

Validation

Validation of fuel beds on the WNF indicated a bias towards fuel beds composed of late seral species (for example, western hemlock, Pacific silver fir, mountain hemlock) and dry forest fuel beds were under-represented (for example, Douglas-fir, ponderosa pine, grand fir) (figure 5). This was not entirely unexpected as one of the spatial data layers was partially developed from modeled potential vegetation. To adjust for this bias, we revisited each classification rule, under the assumption that a systematic shift towards the early seral species in the R6 plant associations would correct the bias. However,

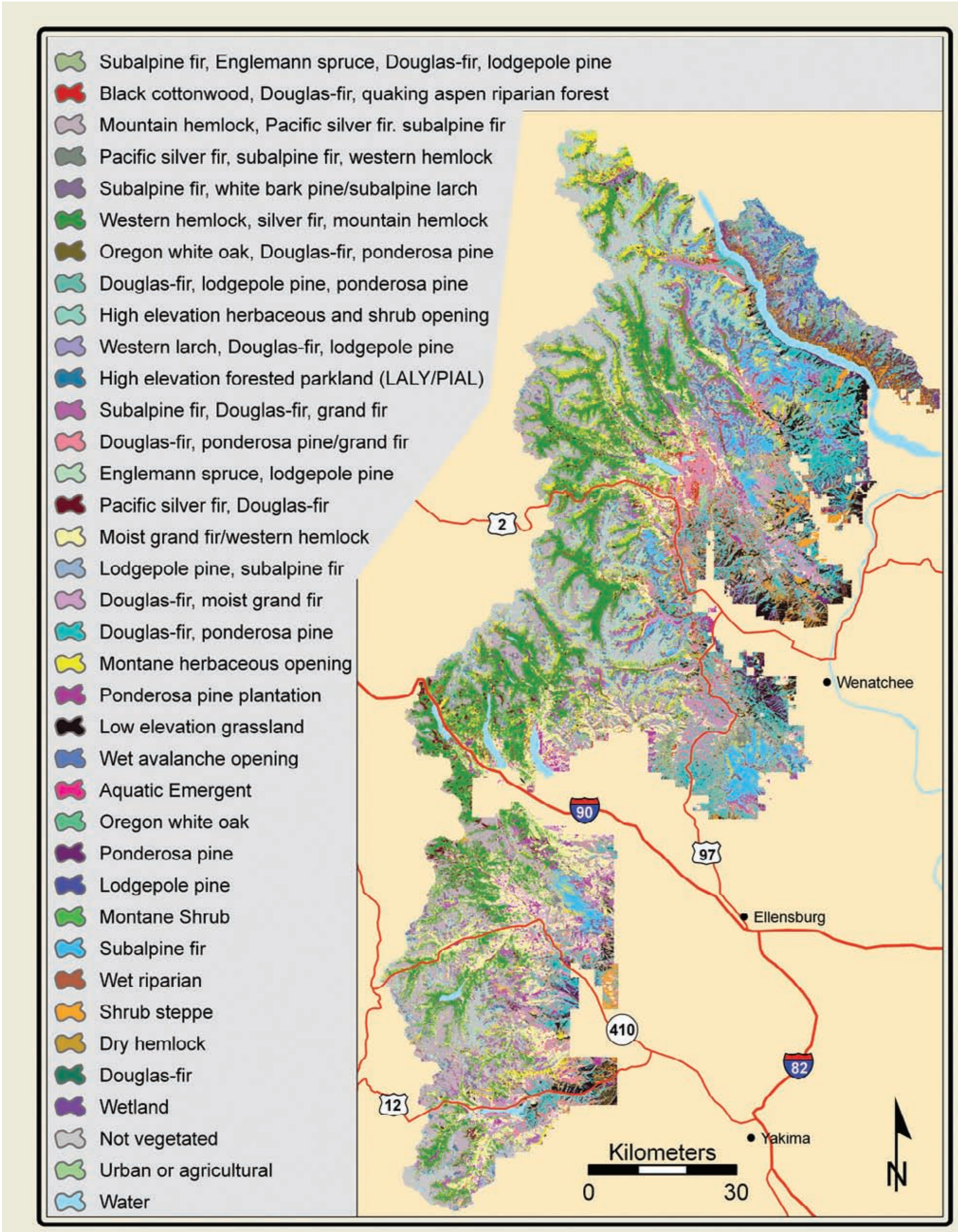

Figure 3—Fuel bed classification for the Wenatchee National Forest, Washington state, at 25-m resolution.

Table 2—Percentage area of the common (> 1,000,000 cells) and rarest (< 10,000 cells) fuel beds in the Wenatchee National Forest map.

Common fuel beds	Area (%)
Western hemlock, Pacific silver fir, mountain hemlock	13.84
Mountain hemlock, Pacific silver fir, subalpine fir	9.66
Douglas-fir, ponderosa pine	9.07
Moist grand fir, western hemlock	8.47
Non-vegetated	8.07
Montane herbaceous opening	7.10
Rare fuel beds	
Dry hemlock	0.038
Oregon white oak, Douglas-fir, ponderosa pine	0.032
Engelmann spruce, lodgepole pine	0.011
Wet avalanche opening	0.002
Oregon white oak	< 0.001

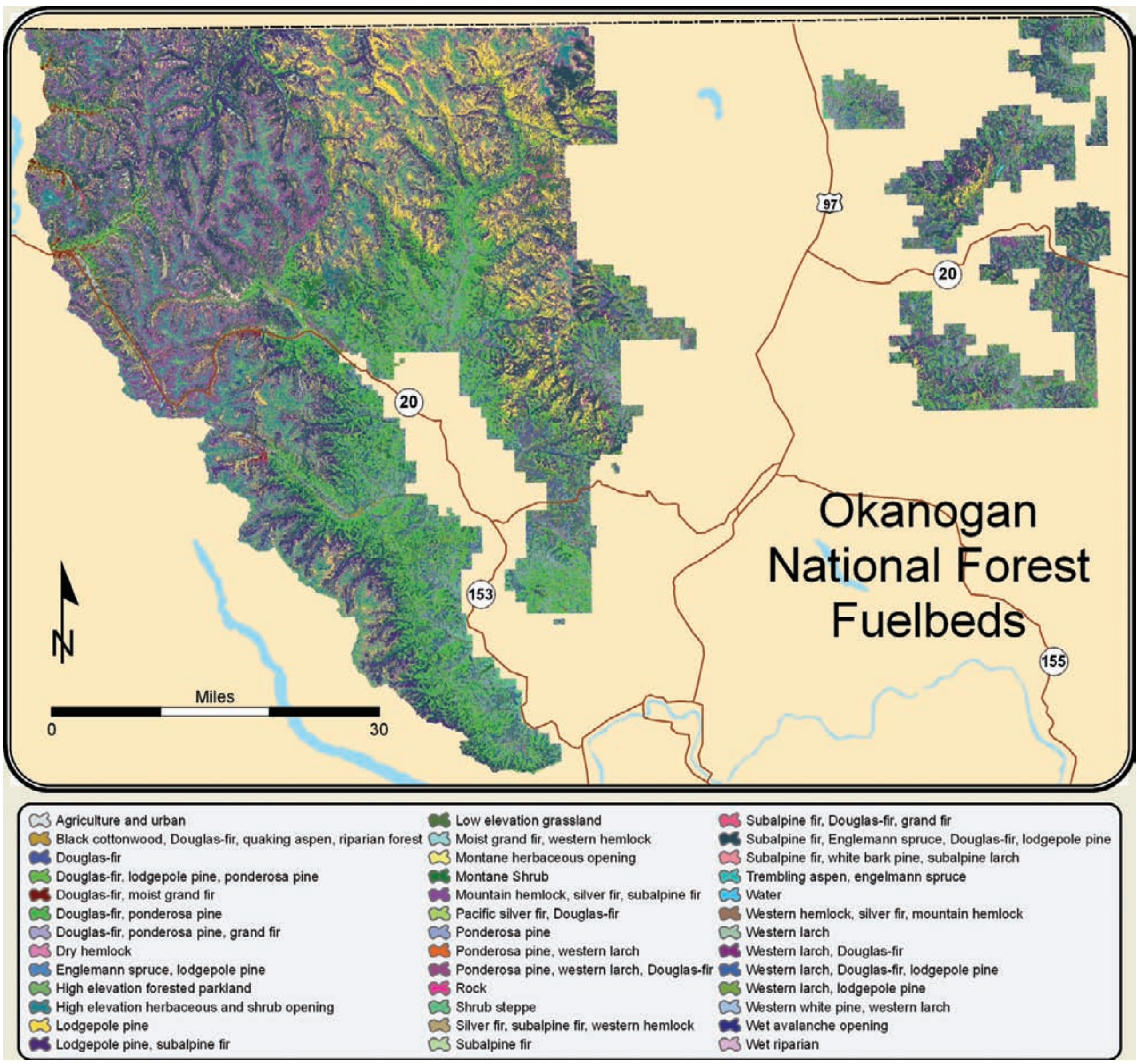

Figure 4—Fuel bed classification for the Okanogan National Forest, Washington state, at 25-m resolution.

Table 3—Percentage area of the most common (> 1,000,000) and rarest (< 10,000) fuel beds in the Okanogan National Forest map.

Common fuel beds	Area %
Subalpine fir, Engelmann spruce, Douglas-fir, lodgepole pine	15.84
Douglas-fir, ponderosa pine	14.29
Lodgepole pine	9.92
Lodgepole pine, subalpine fir	9.10
Rare fuel beds	
Low elevation grassland	0.079
Dry hemlock	0.054
Western larch	0.031
Western larch, lodgepole pine	0.024
Wet riparian	0.016
Ponderosa pine, western larch	0.006

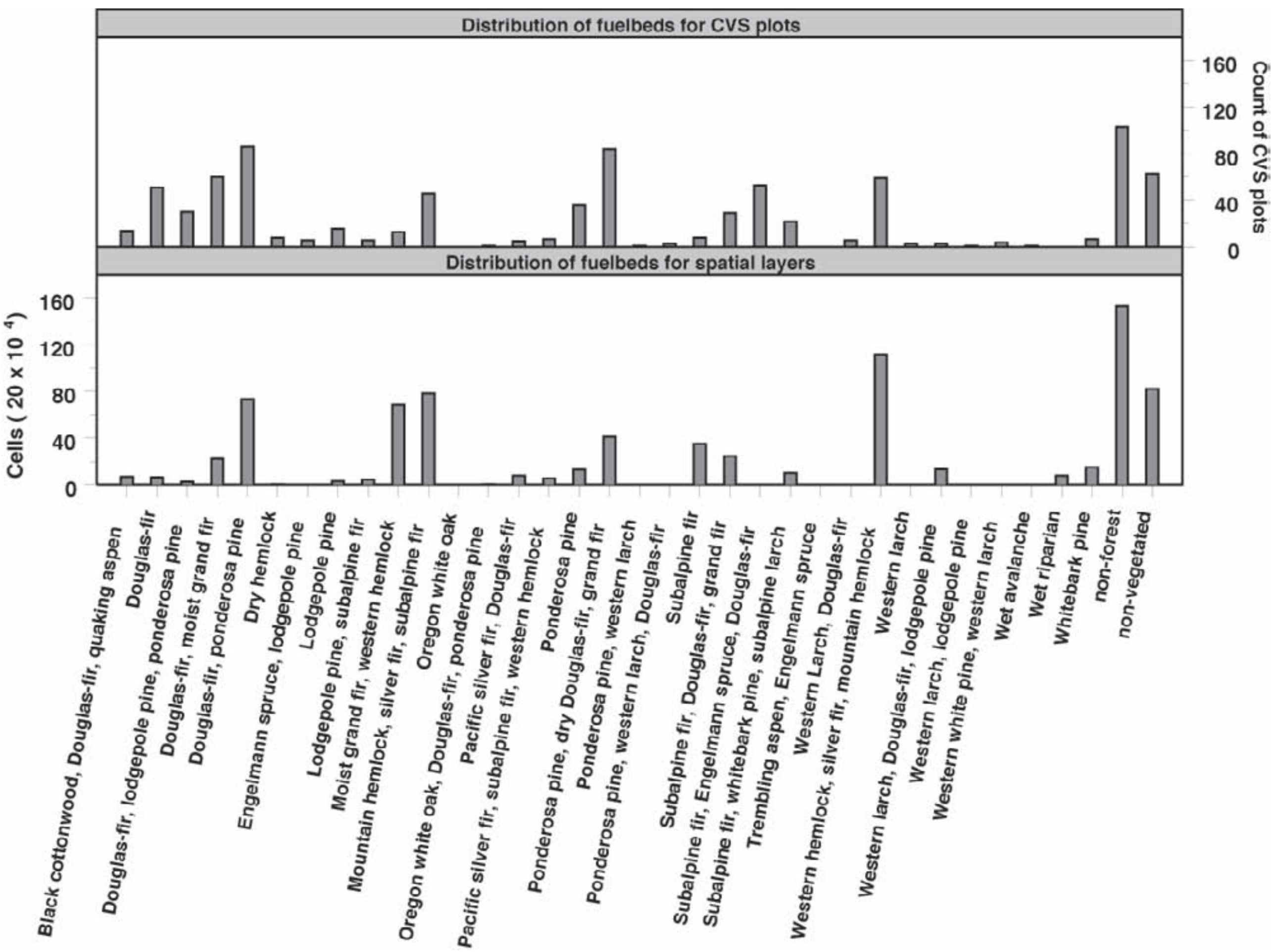

Figure 5—A comparison of fuel bed distributions from two sources on the Wenatchee National Forest, 835 CVS plots and remotely-sensed data.

the only rules amenable to this adjustment represented a small enough number of cells that the distributions changed only slightly toward lesser bias.

Validation with the CVS plots on the ONF indicated that the fuel bed classification process better captured the spatial distribution of fuel beds on the ONF than on the WNF. The distribution of fuel beds represented by the spatial data layers on the ONF was remarkably similar to that of the CVS plots with a few exceptions (figure 6). Classification of the spatial data layers over represented the "lodgepole pine" and "lodgepole pine, subalpine fir" fuel beds. Conversely two Douglas-fir fuel beds, "pure Douglas-fir" and "Western larch, Douglas-fir," occurred with much greater frequency in the CVS plots than in the classification of the combined spatial data layers.

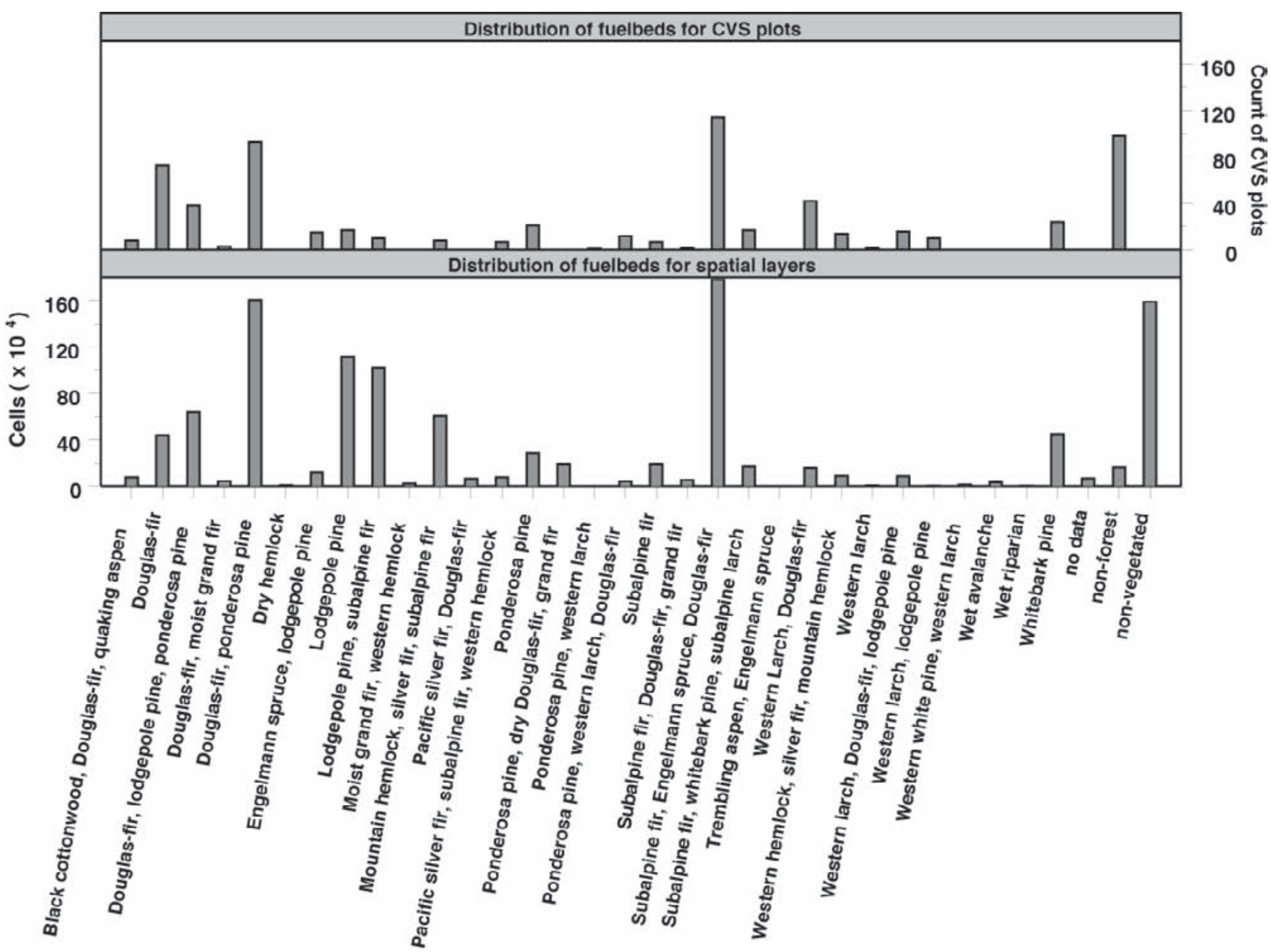

Figure 6—A comparison of fuel bed distributions from two sources on the Okanogan National Forest, 655 CVS plots and remotely-sensed data.

Discussion

We completed classification of FCCS fuel beds on two national forests using a rule-based method that takes advantage of spatial data layers of current and potential vegetation. In order to be useful for management and modeling applications, these fuel beds must be translated into fuel loads by fuel type (for example, canopy, live surface fuels, dead surface fuels, litter and duff). The FCCS has default values so the implementation of mapping fuel loads can proceed by assigning each cell its default value for each fuel category. Fuels are highly variable in space and time, however, so although this approach might produce unbiased estimates of mean fuel loadings, it clearly underestimates the variability of fuels across a region.

We can use high-resolution quantitative GIS layers that cover the WNF and ONF to quantify the attributes of each fuel bed. The Interagency Vegetation Mapping Project estimated both canopy cover and quadratic mean diameter (QMD) at 30-m resolution across the forest from LANDSAT TM imagery. The USU LANDSAT TM imagery included layers of canopy cover and stand size (d.b.h class) at 30-m resolution across the ONF. These layers provide structural information that can be linked to specific fuel beds (for example, table 1), thereby refining estimates of fuel loadings for each cell to the more precise default values associated with the specific fuel beds. This will be particularly valuable for quantifying fuels below the canopy layer—a problematic task in mapping fuels and vegetation in general (Keane et al. 2001).

Fuels are also highly variable over time, because of vegetation succession, disturbance, and land use. The FCCS includes a facility for incorporating "change agents" (Ottmar et al., in review) to account for modification of fuel beds by disturbance and management. This feature, along with the FCCS' basis in vegetation, enables straightforward updates of the mapped layers as new vegetation layers become available and disturbances are identified and mapped. The base maps we developed can be updated to implement a change agent for fuel beds assigned to cells affected by disturbance, or in some cases changed to a new general fuel bed, by incorporating spatial data layers on fire and insect disturbances and logging activities

Applications to Modeling and Management

Any attribute associated with a fuel bed can be mapped at the same resolution as the fuel bed. Not only can the default fuel loads for each of 16 categories of fuels be mapped, but also any output from the FCCS calculator can be similarly mapped. Mapped FCCS attributes can provide input layers for current and future modeling efforts at multiple scales. Managers can use these FCCS-based maps as planning tools for the national forest, because their forest-wide coverage with fine resolution matches the scale of forest plans (R. Harrod, personal communication, 2006). The ability to customize fuel beds within FCCS facilitates the quantitative evaluation of fuel-treatment scenarios across the landscape.

The hierarchical scheme of FCCS enables a crosswalk to existing and future spatial data layers using straightforward decision rules. Fuel bed attributes such as vegetation cover and fuel loads can likewise be matched to quantitative spatial data layers. Dynamic fuel mapping is necessary as we move into the future with rapid climatic and land-use change, and possibly increasing disturbance extent and severity. The rule-based methods we describe here are well suited for updating with new spatial data, to keep local and regional scale fuel assessments current and inform both research and management.

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Fuel Type Classification and Fuel Loading in Central Interior, Korea: Uiseong-Gun

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Abstract*—The objective of this study is classification of fuel type and calculation of fuel loading to assess forest fire hazard by fuel characteristics at Uiseong-gun, Gyeongbuk located in the central interior of Korea. A database was constructed of eight factors such as forest type and topography using ArcGIS 9.1 GIS programs. An on-site survey was conducted for investigating vegetation and fuel loading. Forest distribution of Uiseong-gun is composed of mixed forest, about 43.7%, of coniferous trees such as* Pinus densiflora*, approximately 43.5%, and of broad-leaved trees like* Quercus variabilis*, 8.7%. In order of age class, trees are III-class (11~20 years) 57.6%, IV-class (21~30 years) 25.1% and II-class (1~10 years) 14.4%. By diameter at breast height (DBH) 82.5% are small diameter, 6~16 cm, and 14.9% of young trees are under 6 cm diameter. Most trees are are less than 16 cm DBH. Considering Korean forest characteristics this study led to a classification of ten fuel types. With the utilization of the data taken into account, this research, based on the existing forest type and forest soil map, categorized the 10 fire fuel types into three coniferous forests (C), one broadleaf forest (D), and one mixed forest (M), five fuel type forests in total. In shrub layers and below them, fuel load was found to be 7.64 t/ha in* Pinus densiflora *pure forest (C-1), 10.99 t/ha in the* Pinus densiflora*-middle stratum (C-2), 8.62 t/ha in the* Pinus densiflora*-substratum (C-3), 9.17 t/ha in the mixed forest (M), and 1.01 t/ha in the broadleaf forests (D). To categorize fuel types in drawing a forest fire fuel map, the research analyzed the relationship between the density of coniferous forests (C-1, C-2, and C-3), fuel load and forest soil conditions.*

Introduction

The USDA Forest Service developed a forest fire danger rating system consisting of two fuel models in 1964. The 1972 National Fire Danger Rating System (NFDRS) used nine fuel models (Deeming and others 1972). The 1978 NFDRS uses 20 fuel models (Deeming and others 1977). This research enables people to predict fire behavior in wildlife resources, thereby allowing one to evaluate and control potential forest fire damage. Rothermel's (1972) mathematical fire spread model enables quantitative prediction of fire behavior and forest fire danger rating. This mathematical model requires a description of fuel characteristics to calculate forest fire danger indices, namely, fire behavior potential. Data collection for fuel characteristics can be categorized as fuel models, which consist of four groups: grass, shrub, timber, and slash (from logging or fire or wind damage). Fire danger rating uses 20 fuel models. Thirteen fuel models are used in the fire behavior prediction and application (Albini 1976). Anderson (1982) provided photographs and descriptions of fuel models in particular areas, allowing users to use them

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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with ease. Anderson also linked the fire behavior fuel models with fuel models in the National Fire Danger Rating System.

The Canadian Fire Behavior Prediction (FBP) system categorizes fuel types into five groups consisting of 16 types. The FBP system fuel types are quality-focused rather than quantity-focused, and are categorized into overstory layers (structure and composition of standing tree areas), shrub layers (surface and ladder fuel), and surface vegetation and duff layers.

This research seeks to use fuel management programs fit for Korean circumstances, taking into account geographical and ecological characteristics, and develop fuel models to be used in evaluating forest fire danger levels.

Methods

Study Area

Uiseong-gun belongs to North Gyeongsang Province, and is located in the middle inland area of Korea (Figure 1). The county's topography, except the area of Sinpyeong-myeon to the northwest, is not so rugged. The northwestern area is part of Taebaek Mountain Ridges, featuring overlapped mountainsides and forming highlands, but is in its old age stage and is relatively well-developed. The county is long east to west, and narrow north to south, forming a narrow rectangle. Major mountains include Mt. Geumseong (530 m), Mt. Seonam (879 m), and Mt. Bibong (672 m) to the southwest, as well as Mt. Bibong (579 m), Guksabong Peak (521 m) and Mt. Munam (460 m) to the Northeast. The county's forests consist of mixed forests, coniferous forests, and broadleaf forests. Pine tree forests represent over one-third of the forests. By forest type, mixed forests represent 43.7% of the total forests, coniferous forests 43.5%, and broadleaf forests 8.7%, thereby forming various forest types.

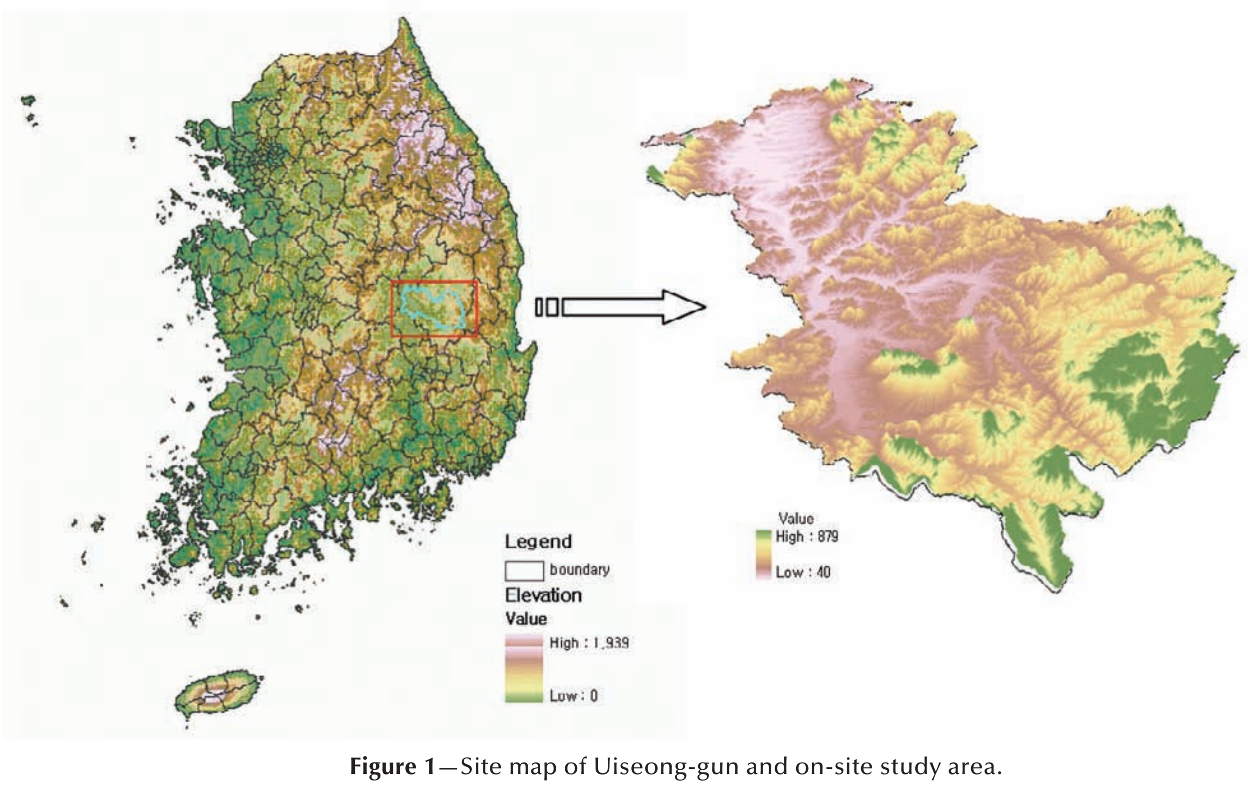


Figure 1—Site map of Uiseong-gun and on-site study area.

Field Methods

The recent-five-year (2001-2005) forest fire outbreak statistics by season indicates an annual average of 543 cases, and of these, in spring (March-May) alone, 364 cases broke out, representing 67% of the total. Thus, to accurately survey fuel load by forest fire type, on-site investigation was conducted in the spring, which is the driest season and has the greatest danger of forest fire.

To survey vegetation with the aim of categorizing forest fire fuel types, quadrates (10 m x 10 m) were installed in each vegetation community type classified by physiognomy and location conditions, and dominance and sociability by hierarchical level were measured using Braun-Blanquet (1964)'s phytosociological method, Z-M tradition. Regarding timbers and Korean dogwood existing in the installed quadrats, their species, tree height, crown base height, DBH, and crown diameter were measured. Also surveyed were each hierarchical level (timber, shrubs, and grass) and the thickness of fallen leaves that may influence forest fire ignition. Since fuel types within forest areas, even though the related trees are of the same kind, may have different structures according to topographical conditions, elevation, aspect, slopes and location coordinates were marked in the survey camp. To categorize Uiseong-gun's forest fire fuel types, live vegetation and dead fuel were surveyed in 46 survey zones. To estimate fuel load, fuel load in surface fuels in shrubs and litter were surveyed (Figure 2).

To survey fuel load, shrub forests were divided in a size of 2 m x 2 m, while grass, fallen leaves, fallen branches, and fruits were divided in a size of 1 m x 1 m. Also related fuels were collected on site and live load was measured. Each collected sample was dried in a drying oven, and dried load was measured again. On-site survey items are as follows (Figure 2).

- Vegetations survey: 10 m x 10 m quadrates
- Overstory: Tree height, crown base height, DBH, density
- Understory: Height of shrubs and grass layer, percent cover
- Fuel load: shrub, grass, fallen leaves, fallen branches
- Topographical conditions: elevation, slope, aspect

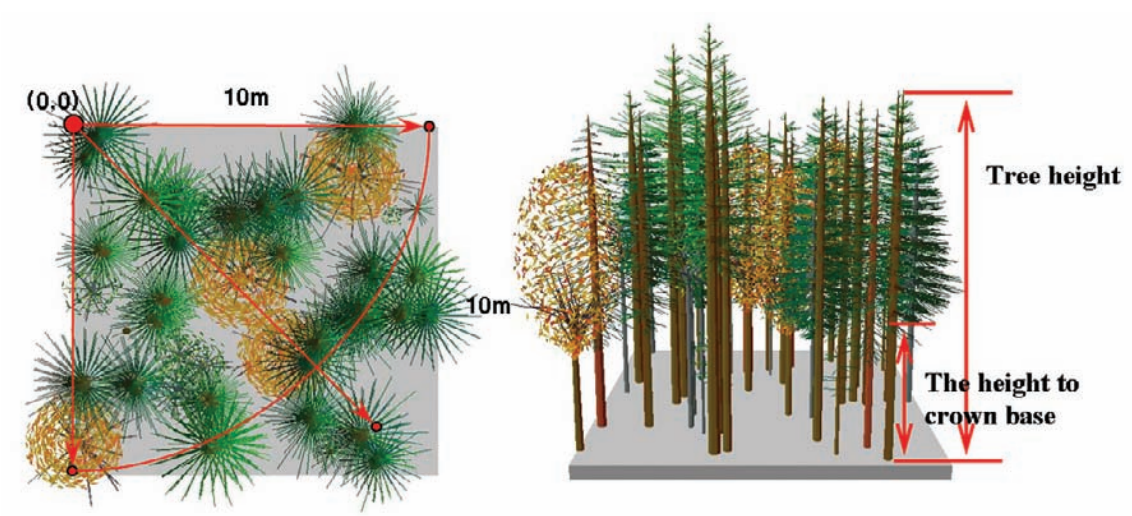


Figure 2—Field methods for fuel type classification.

Building of Database for Fuel Type Classification

To identify the distribution of Uiseong-gun's forest types, using a forest type map with a scale of 1:25,000 crafted by Korea Forest Research Institute and Korea Forest Service, maps by forest type and age class were developed. Using these forest type maps, survey points were selected to categorize forest fire fuel types, and taking account of the distribution ratios of forest types, the survey plan for the Uiseong-gun area was established. Also, to determine topographical features of Uiseong-gun, digital elevation models were crafted to manufacture a map featuring altitude, slopes and four directions (Figure 3). Also, since forest soil conditions have a great effect on the growth of trees and plants, (the map) reflected soil types to be used as reference data in categorizing forest fire fuel types. In this research, to distinguish the fuel type of pine tree forests, which have the highest danger of forest fire, soil types were extracted from the forest type map, and the relationship between the density and fuel load by soil type was analyzed.

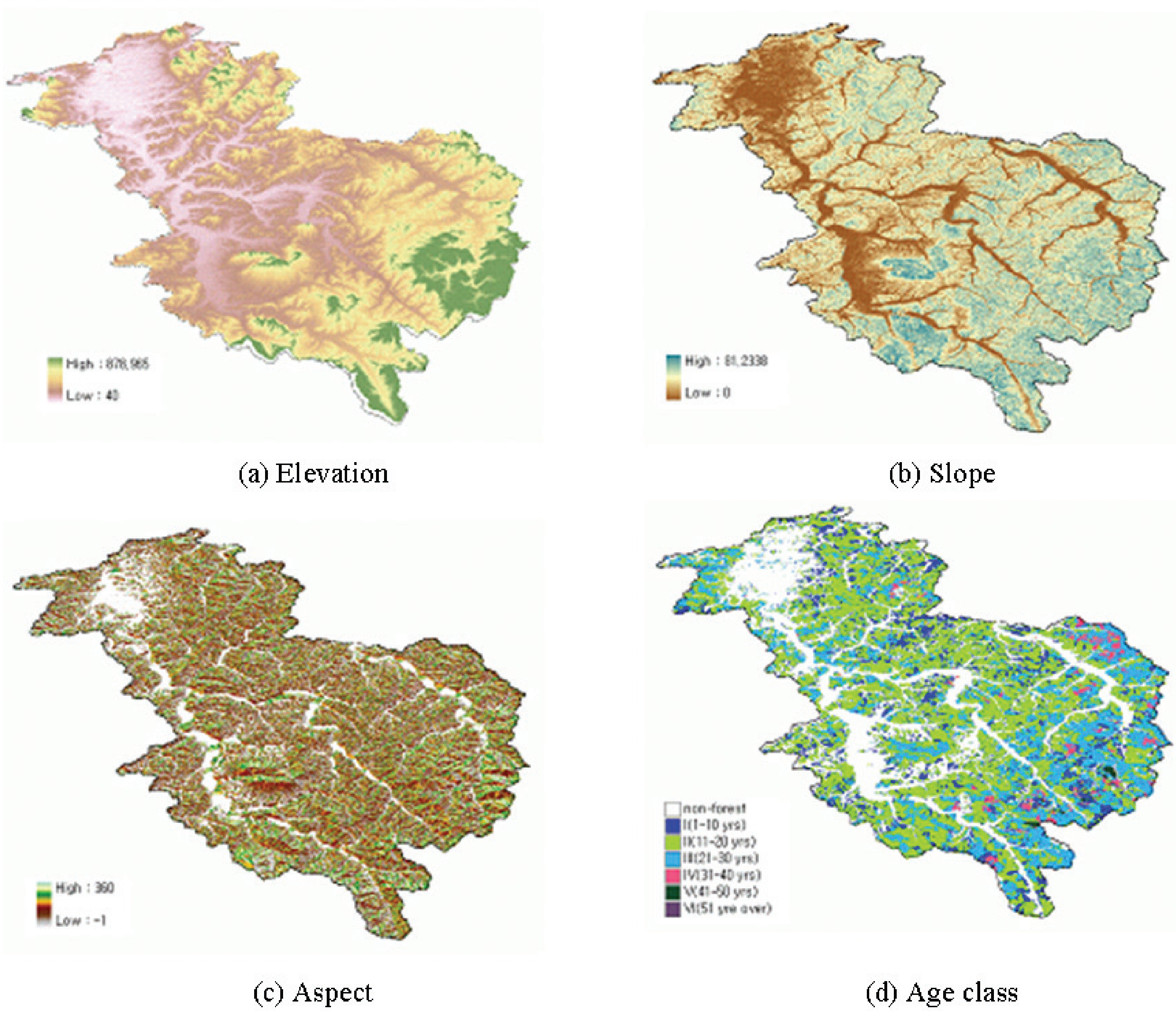


Figure 3—Topographical and forest conditions in Uiseong-gun.

Results and Discussion

Forest Type and Topographic Information

To structure databases designed for categorizing fuel types, using a forest digital map and a forest topographical map with a scale of 1:25,000, maps were crafted to reflect forest types, age class, forest type information by diameter class, DEM, slopes, aspect, and altitude, thereby determining the Uiseong-gun area's topographical information (Figure 4). In Uiseong-gun, mixed forests with coniferous and broadleaf forests represent the largest portion of the total at 43.7%, with pine tree forests accounting for 37.3%. Regarding distribution area by forest type, mixed forests represent 43.7% of the total, coniferous forests 43.5%, and broadleaf forests 8.7% (Table 1). By age class, the third-age class represents 57.6%, 4th-age class 25.1%, and 2nd-age class 14.4%, showing most of forests (72%) consist of forests under 30 years old (Table 2). Regarding distribution by diameter class, small-diameter trees account for 82.5%, thus making trees with the diameter of less than 16cm at the chest's height form the most of the forests (Table 3). Uiseong-gun's slopes are 20-25 degrees for 22.6% of the total area, 25-30 degrees for 40.3%, and over 30 degrees for 36.6%, showing most of the area has steep slopes.

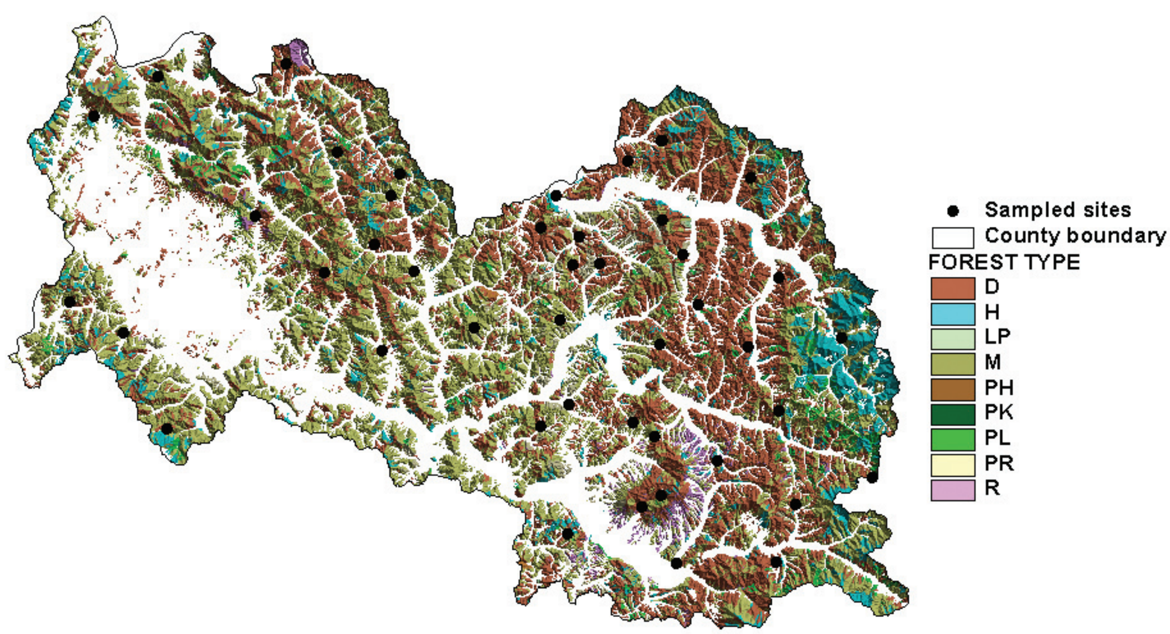


Figure 4—Forest type map in Uiseong-gun. D: *Pinus densiflora* Sieb. et Zucc; H: Deciduous forest; LP: Grass land; M: Mixed forest; PH: Unnatural deciduous forest; PK: *Pinus koraiensis* Sieb. et Zucc., Korean Pine; PL: *Larix leptolepis* (Sieb. et Zucc.) Gordon, Japanese Larch; PR: *Pinus rigida* Mill, Pitch Pine; R: Agricultural area within forest land.

Table 1—Forest distribution of Uiseong-gun by forest type map(1:25,000 scale).

Division	Code	Forest type	Area	Percentage	Total
			(ha)	- - - - - (%) - - - - -	
Coniferous Forest (C)	D,PD	*Pinus densiflora*	29,487.75	37.35	
	PK	*Pinus Koraiensis*	553.44	0.7	43.
	PL	*Larix leptolepis*	1,646.93	2.1	
	PR	*Pinus rigida*	2,713.03	3.4	
Deciduous Forest (D)	Q	*Quercus* sp. forest	108.72	0.1	
	PH	Unnatural deciduous forest	213.35	0.3	8.7
	H	Deciduous forest	6,543.59	8.3	
Mixed Forest (M)	M	Mixed forest	34,542.22	43.7	43.7
Open Land (O)	F	Cutover	7.32	0.0	
	O	Area of canopy cover 30% below	263.18	0.3	2.4
	E	Devastated region	2.95	0.0	
	LP	Pasture	52.6	0.1	
	L	Agricultural area	1,599.46	2.0	
Others	R	Agricultural area within forest land	1,372.57	1.7	1.7
	W	Stream	1.28	0.0	
	Others	—	0.62	0.0	
Total			**79,109.01**	**100**	**100**

Table 2—Distributed area by age class.

Age class	Area	Percentage
	(ha)	*(%)*
2 Class	10,944.95	14.4
3 Class	43,635.66	57.6
4 Class	19,007.94	25.1
5 Class	1,951.14	2.6
6 Class	243.39	0.4
Total	75,783.08	100.0

Table 3—Distributed area by diameter class.

Diameter class	Code	Area	Percentage
		(ha)	*(%)*
Sapling	0	11,314.75	14.9
Small	1	62,605.08	82.5
Medium	2	1,922.31	2.5
Large	3	55.70	0.1
Total	—	75,897.84	100.0

Forest Soil

As surveyed from the forest map, Uiseong-gun's forest soil area covers about 760,000ha, accounting for 65% of its total area. By soil attribute, dry brown forest soil accounts for 35.6%, slightly dry brown forest soil 31.2%, and moderately moist brown forest soil 15.9%, showing most of the forest area is brown forest soil (Table 4). Uiseong-gun's forest soil types are shown in Figure 5.

Table 4—Status of forest soil type in Uiseong-gun

Forest soil type	Percent of area
Dry brown forest soil (B1)	35.56
Slightly dry brown forest soil (B2)	31.18
Moderately moist brown forest soil (B3)	15.91
Slightly wet brown forest soil (B4)	0.34
Dry dark red brown forest soil (DRb1)	4.36
Slightly dry dark red brown forest soil (DRb2)	5.30
Slightly eroded soil (Er1)	3.22
Hardly eroded soil (Er2)	0.02
Lithosol (Li)	2.27
Red forest soil (R)	1.64
Dry reddish brown forest soil (rB1)	0.02
Slightly dry reddish brown forest soil (rB2)	0.19

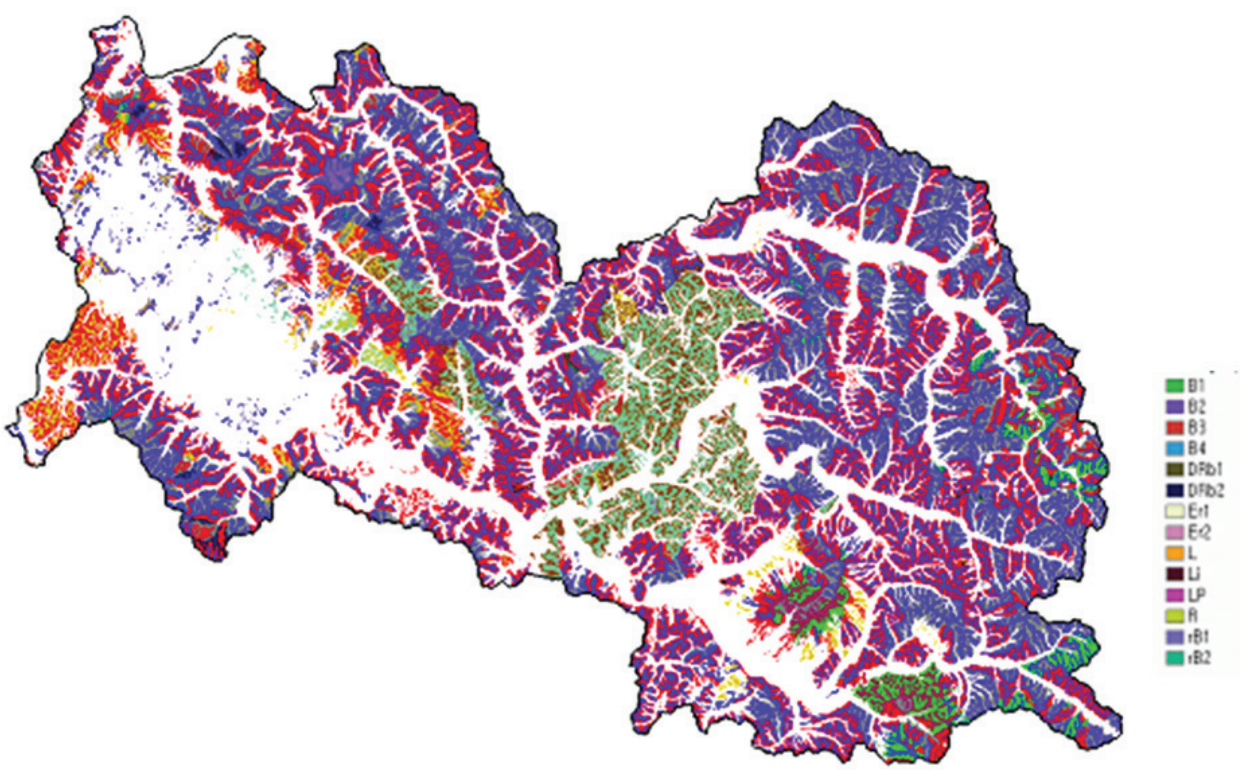


Figure 5—Forest soil type of Uiseong-gun.

Fuel Type Classification

Vegetation data gathered from on-site surveys were analyzed, thereby categorizing forest fire types by 10 items. To categorize forest fire types, based on the density of pine tree forests which are vulnerable to forest fire and have a wide distribution, dense and sparse areas were initially divided, and then four types were divided by the hierarchical level of pine trees. Also, one coniferous forest, one broadleaf forest and one mixed forest were divided. On-site-based forest fire types are divided as shown in Table 5. On the basis of Table 5 the results of vegetation survey classified by ten fuel types are shown in Table 6.

The ten forest fire types from on-site surveys are based on currently existing forest types, density of forest areas, and vegetation structures by hierarchical level, thus presenting limitations in using these forest fire types, categorizing fuel types in the whole survey areas, and crafting a fuel type map. Thus, to craft a fuel type map and put it to practical use, existing available forest type maps, forest soil maps, topographical data, satellite image data and others should first be used to categorize fuel types. This research first took account of cost and time in structuring databases as well as practical usage. A categorization of Uiseong-gun's forest fire types is based on forest type maps and forest soil maps, categorized as ten fuel types and reduced to five fuel types: three coniferous forest types (C), one broadleaf forest (D), and one mixed forest (M). Of these, pine tree forests which are the most vulnerable to forest fire are segmented into sub groups on the basis of forest types and hierarchical structures. The adjusted forest fire fuel types of Uiseong-gun are shown in Table 7.

Fuel Load Each Fuel Types

The type and strength of a forest fire may vary according to fuel load, size, and distribution, as well as depth of the fuel bed, fuel moisture, moisture of extinction and other conditions in the forest area. Thus, taking account of features of Korea's forests, pine tree forests which are the most vulnerable to forest fire were surveyed by hierarchical structure. As a result, in shrub levels, grass levels, fallen leaves, fallen branches, cones and other levels below the shrub levels, fuel load (ton/ha) of surface flammable materials was found to appear the most in broadleaf forests, *Pinus densiflora*-middle stratum,

Table 5—Ten fuel type classifications by field survey.

Forest type	Density	Fuel type
Coniferous forest	-*Pinus densiflora* (dense): 3,000 trees/ha and above	*Pinus densiflora* (dense) *Pinus densiflora* (dense)-shrub-grass *Pinus densiflora* (dense)-shrub
	-*Pinus densiflora* (sparse): 3,000 trees/ha and below	*Pinus densiflora* (dense)-grass *Pinus densiflora* (sparse) *Pinus densiflora* (sparse)-shrub-grass *Pinus densiflora* (sparse)-shrub *Pinus densiflora* (sparse)-grass
Deciduous forest		Deciduous forest
Mixed forest		Mixed forest

Table 6—Survey inventory classified by ten fuel types.

	Overstory (over 8m)				Middle story (2-8m)				Shrub		Grass		Fuel loading					
Fuel Type	TH	DBH	CBH	DEN	TH	DBH	CBH	DEN	SH	%C	GH	%C	shrub	grass	leaf	twig	cone	Total
	(m)	*(cm)*	*(m)*	*(trees/ha)*	*(m)*	*(cm)*	*(m)*	*(trees/ha)*	*(m)*	*(%)*	*(m)*	*(%)*	- - - - - -	- - - - - -	- - - *(ton/ha)*	- - - - - -	- - - - - -	- - - - - -
1	8.9	9.9	4.6	17.0	6.0	5.8	3.6	27.0	1.5	21.3	0.5	21.3	0.4	0.3	5.7	1.5	0.3	8.0
2	—	—	—	—	4.8	6.9	2.2	42.0	1.8	30.0	0.7	65.0	0.7	1.4	6.5	1.8	0.3	10.7
3	9.4	12.4	4.7	15.0	6.1	7.0	3.9	23.0	1.5	70.0	1.0	20.0	1.1	0.1	8.0	2.2	0.3	11.7
4	9.1	13.3	3.7	6.5	5.3	6.4	2.7	41.0	1.8	20.8	0.9	62.9	0.3	0.7	6.1	1.6	0.4	9.0
5	11.3	20.1	6.2	14.0	6.4	10.3	3.8	7.0	1.7	23.3	0.4	20.8	1.3	0.3	5.0	1.2	0.5	8.2
6	9.7	29.7	6.4	9.0	2.8	2.3	—	12.0	1.5	60.0	0.7	50.0	4.2	1.0	4.2	1.2	0.3	10.9
7	9.9	16.8	4.6	12.0	5.5	7.2	2.6	16.8	1.8	50.0	0.6	13.8	0.8	0.4	7.1	1.7	0.2	10.0
8	9.3	14.2	3.7	10.3	5.8	9.4	2.7	13.4	1.6	18.1	0.9	70.0	0.4	1.1	4.5	2.0	0.5	8.3
9	11.3	15.0	3.9	8.4	4.8	8.4	2.2	8.8	1.9	29.0	0.8	13.0	1.4	0.2	5.8	3.7	0.2	11.0
10	10.5	13.5	3.5	8.9	5.1	6.5	2.4	17.0	1.7	22.5	0.4	35.0	0.3	0.2	7.0	1.7	0.1	9.2

TH: tree height, DBH: diameter at breast height, CBH: crown base height,
%C: percent cover, SH: shrub height

Table 7—Fuel type classification justified in Uiseong-gun.

Description	Fuel types	Fuel type code
Coniferous trees such as *Pinus densiflora*	*Pinus densiflora* pure forest	C-1
	Pinus densiflora-middle stratum	C-2
	Pinus densiflora-substratum	C-3
Deciduous trees such as *Quercus variabilis*	Deciduous forest	D
Coniferous and deciduous trees mixed	Mixed forest	M

mixed forests, and *Pinus densiflora*-substratum in this order, and the least fuel load was found in *Pinus densiflora* pure forest (Table 8). Fuel load, in the case of *Pinus densiflora* pure forest (C-1 type), was measured at 0.95 t/ha in shrubs, 0.22 t/ha in grass, 4.87 t/ha in fallen leaves, 1.27 t/ha in fallen branches, and 0.46 t/ha in cones, totaling 7.64 t/ha. In the case of *Pinus densiflora*-middle stratum (C-2 type), shrubs were measured at 0.88 t/ha, grass at 0.70 t/ha, fallen leaves at 7.34 t/ha, fallen branches at 1.89 t/ha, and cones at 0.28 t/ha, showing relatively a greater total amount of fuel load at 10.99 t/ha. Fuel load in *Pinus densiflora*-substratum (C-3 type) totaled 8.62 t/ha, with shrubs standing at 0.52 t/ha, grass at 0.89 t/ha, fallen leaves at 5.16 t/ha, fallen branches at 1.73 t/ha, and cones at 0.37 t/ha, showing a relatively greater grass fuel load, compared with other fuel load types. On the other hand, mixed forests (M type) where pine trees and oak trees were evenly distributed showed 0.29 t/ha, 0.16 t/ha, 6.98 t/ha, 1.67 t/ha, and 0.15 t/ha for a total of 9.17 t/ha of fuel load, in shrubs, grass, fallen leaves, fallen branches, and cones, respectively. Furthermore, fuel load in broadleaf forests (D type) totaled 11.01 t/ha, with fallen leaves and fallen branches standing at 5.78 t/ha and 3.68 t/ha, respectively, thus showing the greatest fuel load (Table 8).

Tree Density and Fuel Loading

To determine fuel features of C-1, C-2, and C-3, equivalent to 33 coniferous forests among 46 survey places, the relations between the density, fuel load below the shrub hierarchical level, tree height and diameter at the chest height were analyzed. The density of individual trees and fuel load in pine tree forests are displayed in a scatter plot in figure 6, which shows a distinctive "U" type on the basis of 3,000-4,000 trees per ha. In zones below 3,000 trees per ha, the more the density increased, the more the fuel load decreased. This is presumably because, in areas with a low density of pine trees, the age of pine trees was advanced at 3rd-4th age class (30-40 years), and biomass increased in forest areas as tree height was in proportion to diameter at the breast height. Also it is deemed that there was relatively greater volume and distribution ratio of thick branches in forest areas, thus increasing fuel load. And, fuel load decreased as the density of forests increased, presumably because competition between individual trees shortened tree height and diameter at the breast height, thus reducing biomass as well. In addition, artificial density management presumably decreased fuel load gradually. However, pine tree forests with 3,000 trees per ha showed trends that fuel load increased as density rose. These fuel features are characterized by low tree height and diameter at the breast height, and a high distribution ratio of small branches with small volume within forest areas. Mainly 2nd-3rd age class (20-30 years old) pine trees were packed closely, and the low hierarchical area had grass well developed, presumably providing a very high fuel load. These areas have not received density management and have been left abandoned, thus having great absolute amounts of fuel load. Thus, fuel load density management beginning with these areas should be conducted to reduce forest fire damage.

Fuel Types Classification by Forest Soil Types

Forest soil conditions have great impact on growth of trees and plants. According to soil moisture conditions, soil is categorized into dry soil, slightly dry soil and moderately moist soil. Dry soil includes B1 and Er1, slightly dry soil B2 and DRb2, and moderately moist soil B3. Thus, criteria for categorizing

Table 8—Survey inventory by fuel type in Uiseong-gun.

	Overstory (8m and over)					Middle story (2-8m)					Shrub		Grass		Fuel loading					
Fuel Type	TH	DBH	CBH	DEN	%C	TH	DBH	CBH	DEN	%C	SH	%C	GH	%C	shrub	grass	leaf	twig	cone	Total
	(m)	*(cm)*	*(m)*	*(trees/ha)*	*(%)*	*(m)*	*(cm)*	*(m)*	*(trees/ha)*	*(%)*	*(m)*	*(%)*	*(m)*	*(%)*	- - - - - - - - - - - - - *(ton/ha)* - - - - - - - - - - - - - -					
C-1	10.1	16.1	5.7	1500	67	6.2	8.1	3.7	1700	37	1.6	18	0.4	18	0.95	0.22	4.87	1.27	0.46	7.65
C-2	9.9	17.4	4.6	1200	66	5.2	6.9	2.8	2000	52	1.7	49	0.7	35	0.88	0.70	7.34	1.89	0.28	10.99
C-3	9.2	13.7	3.8	800	55	5.4	7.6	2.7	2800	51	1.6	22	0.9	64	0.52	0.89	5.16	1.73	0.37	8.62
M	10.5	13.5	3.5	900	54	5.1	6.5	2.4	1700	45	1.7	22	0.4	35	0.29	0.16	6.98	1.67	0.15	9.17
D	11.3	15.0	3.9	800	63	4.8	8.4	2.2	900	27	1.9	29	0.8	13	1.36	0.21	5.78	3.68	0.26	11.01

TH: tree height, DBH: diameter at breast height, CBH: crown base height,
%C: percent cover, SH: shrub height

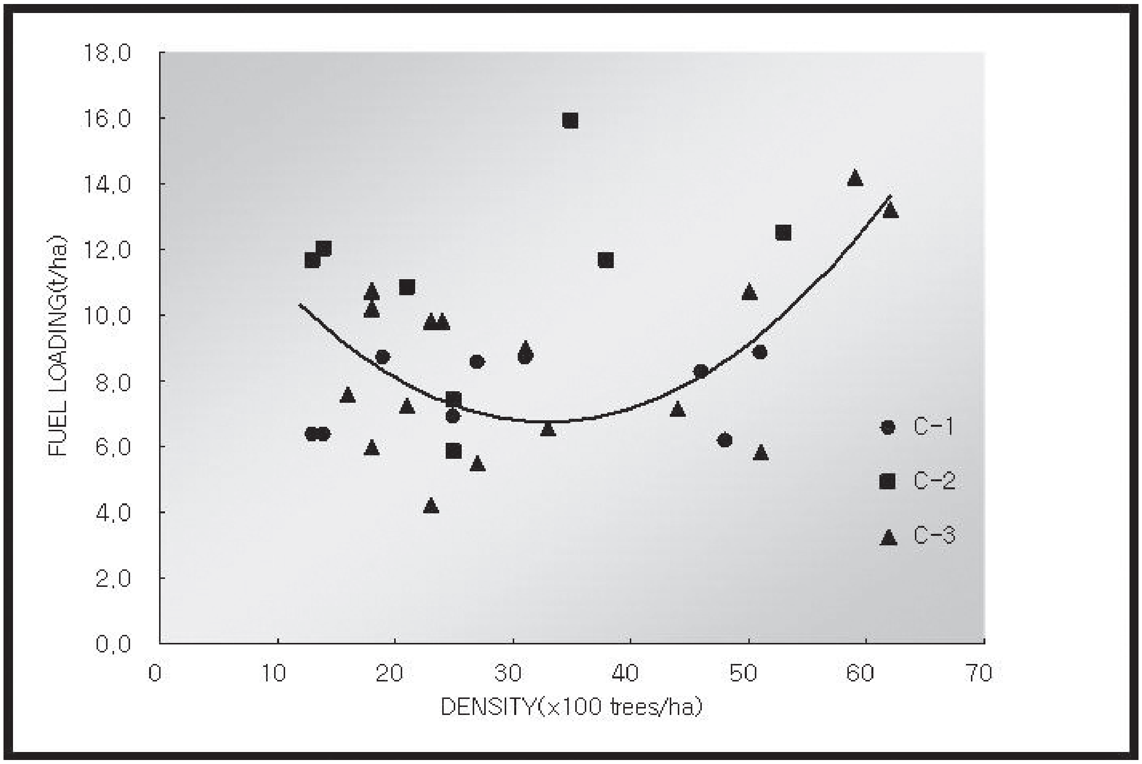


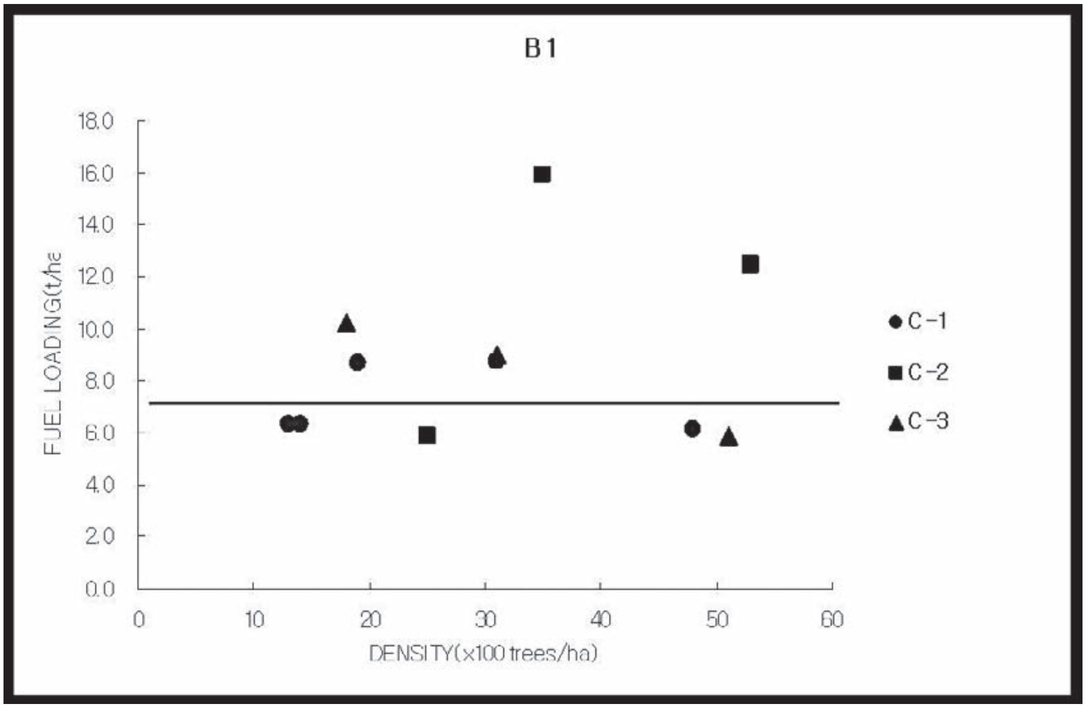
Figure 6—Density and fuel loading of the coniferous forest.

forest fire fuel types for coniferous forests (C-1, C-2, and C-3 types) can be established by utilizing soil types with soil moisture conditions reflected.

The dry soil B1, which is distributed chiefly in areas near ridgelines at the summit, upper areas of mountain slopes and other dry areas, accounts for about 70% of *Pinus densiflora* pure forest (C-1). In Figure 7, B1 soil maintains an average fuel load of 8.0 ton/ha, and the smaller the density is, the bigger the tree height and the diameter at the breast height are, thereby increasing the volume of fallen branches and amounts of fallen leaves and consequently presumably maintaining certain fuel load. With this type, the low hierarchical area usually remains a naked forest area, and thus, when a forest fire takes place, it will highly likely develop into surface fire.

Slightly dry soil B2, which is distributed chiefly at gentle-sloping summits and mountainsides in wind-hit areas, allows forest trees to have relatively good growth. Fuel load tends to decrease as the density of individual trees increases (Figure 7-B2). B2-soil areas saw mainly pine tree forests-low hierarchical type (C-3) distributed (60%), and the low hierarchical area was dominated by grasses, thereby boosting the ratio of grasses of fuel load. If a forest fire takes place in this case, grasses will play a role of ladder fuel, presumably creating danger of surface fire and crown fire in these areas.

Moderately moist soil B3 sees its fallen leaves decompose fast, mostly seeping into topsoil, and boosting the productivity of forest areas. Forest trees grow well in this soil. Fuel load of pine tree forests in B3 increases as density rises. C-1, C-2, and C-3 fuel types are evenly distributed, and the middle hierarchy has many broadleaf trees thus providing high possibility of developing into mixed forests. Pine tree forests-middle hierarchical type (C-2) are distributed at 50%.



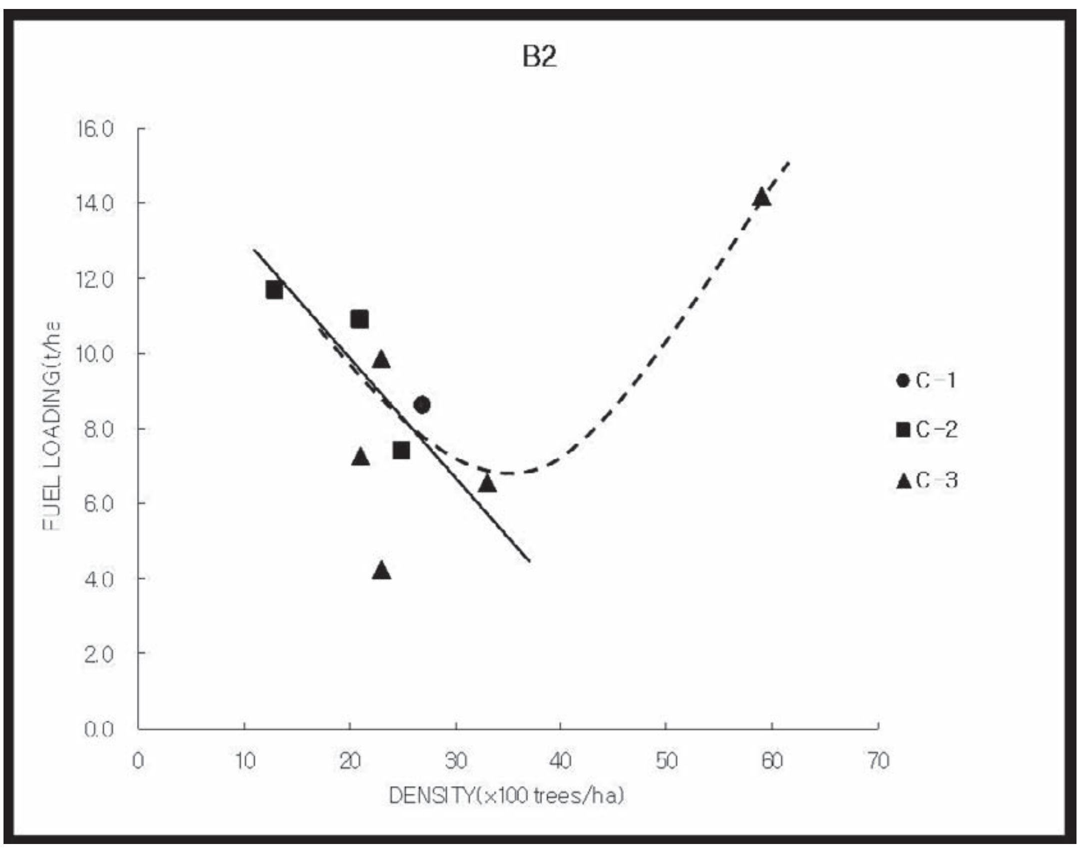
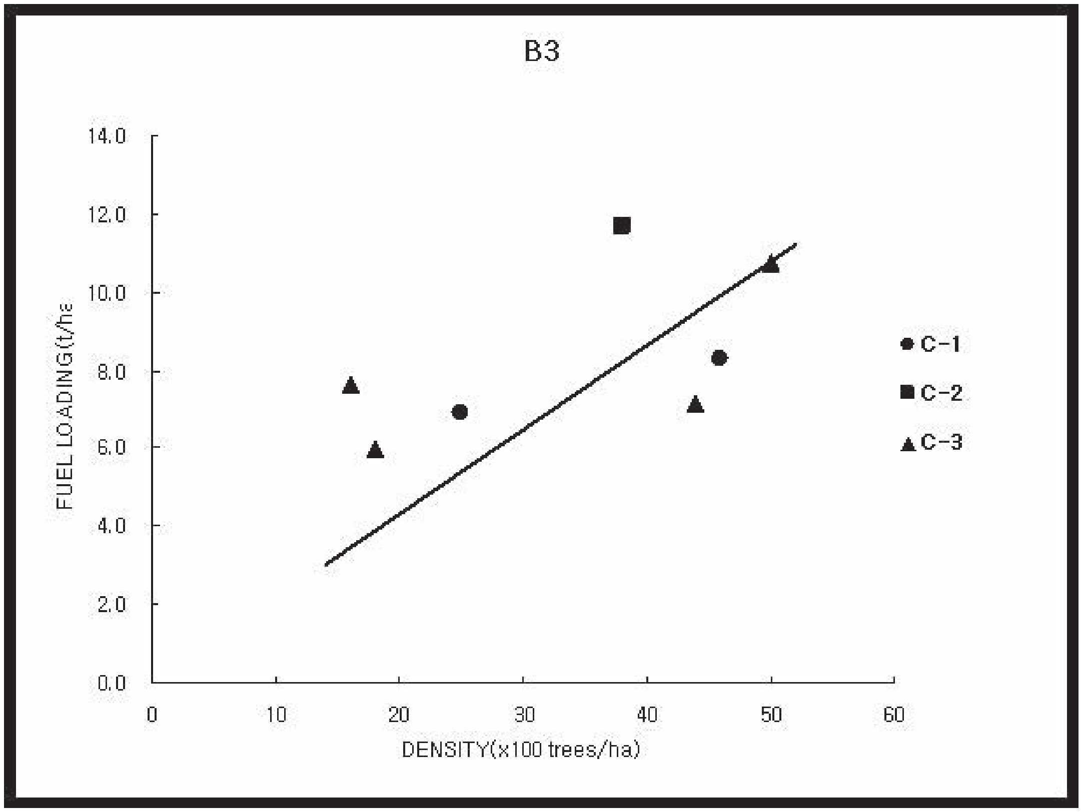


Figure 7—Density and fuel loading by forest soil of the coniferous forest. Dry Soil—B1, Er1; Slightly dry soil—B2, DRb2; Moderately moist soil—B3.



Conclusion

Forest fire occurrence probabilities and risk of fire spread in Korea are the greatest in coniferous forests. To ensure future efficient fuel management and make scientific and accurate prediction of forest fire occurrence and fire spread risk, basic surveys of fuel features of coniferous forests, particularly, pine tree forests, should be first conducted. Thus, to evaluate and quantify forest fire risk according to characteristics of forest fire fuel, fuel types should be categorized based on hierarchical structures by forest type, and the fire risk should be quantified on the basis of the survey of fuel load that allows one to estimate flammable amounts on topsoil. With the utilization of the data taken into account, this research streamlined forest fire fuel types from 10 to 5 (C-1, C-2, C-3, M, and H). In the future, nationwide-based forest fire fuel models will be developed by determining tree height and diameter at the breast height by density, and adding topographical factors such as mountain foot, mountainside, and summit in connection with fuel types.

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Understanding Ozark Forest Litter Variability Through a Synthesis of Accumulation Rates and Fire Events

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Abstract—*Measuring success of fuels management is improved by understanding rates of litter accumulation and decay in relation to disturbance events. Despite the broad ecological importance of litter, little is known about the parameters of accumulation and decay rates in Ozark forests. Previously published estimates were used to derive accumulation rates and combined litter measurements, model estimates, and fire scar history data were used to derive a decay constant (k = 0.38). We used accumulation equations to demonstrate temporal changes in litter loading. For example, after a fire event that consumes nearly 100 percent of the litter, about 50 percent of the litter accumulation equilibrium is reached within 2 years, 75 percent within 4 years, and the equilibrium (99 percent accumulation) after approximately 12 years. These results can be used to determine the appropriate prescribed burning intervals for a desired fire severity. For example, fire history data show that the percentage of trees scarred, a surrogate for fire severity, is influenced by the length of historic fire intervals (i.e., amount of litter accumulated). This information will be incorporated into regional fire risk assessments and can be used as a basic knowledge of litter dynamics for both fire management planning and forest ecosystem understanding.*

Introduction

The Ozark Highlands lacks a general synthesis of the rate of litter accumulation and temporal variability of litter following fire events. Information on the temporal variability of fuels is needed by fire and forest managers in order to measure the success of management activities. In addition, information on litter accumulation is critical for modeling and monitoring of fuel loading and fire effects. This information is regionally specific and depends on the balance between rates of litter accumulation and decomposition (Olson 1963). Litter accumulation rates are controlled by vegetation type, decomposition rate, ecosystem productivity, and their interrelationships. Litter accumulation rates can be difficult to predict because of the high variability imposed by changes in species, tissues, vertical structure of vegetation, elevation, site, and time of year (Gosz and others 1972). Litter decays by leaching, physical weathering, faunal activities, and microbial consumption. Microbial consumption is the primary mode of decay and it is a process controlled by physical and chemical litter properties and climatic conditions (Meentemeyer 1978, McClaugherty and others 1985). Meentemeyer (1978) presented a general equation for predicting average annual decomposition rates (k) from actual evapotranspiration (AET) and leaf lignin contents.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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In order to provide general information for the Ozark region we synthesized data from existing studies and produced a model for predicting litter accumulation. In this paper we 1) provide a regionally averaged fuel accumulation equation for use in estimating fuel loading and 2) describe the long-term variation in Ozark fuel loading with fire history data. The objectives of the paper are to develop a quantitative relationship between litter amounts and time, and use this relationship to examine the effects of fire management on the accumulation and decay of litter.

Methods

Ozark Litter Accumulation and Decay Estimates

Estimates of litter accumulation and decay parameters were derived from four sources: 1) previous published studies, 2) actual litter loading measurements, 3) empirical litter relationships, and 4) analysis of historic fire intervals and tree scarring.

Previous Studies—In a study in the northern Ozarks, Kucera (1959) ranked litter from oaks (*Quercus alba, Q. rubra, Q. marilandica*) as being most resistant to decay, followed by sugar maple (*Acer saccharum*), shagbark hickory (*Carya ovata*), and American elm (*Ulmus americana*). At the same location, Rochow (1974) estimated a litter decomposition rate (k) of 0.35 for oak-dominated forest. More recently, Ryu and others (2004) arrived at a similar estimate for a larger portion of the Missouri Ozarks using an ecosystem productivity model (PnET-II) (Aber and others 1995).

Litter Loading Measurements—Missouri Ozark region litter loading data was gathered for many forested sites and time periods (table 1). Litter was collected using clip plot methods, dried to a constant weight, and reported on a dry-weight basis. In addition, we gathered associated data, including collection date (pre- and post-burn), dates of fires, number of previous fires, and physical plot attributes (slope, aspect, vegetation type, overstory basal area, and stand density). Variability in litter sample weights likely occurred due to collection by different investigators, years of collection, and forest conditions. When possible, we only used measurements that excluded the zone of highly decomposed material commonly called the humus or duff layer. We estimated the litter decomposition rate (k) using the equation developed by Olson (1963), where the annual production of litter is divided by the standing crop litter. The mass of annual litter production was estimated using mean litter loading values collected one year after burning. Estimates of the average standing crop (steady-state level) of litter were derived from litter masses that had accumulated for >20 years and were based on multiple measurements taken from many Ozark sites (table 1).

Empirical Litter Relationships—We also estimated litter decomposition rates using Meentemeyer's (1978) general equation, which incorporates lignin contents and actual evapotranspiration (AET). Average litter lignin content for the important Ozark tree species was derived from previously published studies. Tree species included black oak (*Q. velutina*), scarlet oak (*Q. coccinea*), white oak (*Q. alba*), post oak (*Q. stellata*), and shortleaf pine (*Pinus echinata*) (table 2). No lignin contents were obtained for hickories (*Carya* spp.). Though there is likely high variability in decomposition rates due to

Table 1—Data on oven dry-weights of litter from 35 Ozark Highlands sites. Forest structure codes and site information are given at the bottom of the table.

Site	Forest structure	n	Basal area (ft^2/ac)	Years accumulation	Litter (tons/ac)	Litter (tonnes/ha)	Source
Knob Noster S.P.	1	5	80	2	3.02	1.11	authors
HaHa Tonka S.P.	1	5	58	2	3.12	1.14	authors
Meremac S.P.	1	7	108	3	2.50	0.92	authors
Taum Sauk Mnt S.P.	1	7	52	2	2.90	1.06	authors
Bennett Spring S.P.	1	4	66	1	2.56	0.94	authors
USFS - Mark Twain	1	7	51	1	2.71	0.99	authors
University Forest A1	1	2	55	1	2.18	0.80	authors
Baskett WMA A1	2	9	na	1	1.56	0.57	Rochow 1974
Stegall Mtn.	1	3	38	2	2.76	1.01	authors
Chilton Creek 2003	1	26	na	1	2.00	0.73	Hartman 2004
Chilton Creek 1998	1	26	na	>20	3.40	1.25	Hartman 2004
University Forest B1	1	na	na	1	1.64	0.60	Scowcroft 1965
University Forest B2	2	na	na	>20	5.45	2.00	Scowcroft 1965
University Forest C1	2	na	na	>20	3.88	1.42	Meier 1974
University Forest D1	2	na	na	>20	6.10	2.23	Paulsell 1957
Jerktail Mtn.1	2	18	96	>20	5.77	2.12	authors
Jerktail Mtn. 2	2	6	67	>20	4.17	1.53	authors
Powder Mill 1	2	10	82	>20	4.97	1.83	authors
Powder Mill 2	2	6	93	>20	4.00	1.47	authors
Akers1	2	14	99	>20	3.49	1.28	authors
Akers2	2	10	86	>20	3.88	1.42	authors
Alley Spring	2	6	93	>20	3.76	1.38	authors
Bay Creek 1	2	6	90	>20	3.84	1.41	authors
Bay Creek 2	2	6	73	>20	4.13	1.52	authors
Black River 1	2	15	na	>20	3.02	1.11	Kolaks 2004
Black River 2	2	15	na	>20	3.19	1.17	Kolaks 2004
Black River 3	2	15	na	>23	2.92	1.07	Kolaks 2004
Coot Mtn.	2	6	103	>20	3.23	1.19	authors
Williams Mtn.	2	6	90	>20	6.53	2.40	authors
Wildcat Mtn.	2	8	93	>20	4.29	1.57	authors
Baskett WMA B1	2	102	129	>20	6.52	2.39	authors
Goose Bay Hollow	2	8	110	>20	5.44	2.00	authors
Dent & Iron Co.'s [a]	2	na	na	>20	6.60	2.42	Loomis 1975
Sinkin Exp. Forest 1 [a]	2	na	na	>20	6.20	2.28	Loomis 1965
Sinkin Exp. Forest 2 [b]	2	na	30	>20	5.00	1.84	Crosby and Loomis 1968
Mean maximum accumulation (>20 years accumulation)					4.57	1.68	

forest structure: 1 = savanna/woodland, 2 = forest
na = not available
[a] contains organic matter
[b] shortleaf pine plantation

Table 2—Lignin contents of important Ozark forest species.

Species	Lignin content (%)	Source
Quercus velutina	25.70	Martin and Aber 1997, Aber (online data)
Quercus coccinea	18.70	Washburn and Arthur 2003
Pinus echinata [a]	25.50	Washburn and Arthur 2003
Quercus rubra [b]	23.43	Martin and Aber 1997
Quercus rubra and *Quercus alba*	23.48	Martinand Aber 1997
Mean	23.36	

[a] samples include *Pinus rigida* litter.
[b] samples include *Acer rubrum* litter.

variability among sites, climatic conditions (for example AET), and numerous vegetation assemblages, we utilized a multi-species average of lignin contents for the region since our aim is to develop a better general understanding of litter dynamics in the Ozarks. We obtained AET estimates for the Ozark Highlands region from the Global Hydrologic Archive and Analysis System (GHAAS). Data were 0.5 degree gridded average annual AET estimates given in millimeters per year (Vörösmarty and others 1998). We averaged long-term grid means for the Ozark region to get a mean regional AET value.

Historic Fire Intervals—Historic fire intervals were derived from four previously constructed published and unpublished fire scar history studies in the Ozarks. Study sites were located in Shannon County, Missouri and included Stegall Mountain (Guyette and Cutter 1997), Mill Hollow, MOFEP Site 3, and MOFEP Site 4 (Guyette and Dey 1997). Methods for sample collection, tree-ring crossdating, and fire scar dating can be found in several published studies (Guyette and others 2003, Stambaugh and others 2005). Site level fire scar chronologies were input to FHX2 software (Grissino-Mayer 2001) where fire intervals were calculated for each fire at each site as the number of years between fire events. Fire intervals were paired with the percentage of trees scarred in the fire year that ended each interval. The percentage of trees scarred was calculated as the number of sample trees scarred in a given year divided by the number of recorder sample trees in the same year. All data were pooled into a single dataset with 111 paired observations of fire intervals and percentage of trees scarred. Due to the changing characteristics of the anthropogenic fire regime (Guyette and others 2002), we only used data from the period A.D. 1700 to 1850 in the analysis. This period was selected because it is well replicated (9-20 recorder trees at any given year) at all sites and because there exists high variation in the length of fire intervals. We used non-linear regression (exponential equation) to describe the variability in the percentage of trees scarred from fire intervals. We assumed that the variation in percentage of trees scarred is related to fuel accumulation. Based on this assumption, an exponential function should approximate the litter accumulation rate and the exponential term of the regression model would be an estimate of litter decomposition rate (*k*).

Temporal Litter Variability Model

The mass loss of litter as a function of time is generally expressed as an exponential decay model (Bärlocher 2005, Olson 1963). The temporal litter variability for Ozark forests was described using an exponential decay function:

$$X_t = X_0 * e^{-kt},$$

where X_t is the amount of litter remaining after time t, X_0 is the initial quantity of litter, and t is time of accumulation. The estimated rate of litter decomposition ($k = 0.38$) was a mean derived from four different procedures (table 3). The mean standing crop of litter (4.57 tons/acre, see results on next page) was used to define maximum mass accumulation. We used the exponential decay function to describe the rate of accumulation of litter and the time required to reach maximum litter accumulation. Additionally, the equation was applied to historic fire event data from four Ozark fire scar history sites (Stegall Mountain, Mill Hollow, MOFEP Site 3, MOFEP Site 4) in order to reconstruct past temporal variability in litter loading. Using fire scar chronologies, the model was initiated at the first year of record. Fire event

Table 3—Litter decomposition rates (*k*) from the Missouri Ozark Highlands.

Method	*k*	Source
Litter loading measurements	0.46	this paper
Climate/leaf lignin model	0.64*	this paper
Historic fire intervals	0.34	this paper
Litter loading measurements	0.35	Rochow 1974
Climate/leaf lignin model	0.35	Ryu and others 2004
Mean	0.38	

*not used to calculate mean

years were used to reset the litter accumulation model to zero. Accumulation following fire events assumed 100 percent fuel consumption and a constant weight of annual litterfall.

Results

Ozark Litter Accumulation and Decay Estimates

Litter Loading Measurements—The mean mass of annual litter production was 2.11 tons/acre (n = 6, s.d. = 0.47) or 0.77 tonnes/hectare. The mean standing crop of litter was 4.57 tons/acre (n = 24, s.d. = 1.22) or 1.68 tonnes/hectare. Based on the ratio of mean annual production of litter to the mean standing crop, the estimated litter decomposition rate (*k*) was 0.46.

Empirical Litter Relationships—Average percent lignin contents of litter for the important Ozark overstory forest tree species (table 2) was 22.63%. AET values ranged from 675 to 760 mm/yr and the mean was 712 mm/yr. Based on Meentemeyer's (1978) equation the estimated litter decomposition rate (*k*) ranged from 0.59 to 0.69.

Historic Fire Intervals—The relationship between the percentage of trees scarred in a fire event and the preceding fire interval (years since last fire) was established using the non-linear equation:

$$\text{percent trees scarred} = 13.8 + 7.72\,(\ln[\text{fire interval}]),$$

where the fire interval is years since last fire event (model $r^2 = 0.21$, intercept and variables significant $p<0.0001$, n = 111). Although the fire-free interval model explained only about one-fifth of the variance, the model and variables were highly significant. The form of the equation resulted in an exponential term (litter decomposition rate (*k*)) of 0.34.

Temporal Litter Variability Model

The temporal litter variability for Ozark forests was described using an exponential decay equation and is presented in terms of percent accumulation (eq. 1) and mass accumulation (eq. 2).

$$\text{Percent accumulation} = 100 - (100e^{-0.38t}) \qquad \text{(eq. 1)},$$

$$\text{Mass accumulation} = 4.57 - (4.57e^{-0.38t}) \qquad \text{(eq. 2)},$$

where t is the years of litter accumulation. The equation predicts that litter accumulates to 25 percent, 50 percent, and 75 percent of maximum accumulation at approximately 1 year, 2 years, and 4 years, respectively (fig. 1). An equilibrium accumulation (99 percent) is reached at approximately 12 years. In terms of mass accumulation, roughly one ton of litter per acre is accumulated per year up to 3 years post-fire (fig. 1).

The litter accumulation function showed important differences in litter accumulation with burning frequency (fig. 2). For example, annual burning allows a maximum of 32 percent of the total litter to accumulate. A burning frequency of 5 years allows a maximum of 85 percent of the total litter to accumulate, while a burning frequency of 10 years allows a maximum of 97 percent of the total litter to accumulate. In terms of litter loading, the difference between annual and 5-year burning frequency is over two times greater than the difference between 5-year and 10-year burning frequencies.

The effects of variable burning frequencies were further exhibited by a reconstruction of long-term Ozark litter loading (fig. 3). The long-term variation in historic fuel loading is striking and a result of frequent anthropogenic ignitions. Prior to EuroAmerican settlement (pre-1800), fuel loading was both spatially (between sites) and temporally variable. Comparisons between sites show that Stegall Mountain has undergone conditions of continuous burning and rapid fuel replenishment. Mill Hollow and MOFEP Sites 3 and 4 underwent prolonged frequent fires (1-3 years) that lasted most of the 19th century and had a long-term effect on minimizing fuel loading. Mean fuel loading of the four sites was 2.91 tons/acre prior to 1800 and 1.45 tons/acre from 1800-1900. Since about 1930 to 1940, the effects of fire suppression has resulted in maximum litter loading and lowered temporal litter variability. An exception is Stegall Mountain, where prescribed burning management has been in practice since about 1980.

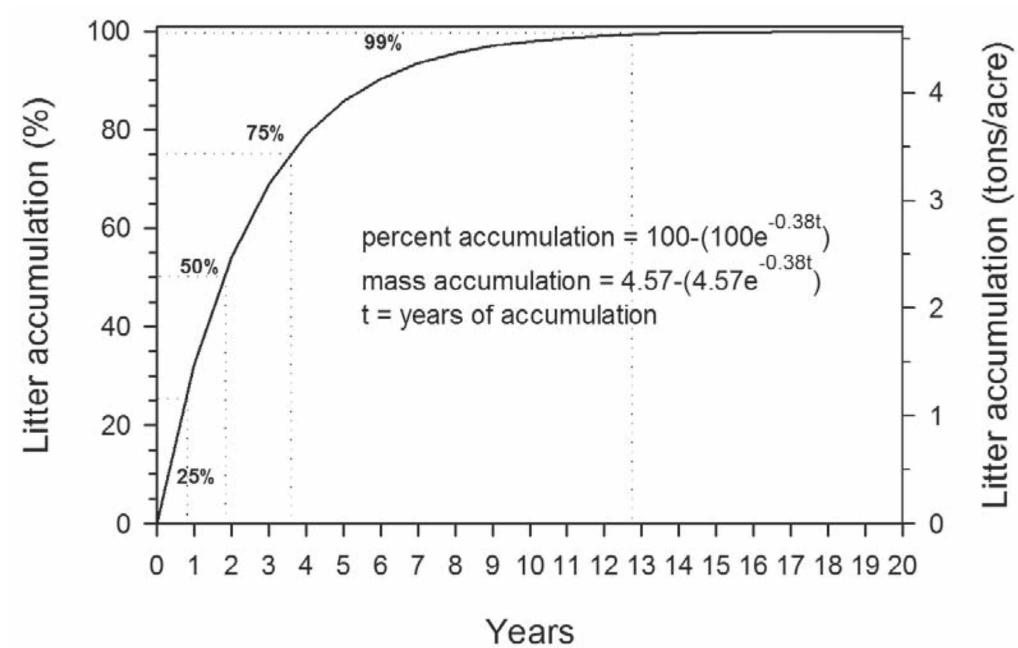

Figure 1—Plot illustrating a litter accumulation function in terms of percent of maximum and mass for forests of the Ozark Highlands, Missouri. The decomposition constant (*k*) was based on the mean from multiple sources and methods (table 3).

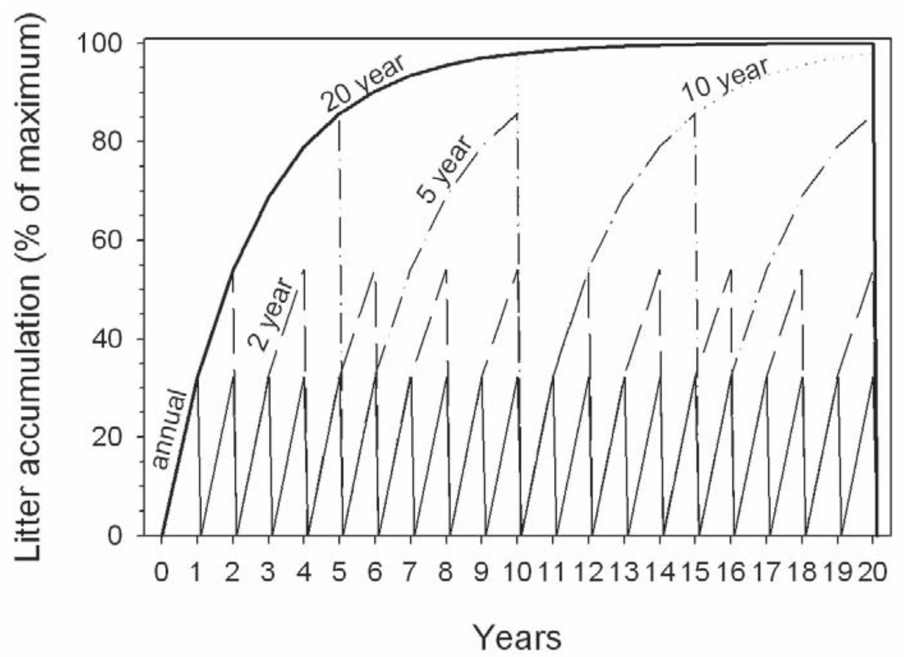

Figure 2—Litter accumulation dynamics with litter removed by fire (or other means) at different but regular intervals. Given here are litter accumulation patterns for annual fire intervals (solid fine line), 2-year fire intervals (short dashed line), 5-year fire intervals (dot dashed line), and a single 20-year interval (solid bold line).

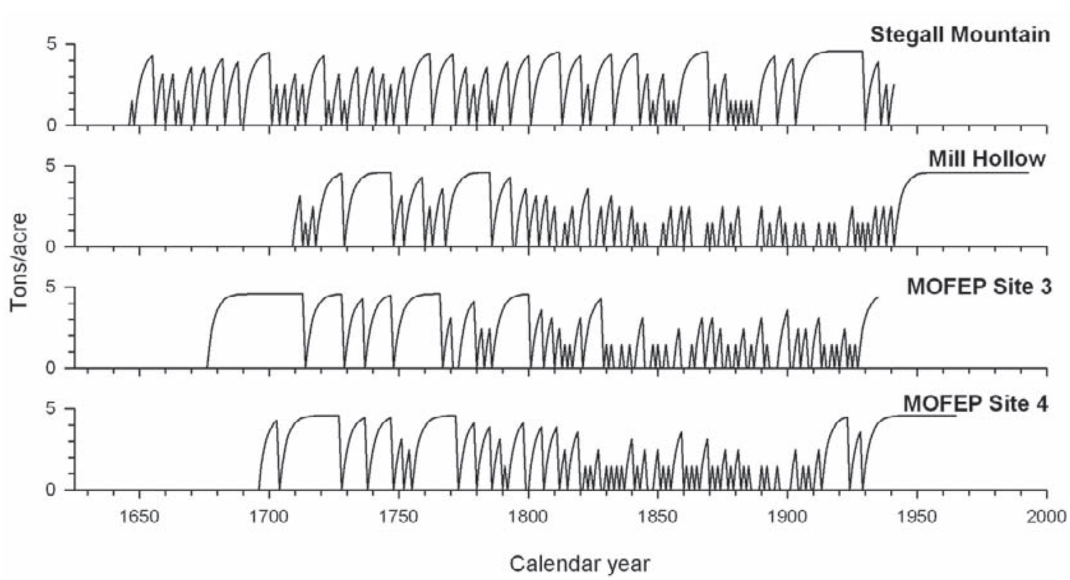

Figure 3—Litter loading reconstructions for four forest sites in the Ozark Highlands, Missouri. Reconstructions are based on fire scar history data and a litter mass accumulation function (fig. 1). Site reconstructions begin and end at different calendar years based on the period of fire scar chronology records.

Discussion

Fire suppression policies of the past 75+ years have altered Ozark forest ecosystems, often in ways that are not fully understood at this point in time. From fire scar studies, we know that much of the Ozarks landscape burned relatively frequently (8-15 years) for at least 200 years prior to Euro-American settlement. The natural communities that developed during that time are now changing, and restoration efforts often include the reintroduction of fire, despite a lack of quantitative information on how fire might behave under the conditions resulting from years of fire suppression. One of the many ways in which fire suppression has affected Ozark forests is by altering the nature of fuels at the forest floor, though there has not previously been a way to quantify these changes. In this paper, we present a litter accumulation model specific to the Ozark region, which we hope will improve our general understanding of the temporal variability in litter accumulation and our ability to manage fuels effectively in the Ozarks. The litter accumulation equations provide managers and scientists with a standard of expected fuel loading, the potential effects of different burning frequencies on fuel accumulation and loading, and estimates of the historic variability in fuel loading at four Ozark sites.

Estimates of temporal changes in fuel depend primarily on the litter decomposition rate (k) and level of maximum litter accumulation. The best estimates of litter decay and accumulation in the Ozarks were based on litter loading measurements and the historic fire record. We chose not to include the value of k derived from mean annual AET and lignin contents as the estimate was extremely high (k = 0.64). Though litter decomposition rates differ from year to year due to changing conditions (for example climate, species, forest density), we felt that the value was a gross overestimate and outside of a plausible range of rates (Ryu and others 2004). The increased rate of decomposition of mixed-species litter (Gartner and Cardon 2004) was unaccounted for, and may be one important reason why Meentemeyer's equation yielded a decay constant much higher than other estimates.

The rapid accumulation of litter following disturbance events likely leads to large differences in burn coverage and fire behavior between fire frequencies of 1, 2, and 3 years. To illustrate this point Behave Plus 3.0.1, fire behavior prediction software, was used to estimate the different fire rates of spread and flame lengths between fuel accumulation rates at 1, 2, and 3 years (table 4). All else equal, fires occurring at 10-year intervals versus 20-year or longer intervals may not differ significantly in behavior or severity (percent trees scarred)

Table 4—Behave Plus prediction of fire behavior using litter accumulation rates from this study. Behave Plus was run using fuel model 9 and 1 hour fuel loading was adjusted according to accumulation rates.

Litter Accumulation Rate	Midflame Windspeed (mph)	Slope (%)	1hr % Moisture Content	10hr % Moisture Content	Rate of Spread (chains/hr)	Flame Length (ft)
1 yr (25% max)	10	5	5	7	24.8	3.3
2 yr (50% max)	10	5	5	7	29.4	4.5
3 yr (65% max)	10	5	5	7	30.1	4.9
10 yr (97% max)	10	5	5	7	29.5	5.3
20 yr (100% max)	10	5	5	7	29.6	5.3

because the level of litter accumulation is similar (table 4). One important factor in surface fire behavior is litter moisture content which can be highly variable by aspect and drought condition (Stambaugh and others, in press). Litter profiles can also be highly variable with dry litter on the surface covering a relatively moist "mat" of partially decomposed but identifiable leaves of the previous few growing seasons (Crosby 1961, Loomis 1975). Furthermore, although fuel loading following 10 and 20 years of accumulation may be marginal, important differences in the development and conditions of the underlying litter profile likely exist.

In addition to the quantification of accumulation and decay rates, the reconstruction of long-term litter loading under different fire regimes provides a unique perspective for fuels management. Although difficult to substantiate, frequent burning during the 19th century may have altered the nature of Ozark fuels by increasing herbaceous and grass vegetation, possibly leading to even lower fuel loading (for example tons/acre) than reconstructed (fig. 3). Frequent and long-term burning likely led to a transition in the dominant litter type from forest leaf litter to herbaceous grass and forb litter, which possibly resulted in increased decomposition rates and decreased total litter loading. In the southeastern Missouri Ozarks, Godsey (1988) found that both annual and periodic and annual burning of an oak-hickory forest after 36 years resulted in an increased abundance of grasses, forbs, and legumes that only comprised about 0.02 tons/acre. Additionally, Hector and others (2000) discussed the differences in decomposition between plant functional groups (legumes, grasses, herbs) and showed increasing decomposition rates with decreasing litter carbon to nitrogen ratios. The conditions conducive to high litter loading potential are most likely found where forest floors are dominated by leaf litter and have been subject to fire suppression for more than 12 years. Much of the forested area of Missouri has had no fire disturbance since the mid-20th century, which has resulted in relatively high litter loading and reduced variability in litter loading compared to the previous 200+ years.

The accumulation of organic litter on forest floors has implications for many processes which involve soils, litter invertebrates, floral diversity, hydrology, and carbon cycling. Furthermore, the effects of historically frequent fire and reduced litter, as well as current and future effects, are poorly understood. Several studies have commented on the slow recovery of endophage populations and activity following burning (Crossley and others 1998). Auten (1934) and Meier (1974) found that burned Ozark sites had significant reduction in water infiltration compared to unburned sites. Studying the same Ozark experimental burn plots, Scowcroft (1965) speculated that prolonged, frequent burning eventually led to decreased soil productivity. Frequent fire also results in decreased fuel connectivity, particularly as canopy trees are killed and inputs of litter are reduced (Miller and Urban 2000). These represent only a few of the myriad of ways that frequent fire may impact forest processes, and highlight the value of continued research into the dynamics of fire frequency and severity and the subsequent impact on organic litter accumulation.

Prescribed burning management is faced with multiple challenges in the Ozark region. Few studies have been conducted to investigate the effects of fire on multiple ecosystem components. Meanwhile, previously fire-maintained communities and species are decreasing in area and abundance, and require fire disturbance to persist. Even with relatively general information about litter decay and accumulation, decisions about forest management and prescribed burning activities are better informed. For example, successful regeneration of shortleaf pine, a species of restoration concern in the Ozarks, could be greatly enhanced through better understanding of the rate of litter accumulation, which often precludes seedling establishment. Also, burning prescriptions for areas being managed for multiple resources can be tailored to achieve an optimal level of fuel loading and desired fire behavior.

Though based on regionally specific data from the Ozarks, the litter accumulation and decay estimates presented here are generalized and do not take into account interannual variability due to variable fire effects (for example partial litter consumption), climate, litter production, litter chemistry, and other influencing factors. Despite these limitations, the approach to understanding long-term litter variability is new and applicable to other locations. Many improvements to this approach are attainable, including: the incorporation of variability in fuel accumulation and decomposition between leaf fall events; taking changing climate into account; addressing differences in species and vegetation densities; and, addressing differences in modern and historic fire conditions (for example fuel consumption, fire severity). The estimates and equations provide a context for fuels management under current conditions, facilitate a new understanding of historic fire regimes, and provide the foundation for a more refined understanding of the fuel-fire interaction.

Acknowledgments

This study was supported by a grant from the USDA Forest Service, North Central Research Station. We are grateful to the support of previous fuels studies whose litter dry-weight data were used in the analysis for this paper. We appreciate the efforts by Joe Marschall in fuels data collection and measurement and Erin McMurry for her assistance in data analysis and editorial comments. In addition we thank John Kabrick and Zhoufei Fan for their helpful comments.

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Estimating Fuel Bed Loadings in Masticated Areas

Sharon Hood[1] and Ros Wu[2]

***Abstract**—Masticated fuel treatments that chop small trees, shrubs, and dead woody material into smaller pieces to reduce fuel bed depth are used increasingly as a mechanical means to treat fuels. Fuel loading information is important to monitor changes in fuels. The commonly used planar intercept method however, may not correctly estimate fuel loadings because masticated fuels violate the assumption that fuel particles are round. A sampling method was developed for estimating masticated fuel bed loadings using percent cover, average depth, and bulk density in three vegetation types: Jeffrey pine-white fir, ponderosa pine-Gambel oak, and pinyon-juniper. Masticated material, duff, and litter samples were collected to determine bulk densities. Loadings were calculated as the product of bulk density and depth. Total fuel median bulk densities equaled 129 (Jeffrey pine-white fir), 128 (ponderosa pine-Gambel oak), and 226 kg/m^3 (pinyon-juniper). Correlations between loading and depth were best for the Jeffrey pine-white fir type. Bulk density was most variable in pinyon-juniper. Woody material loadings calculated from the cover-depth method were generally lower than the loadings calculated from the planar intercept method, while duff and litter loadings from the cover-depth method were higher than the loadings calculated from the vertical profile measurements on the planar-intercept transect.*

Introduction

Mechanical methods to treat fuels are used increasingly in the wildland urban interface (WUI). The goal of many of these projects is to reduce wildfire or prescribed fire intensity and spread rate through modification of surface fuels and increased canopy base heights. Masticating fuels compacts the surface fuel bed by both shredding small trees and shrubs and by chipping dead and down fuels into smaller size classes. While the mastication treatment reduces fuel bed depth, it can also result in a more continuous horizontal surface fuel layer and cause mixing of the woody material into the duff and litter layers. Because mastication is a relatively new fuels treatment, it is unclear how these treatments will affect surface fire behavior or the resulting fire effects.

Gathering fuel loading information is important for predicting fire behavior and explaining post-fire effects for any fuels treatment. However, Brown's planar intercept and duff/litter profile method (Brown 1974; Brown and others 1982) may not estimate fuel loadings accurately in masticated areas because masticated fuels are highly irregular in shape and size and may violate the assumption of round fuel pieces. In this paper, we propose the cover-depth method as an alternative to the planar intercept method when estimating masticated fuel bed loadings. For the cover-depth method, square one meter frames are placed along a fuel transect and the percent cover of the fuel bed (masticated/woody material, litter, and duff) and masticated/woody only is estimated. Depth to mineral soil is then measured and the percent that

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is masticated/woody and the percent that is litter of the vertical profile are estimated. Loadings can then be estimated by multiplying the bulk densities presented here by the fuel bed depth and cover class.

Specifically our objectives were: 1) determine bulk densities of the total fuel bed and the individual woody, litter, and duff layers, 2) test a new method to estimate fuel loadings using cover and depth (cover-depth method), and 3) compare loadings estimated from the cover-depth method and the planar intercept method in masticated areas.

Methods

Study Sites

Treatment areas were located on the San Juan National Forest in southwestern Colorado (CO) and the Lassen National Forest in northern California (CA). We chose sites on the San Juan National Forest that had pre-treatment fuels data in two vegetation types: pinyon-juniper (*Pinus edulis* Engelm. and *Juniperus osteosperma* (Torr.) Little) and ponderosa pine-Gambel oak (*Pinus ponderosa* P. & C. Lawson and *Quercus gambelii* Nutt.). There were three pinyon-juniper sites, IC, MAHN, and KRC, and three ponderosa pine-Gambel oak sites, HAYD, MLCK, and NJAK. The California site, GRAYS, was dominated by Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) and had no pre-treatment fuels data. It was part of a separately funded Joint Fire Science Program proposal.

Both vertical and horizontal shaft machines were employed for mechanical treatment of fuels. Vertical shaft hydro-mowers or hydro-axes were used more commonly because of superior maneuverability on steep slopes and less ground disturbance. The size and distribution of fuel pieces after a treatment was dependent on the equipment, the operator, and site conditions. No material was removed from the CO sites. The CA site was thinned from below and merchantable trees were whole tree yarded before mastication treated activity fuels and small trees and shrubs.

Field Measurements

Existing fuel transects were used to compare loadings estimated from the planar intercept method and the cover-depth method on all sites. The CA site had two transects per plot, with transects radiating from plot center at right angles to each other. The CO sites had multiple transects per plot and followed FIREMON protocols (Lutes and others 2006). All transects were established from random start locations. We placed square frames (1 m^2 area) at 5, 10, 15, 20, and 25 meters at the CA site and at 15 and 24 meters at the CO sites on each transect (fig. 1). Photographs were taken approximately one meter above each frame in order to develop a visual aid for estimating cover. Total cover of duff, litter, and woody material and only woody cover (dead and down fuels and masticated material) were estimated for each frame using FIREMON cover classes (Lutes and others 2006).

If fuels were evenly distributed throughout the frame, depth was recorded at each corner and the middle of the plot to the nearest 0.5 cm. Fuel depth was measured from the top of the masticated material to the mineral soil. We

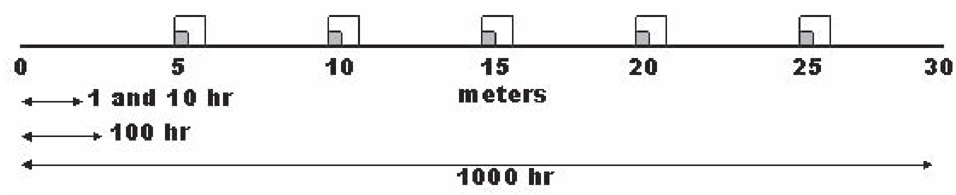

Figure 1—Example transect and frame layout of masticated fuel loading study. Each plot contained multiple transects.

estimated the percent of the vertical profile consisting of masticated/woody material and the percent litter following FIREMON methodology at each point where depth was measured. If fuel distribution inside the frame was markedly uneven, we assessed fuels by visually dividing the area into homogenous clumps. The proportion of each clump was recorded and fuel bed depth measured. We took one depth measurement for every 25 percent area the clump covered.

A 30 x 30 cm square sub-frame was placed in the lower left-hand corner of each one meter frame for collection of fuels to determine bulk density (fig. 1). If fuel bed total cover inside the sub-frame was 100 percent, depth was recorded using the same method as described for the 1 m^2 frame. Care was taken to minimize disturbance to the fuel bed while measuring depth. We did not sample the sub-frame if total cover was less than 100 percent because of the difficulty in calculating volume and bulk density. We collected all fuels inside the sub-frames with 100 percent cover to mineral soil separately by three fuel types: masticated/dead and down fuels, litter, and duff. Duff and litter were combined on the pinyon-juniper subplots because of difficulty in separating the two layers. While the fuels were generally arranged in layers, we found more mixing and compression of the woody material into the litter and duff layers than is seen on unmasticated sites. Woody material was placed into litter and duff collection bags if the particle's cross-section was in the litter or duff layer, leading to higher weights for these layers. Pieces extending outside the sub-frame were cut with clippers or a hand saw.

Dead and down woody fuels were counted along 23 m transects using the planar intercept method (Brown 1974). Masticated pieces are often irregularly shaped; therefore, diameters of the pieces were averaged for placement into a time-lag fuel size class (1, 10, 100, and 1000 hour). Duff and litter depths were recorded at 14.5 m and 24 m along each transect.

Data Analysis

Fuel bed samples from the sub-frames were dried at 105°C for 48 hours or until sample weight stabilized and then weighed to the nearest gram. Total fuel bed volume and individual fuel bed component volume was calculated by multiplying dimensions of the sub-frame by the average depth of the vertical profile. Bulk density of each sample was then calculated by dividing the oven-dry weight of the sample by the volume. Because of the mixing and compression of fuel bed layers and difficulty in separating the layers during collection, we feel it is more accurate to use the total subplot sample weight and the individual fuel component depth to calculate loadings and bulk densities.

Fuel bed loading was determined by multiplying the median bulk density of each vegetation type by the average depths of the one meter frames as if cover was 100 percent. The loadings were then reduced based on recorded cover class and clumping proportions. Loadings were calculated individually by fuel bed component and together. The total bulk density and loadings were calculated using average total depths and summed masticated, duff, and litter weights. All loadings reported here were calculated using the median total fuel bed bulk density and individual fuel bed component depth.

We also developed linear regression equations by vegetation type to estimate loadings using fuel bed depth as the independent variable (SAS Institute Inc. v 9.1). If the intercept was not significant ($p\text{-}value \geq 0.05$), it was dropped from the regression equation.

Five sub-samples of duff and litter from each vegetation type were randomly selected to determine mineral ash content because of potentially higher mineral soil contents in the fuel bed from the mixing and compression of layers during mastication. Higher mineral soil content increases bulk densities. The samples were placed in a muffle furnace at 450°C for 24 hours to combust all organic matter. The mineral ash content (percent) was calculated by dividing the weight of the mineral ash by the weight of the oven-dried sample.

Loadings were also calculated from data collected using the planar intercept/duff-litter profile method. We used the FIREMON v. 2.1.2 software to calculate these fuel loadings (Lutes and others 2006). All frame loadings and transects loadings were averaged by vegetation type and site to determine average site loadings.

Results and Discussion

We collected 17, 41, and 26 sub-frame (30 x 30 cm) samples on 3, 17, and 13 plots in the Jeffrey pine-white fir, ponderosa pine-oak, and pinyon-juniper vegetation types, respectively. Fuel bed depth was highest on the Jeffrey pine-white fir site and lowest on the Pinyon-Juniper sites (fig. 2). The masticated layer averaged approximately 3.0 cm for all vegetation types.

Average litter mineral ash content was 3.9 percent in the Jeffrey pine-white fir, 11.2 percent in the ponderosa pine-oak, and 26.2 percent in the pinyon-juniper (includes duff). Average mineral content of the duff samples were high. We found 32.4 and 42.4 percent mineral content for Jeffrey pine-white fir and ponderosa pine-oak, respectively. The high mineral content for the pinyon-juniper litter samples was probably a result of combining the duff and litter into one sample bag during collection. The pinyon-juniper sites also have a much higher percentage of bare soil than the other vegetation types which may have resulted in mixing of bare soil into the duff and litter material when the mastication treatment was applied.

Median fuel bed bulk density was very similar for Jeffrey pine-white fir and ponderosa pine-oak (129 and 128 kg m^{-3}), but pinyon-juniper bulk density was much higher (226 kg m^{-3}) (fig. 3a). Median bulk density of the masticated/woody layer only was 155, 136, and 218 kg m^{-3} for Jeffrey pine-white fir, ponderosa pine-oak, and pinyon-juniper, respectively (fig. 3b). Variability decreased when litter, duff, and woody material samples were combined into one forest floor sample per plot to calculate bulk densities (fig.3). This was likely due to the difficulty of accurately separating the individual fuel components during collection.

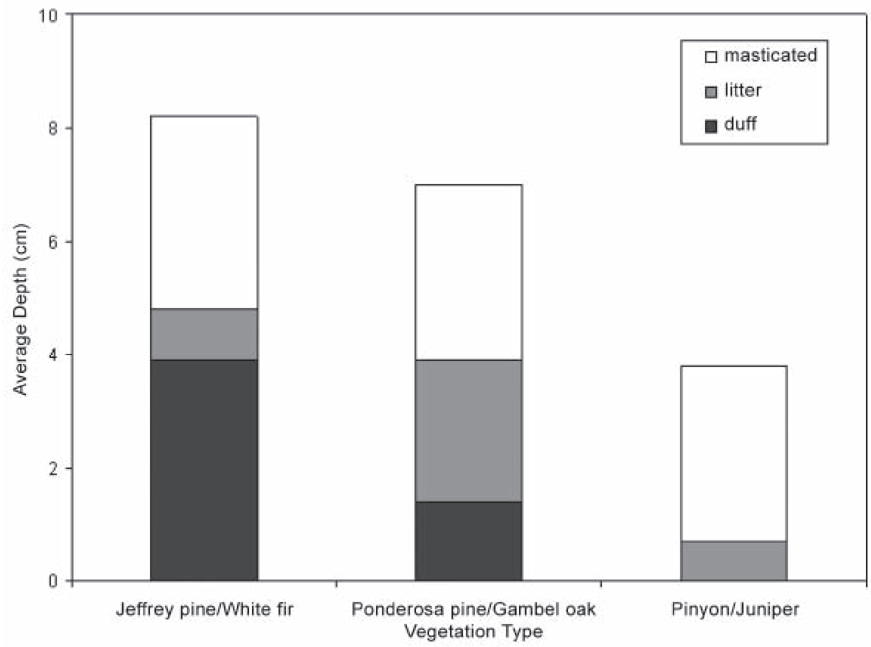

Figure 2—Average depth of surface fuels and forest floor by vegetation and fuel type.

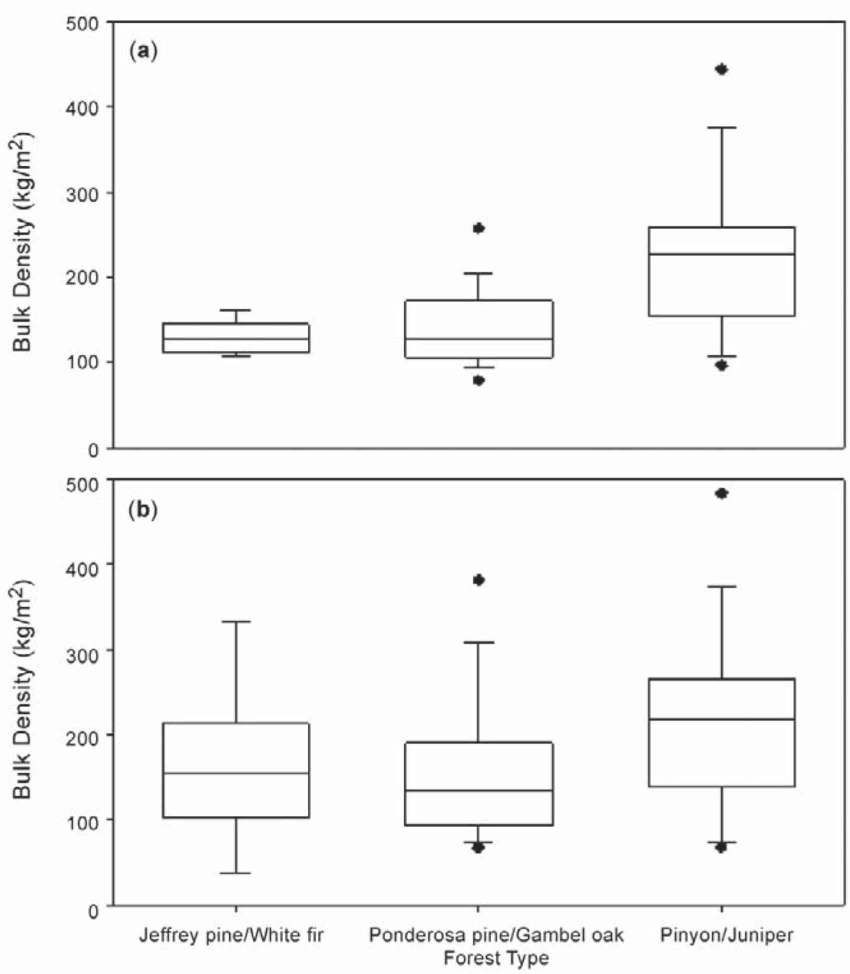

Figure 3—Bulk density of (a) total surface and forest floor fuel loadings and (b) only surface masticated and woody fuel loadings in subplots by vegetation type. Solid lines represent median values. Dots are 5th and 95th percentile outliers.

Total fuel bed loadings calculated from the sub-frames where cover was 100 percent were highest in the Jeffrey pine-white fir type (9.6 kg m^{-2} (42.8 tons/acre)), followed by ponderosa pine-oak (8.2 kg m^{-2} (36.6 tons/acre)) and pinyon-juniper (7.3 kg m^{-2} (32.6 tons/acre)). Average masticated/woody fuel loadings were highest in the pinyon-juniper plots (5.6 kg m^{-2} (25.0 tons/acre)). Masticated loadings in the Jeffrey pine-white fir and ponderosa pine-Gambel oak plots were similar (4.0 and 3.9 kg m^{-2} (17.8 and 17.4 tons/acre)). Loadings increased generally linearly with depth. Variability was high except for the Jeffrey pine-white fir type (fig. 4). The intercept was non-significant for only the Jeffrey pine-white fir type. Regressions equations for estimating total loadings are given in figure 4.

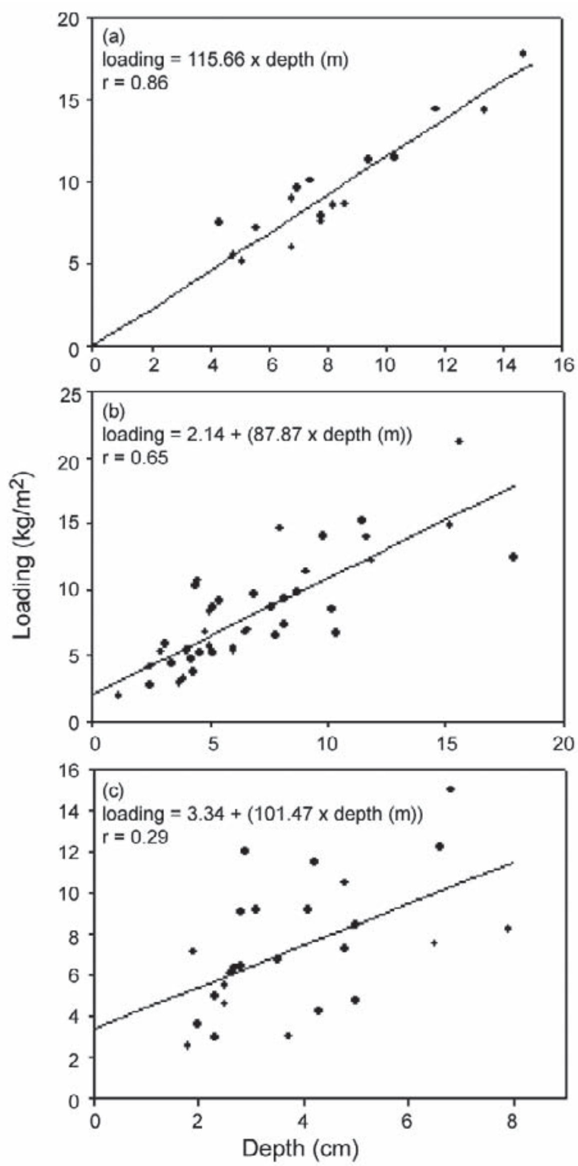

Figure 4—Regression showing relationship of total fuel bed depth and loading for samples in (a) Jeffrey pine-white fir, (b) ponderosa pine-Gambel oak, and (c) pinyon-juniper vegetation types.

Woody fuel loadings estimated with the cover-depth method were usually lower (fig. 5a) and duff and litter loadings higher (fig. 5b) than the loadings estimated with the planar intercept method. The difference between the two methods can be attributed to both differences in average depths and bulk densities. The cover-depth method requires more depth measurements (5 per 1 m^2 per frame) than the planar intercept method (2 per transect). The duff and litter bulk densities calculated from the 30 x 30 cm sub-frames were higher than the ones used by FIREMON to calculate loadings (44 kg m^{-3} for litter and 106 kg m^{-3} for duff), especially for the pinyon-juniper vegetation type.

The Jeffrey pine-white fir vegetation type had the strongest correlation between loading and depth. This could be due to more uniform stand conditions than the ponderosa pine-Gambel oak and pinyon-juniper types, both inherently and from treatment application. Also, all data collected in the Jeffrey pine-white fir type came from one site, whereas data for the other vegetation types were collected across several sites. The pinyon-juniper type was the most variable type and had the highest bulk density.

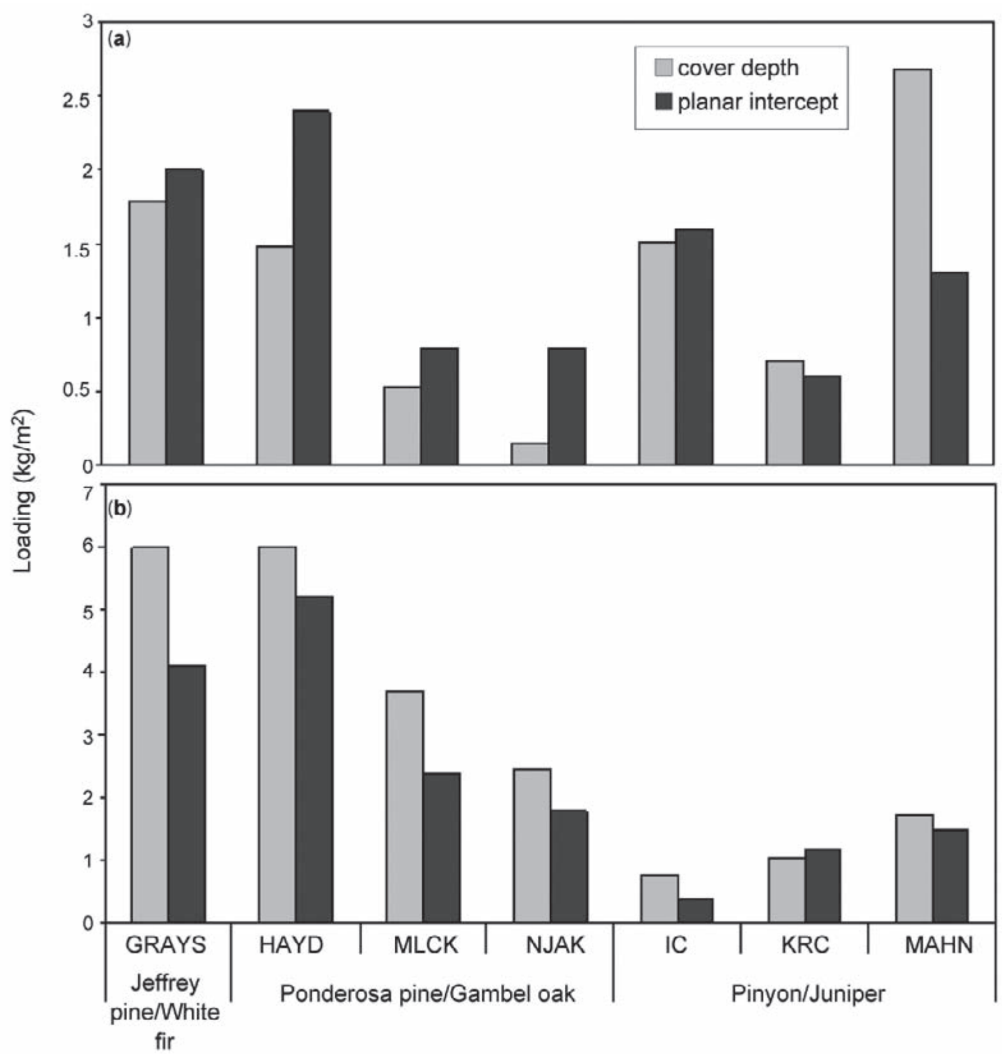

Figure 5—(a) Masticated and down woody and (b) litter and duff fuel loading estimations using the cover-depth method and Brown's planar intercept/duff-litter profile method.

The cover-depth method estimated higher duff and litter loadings and lower woody fuel loadings than the planar intercept method for most sites. Our next step is to perform an accuracy assessment based on the data collected in the sub-frames to determine which method is better for estimating fuel bed loadings in masticated areas. We also plan to assess if fewer depth measurements would produce similar results, thereby speeding the data collection process. If the cover-depth method proves to more accurately estimate loadings than the planar intercept method, more sampling in more vegetation types will be necessary to completely test this method.

Aknowledgements

We wish to thank Duncan Lutes and Robert Keane for their advice during the project development and data analysis stages and for review of the manuscript.

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Variability in Loading of Mechanically Masticated Fuel Beds in Northern California and Southwestern Oregon

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Abstract*—The use of mechanical mastication to treat non-merchantable fuels is becoming increasingly popular, but loadings and other characteristics of masticated fuel beds are unknown. Surveys of eight recently masticated sites in northern California and southwestern Oregon indicate that significant site level differences were detected for 1 hr and 10 hr time-lag classes and total woody fuel loading ($P < 0.0001$). The majority of the total woody fuel loading occurred in the 10 hr time-lag class (76.9 ± 14.1 percent) at all 10 sites. At one particular site, planar intercept estimates of woody fuel loading were 181.7 (± 20.3) % higher than estimates using a plot-based method. When the actual average squared quadratic mean diameter values (1 hr = 0.06 cm^2, 10 hr = 1.09 cm^2 and 100 hr = 11.8 cm^2) were used, woody fuel loading estimates between the two methods did not differ statistically. Across sites, fuel depth was not a significant predictor of fuel loading ($R^2 = 0.24$, $P = 0.22$). However, a significant relationship between fuel depth and loading was found at the individual site level, except for one site (WFR). Species masticated, mastication machinery used, and operator experience are some of the potential reasons why the depth to loading relationship differed among sites.*

Introduction

In the foothill and montane regions of northern California and southwestern Oregon, the combination of weather and fuel conditions has led to many recent catastrophic wildfires (e.g., Fountain, Jones and Biscuit fires). These events are a deviation from the historical fire regime of relatively frequent, low to moderate intensity fires of this region (Skinner and Chang 1996, Taylor and Skinner 2003). Due to the successful fire suppression over the last century (Agee 1993), wildfire size and intensity has increased, bringing national attention to fire management and policy. Public awareness is especially pronounced in residential communities located within or adjacent to areas of elevated fuel accumulation. Solutions to reduce the risk of wildfire in these areas have often resorted to the use of mechanical fuel treatments.

One method of mechanically treating non-merchantable fuels that has become increasingly popular in the western United States is mastication. Mastication is the process of converting live or dead standing biomass into surface fuel by "chewing" or breaking up larger pieces into smaller portions by the means of a front-end or boom-mounted rotary blade or head (fig. 1). In northern California and southwestern Oregon, mastication equipment is primarily used to treat shrub and small tree fuels, typically along fuel breaks and within the wildland-urban interface. Machinery used to masticate woody fuels is highly varied but have similar mechanical treatment properties.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Figure 1—General masticator types: front-end mounted, Takeuchi®,TL150 w/ FECON Bull hog®shredder head (left) and a boom-mounted FECON Bull hog® shredder head mounted on an excavator (right). (left-Photo courtesy of Nancy Curran, USDA Forest Service).

Mastication results in the translocation of typically living shrub and midstory fuel beds, thereby increasing dead surface woody fuel loading (fig. 2). The reduction of potential ladder fuels and compaction of surface fuels as a result of mastication are appealing to land managers and have contributed to the dramatic increase in its use.

While the popularity of mastication to treat fuels is increasing, little work has been conducted to quantify and characterize the variability in masticated fuel beds. This lack of information is an important shortcoming to installing subsequent fuel treatments and an impediment to modeling potential fire behavior and effects in treated areas. In order to provide land managers with appropriate information regarding the use of mastication and subsequent fire behavior and effects, research accurately quantifying and characterizing masticated fuel beds is necessary.

Figure 2—Mad River (MAD) masticated site contrasting untreated shrub fuels in the background with treated dead woody fuels in the foreground.

The purpose of this study was to provide preliminary analyses characterizing the variability among masticated sites in northern California and southwestern Oregon as part of a larger study that aims to create custom fuels models for masticated fuel beds. Specifically, the objectives of this paper were to:

1) Quantify site level variability in masticated fuel bed loading
2) Compare and contrast methods of estimating fuel loading in masticated areas
3) Determine if fuel bed depth is significantly related to total woody fuel loading

Methods

Study Sites

Throughout northern California and southwestern Oregon, eight study sites were selected to investigate variability in loading of masticated fuel beds. Study sites were located primarily on federal land (USFS, BLM and NPS), with one site on a private forest (Whitmore). The vegetation masticated within each of the study sites varied but was predominantly shrub (*Arctostaphylos* spp., *Ceanothus* spp.) and/or small hardwood tree species (*Lithocarpus densiflorus*, *Arbutus menziesii*). All mastication treatments were completed using either a front-end or boom-mounted masticator, and all mastication was conducted between November 2002 and May 2005 (table 1).

Field Sampling

Surface fuel loading was calculated for each study site using two methods: the planar intercept (Brown's transect) method (Brown 1974) and a plot-based sampling method. At each study site, long baseline transects traversing the treated areas were placed at random azimuths. At 25 m increments along these baseline transects, a Browns transect was established at a random azimuth. Brown's transect lengths were typically 20 m but occasionally less when the transect neared the edge of a treated area. At each Brown's transect, 1 hr

Table 1—Site names, locations, date of mastication and masticator type for all masticated study sites in northern California and southwestern Oregon, U.S.A. (BM= boom-mounted, FE = front-end mounted).

Site Code	Site Name	Location	Mastication Date	Masticator Type
APP	Applegate Valley	Applegate Valley, Oregon (BLM)	Apr./May 2005	BM-Slashbuster® brush cutter
CFR	Challenge Fuel Reduction	Plumas National Forest, California (USFS)	Dec. 2002 Mar. 2003	BM-Slashbuster® mounted on an excavator
IMR	Iron Mountain Rd.	Redding, California (BLM)	Nov. 2004	FE-Masticating head on an ASV Positrack™
MAD	Mad River	Six Rivers National Forest, California (USFS)	Dec. 2004	FE-Takeuchi®,TL150 w/ FECON Bull hog® shredder head
SFR	Sierraville Fuel Reduction	Tahoe National Forest, California (USFS)	May/June 2003	FE-Rayco® Forestry Mower (small) on a bulldozer
TAY	Taylor Ridge	Klamath National Forest, California (USFS)	Apr./May 2005	BM-"Brontosaurus" head on excavator
WFR	Whitmore Fuel Reduction	Whitmore, California (Private)	May 2003	FE-Rayco® Forestry Mower (small) on a bulldozer
WHI	Whiskeytown	Whiskeytown NRA (NPS) California	Nov. 2002	FE-Slashbuster® on an ASV Positrack™

(0.0-0.6 cm-diameter) and 10 hr (0.6-2.54 cm-diameter) time-lag fuel size classes were tallied along the first 2 m, while 100 hr (2.54-7.6 cm) fuel particles were tallied along the first 4 m. The entire transect length was surveyed for 1000 hr (>7.6 cm) fuel particles and their actual diameters were measured, species recorded, and decomposition category (sound or rotten) assigned. Since masticated fuel particles are often irregularly shaped, determination of the size class of each particle was made along the narrowest diameter that intersected the planar transect. Fuel bed depth measurements were made at three points along the transect (5 m, 10 m, and 15 m).

For the plot-based sampling method, a 50 cm x 50 cm metal frame was placed at the 7 m mark along the planar intercept transect. All woody fuels inside the frame were collected; in the event that a woody fuel particle crossed the frame, the piece was cut along the boundary and the interior portion was retained. To characterize fuel bed bulk density, four large pins were placed 10 cm from each of the frame corners. At each pin, fuel bed depth was measured by progressive removal of each fuel layer. All woody fuels were separated in the lab by time-lag classes and then oven-dried for at least 72 hrs at 75 °C in a mechanical convection oven and then weighed on an analytical balance.

At the Mad River (MAD) mastication site, loading estimates for woody fuels were calculated using the composite squared average quadratic mean diameter values for each fuel size class (1 hr = 0.08 cm^2, 10 hr = 1.3 cm^2, 100 hr = 11.9 cm^2) provided by Brown (1974). In addition, woody fuel loading was calculated using actual squared average quadratic mean diameter values (1 hr = 0.06 cm^2, 10 hr = 1.09 cm^2 and 100 hr = 11.8 cm^2) determined from collected fuels. Fuel quadratic mean diameters were generated by measuring the average of the minimum and maximum squared diameters for a subsample of fuel particle collected with the plot sampling method (1 hr, n = 1187; 10 hr, n = 170; 100 hr, n = 4).

Data Analysis

Means and standard errors were calculated for site-level estimates of total fuel loading and loading of different time-lag classes for both the planar intercept and the plot-based sampling methods. A one-way analysis of variance (ANOVA) was conducted to detect a site level effect for mean total woody fuel loading and mean loading by time-lag classes. If differences were detected, a post-hoc Bonferoni means comparison test was used to detect significant differences among sites (Sokal and Rohlf 1995). Linear regression analysis was used to determine the relationship between total woody fuel loading calculations and fuel bed depth across all sites and at the individual site level. All statistical tests were computed using STATA (Statacorp 2005) and statistical significance was based on an $\alpha = 0.05$.

Results

Site Level Variation

For estimates made using the plot-based method, sites differed significantly in total woody fuel loading and loading by 1 hr and 10 hr time-lag classes ($P < 0.001$; table 2). The MAD site had the highest total woody fuel loading (63.4 Mg ha^{-1}) and contained more 10 hr fuel loading than all sites except Applegate Valley (APP) and Taylor Ridge (TAY; fig. 3). The

Table 2—Plot based sampling method estimates of mean fuel loading (± standard error) of woody fuel classes and fuel height for masticated sites in northern California and southwestern Oregon.

		Plot-based sampling method					
Site	**n**	**1 hr**	**10 hr**	**100 hr**	**1000 hr**	**Total Woody**	**Fuel Depth**
		(Mg ha^{-1})					*(cm)*
APP	15	12.3 (2.8)	24.6 (4.3)	8.6 (4.8)	5.3 (5.3)	50.7 (9.9)	6.9 (0.7)
CFR	40	8.1 (0.7)	19.2 (1.6)	7.9 (1.7)	3.5 (2.2)	38.7 (7.2)	N/A
IMR	15	6.2 (1.7)	13.8 (2.5)	3.6 (1.7)	0.0 (0.0)	23.6 (6.9)	4.9 (0.8)
MAD	15	23.5 (2.6)	34.8 (2.6)	5.1 (2.5)	0.0 (0.0)	63.4 (7.8)	4.6 (0.8)
SFR	15	5.2 (1.0)	11.1 (1.4)	6.6 (2.9)	0.0 (0.0)	22.9 (5.4)	3.2 (0.5)
TAY	15	13.2 (2.9)	21.7 (2.7)	2.1 (0.8)	0.0 (0.0)	37.0 (6.4)	5.0 (0.5)
WFR	40	4.4 (0.7)	9.4 (1.7)	1.6 (0.6)	0.0 (0.0)	15.3 (2.8)	4.4 (0.6)
WHI	15	11.8 (2.4)	16.4 (1.8)	3.6 (1.5)	0.0 (0.0)	31.8 (5.2)	5.8 (0.3)
All Sites		10.6 (2.2)	18.9 (2.9)	4.9 (0.9)	1.1 (2.8)	35.4 (2.8)	4.9 (0.6)

Whitmore fuel reduction (WFR) site had the lowest total woody fuel loading (15.3 Mg ha^{-1}) and contained significantly less in 10-hr fuel loading than all other masticated sites (fig. 3). Post-mastication fuel loading was concentrated in the 10-hr and 100-hr time-lag classes, which made up 76.9 (± 14.1) percent and 11.5 (± 5.8) percent of the total woody fuel load, respectively. Loading of 10-hr time-lag class was approximately 250-300 percent greater in some sites (e.g., MAD, APP) than others (e.g., SFR, WFR).

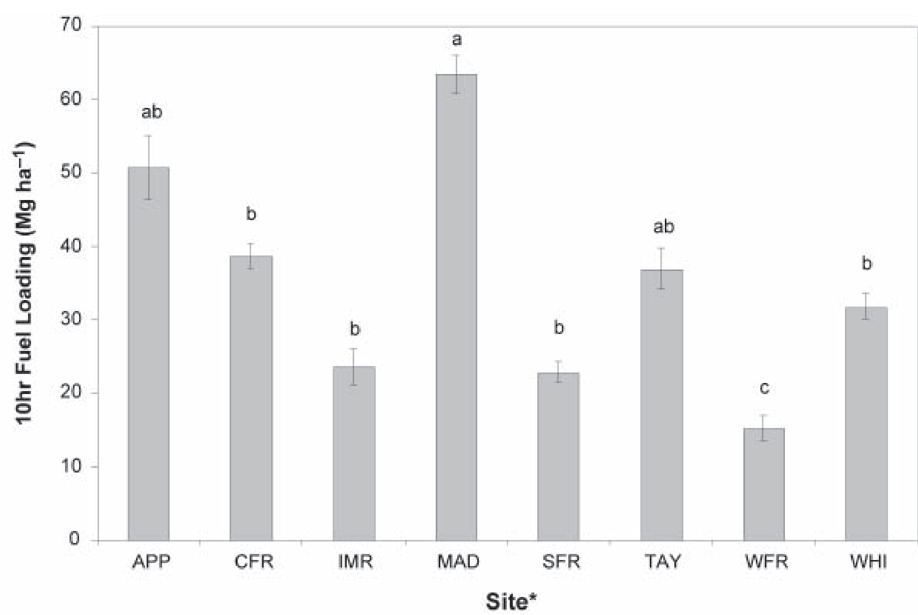

Figure 3—Ten-hour fuel loading in masticated sites in northern California and southwestern Oregon across all sites from the plot-based method estimates (letters above error bars denote significant difference between sites using Bonferoni means comparison test).* = full site names provided in table 1.

Fuel Load Methods Comparison

At the MAD site, total woody fuel estimates using the Brown's planar intercept method with the composite squared average quadratic mean diameter values given by Brown (1974) were 180.5 (± 55.4) percent higher than the estimates made using the plot-based sampling method. Preliminary results from the MAD site suggest that the actual average quadratic mean diameters of masticated particles are smaller than the composite values given in Brown's formula (1974). When the actual quadratic mean diameter measures at the MAD site were used in the fuel loading calculations, the total loading values no longer differed from those estimated using the plot-based method (fig. 4). Even though the total fuel loading did not differ, Brown's transect values were substantially greater than the plot-based sample values for 10-hr fuels and substantially less than the plot-based sample values for 1-hr fuels (fig. 4).

Predictors of Total Woody Fuel Loading

Land managers and researchers are often interested in simplifying measures of fuel loading to improve cost effectiveness and sampling efficiency. Fuel depth is a measure that is often sought to correlate with total woody fuel loading. Average fuel depth values for masticated sites ranged from 3.0 to 6.9 cm. Based on linear regression analysis, fuel depth and total woody fuel loading over all study sites were not related ($P = 0.22$, $R^2 = 0.24$). However, within sites, a significant relationship between depth and woody fuel loading

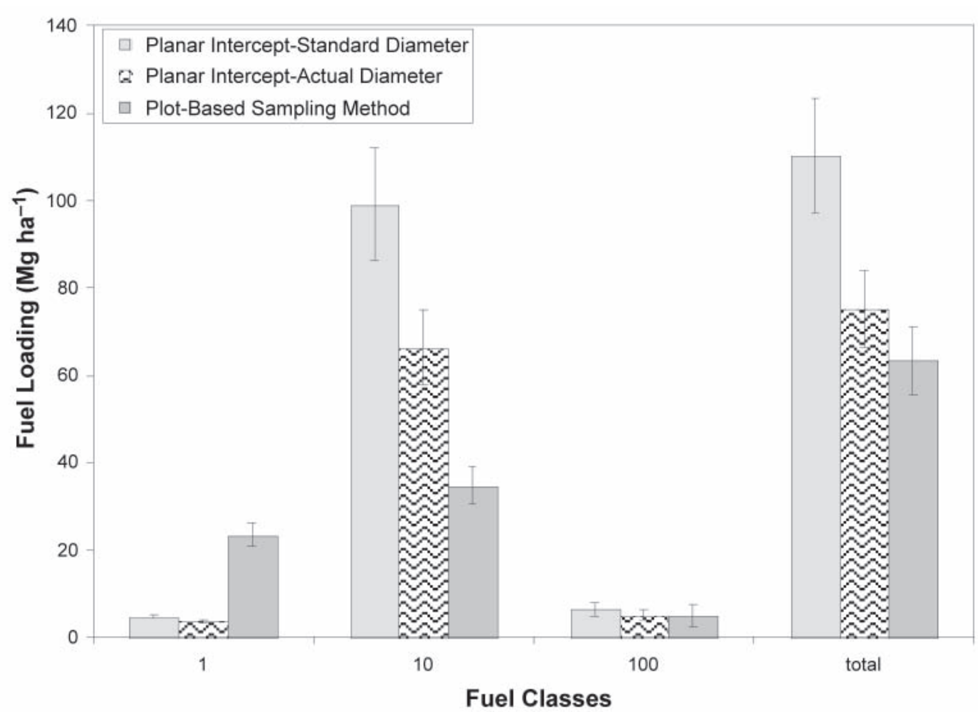

Figure 4—Total woody fuel loading comparisons of the planar intercept method with standard calculation of quadratic mean diameter, planar intercept method with actual quadratic mean diameter and estimates from the plot-based sampling method for the MAD mastication site.

was found at all except the WFR site ($R^2 = 0.03$, $P = 0.28$). The MAD site had the strongest relationship between depth, and woody fuel loading of all sites ($R^2 = 0.84$), while the R^2 values of other sites ranged from 0.24 to 0.74. Equations are still being developed and are not shown here.

Discussion

Variation in woody fuel loading has many implications for both fire behavior and effects. The results of this study suggest that large variations in woody fuel loading exist across 1-hr and 10-hr time-lag classes within masticated areas of northern California and southwestern Oregon. Site level differences in total woody fuel loading found in this study were largely driven by the MAD and WFR sites, which had both the highest and lowest fuel loading in the 10-hr time-lag class, respectively (fig. 3). Variation in woody fuel loading of masticated sites in our study suggests that different fuel models may be necessary to accurately assess fire behavior and effects in these areas.

Site level variation in total woody fuel loading across all time-lag fuel classes for masticated sites was not entirely unexpected. Primary sources of variation in masticated fuel beds may be linked to pretreatment biomass and time since mastication, although secondary factors such as decomposition rate and time since disturbance may be important in determining total woody fuel loading. Masticator type, mastication intensity, and the size and/or age of treated fuels are likely contributors to variation in the proportion of fuels in different time-lag classes.

Independent of the variability found in loading, fine fuel particles (particularly 10 hr) were the dominant woody fuel across all sites. These findings have broader implications, suggesting that in spite of the many different types of masticators used and the level of variability in loading, there are consistent trends in the size of the fuel particles produced by mastication. The presence and quantity of fine fuel particles are well-known to influence fire behavior (Rothermel 1983) and may strongly influence fire effects in masticated areas.

When actual quadratic mean diameter measurements of masticated particles were used in the planar intercept fuel loading calculations, the two methods produced similar estimates of fuel loading. However, the planar intercept method underestimated 1-hr fuel loading while simultaneously overestimating 10-hr fuel loading. An explanation for this inconsistency may be due to the fact that the Brown's transect estimates were made in the field after significant fall rains, while the material collected with the plot-based method was dried in an oven prior to sorting into size categories. Prolonged drying of fuels may have caused a reduction in particle diameter, with 10-hr fuels in the field becoming 1-hr fuels in the lab. Since fires occur when the fuels are dry, the numbers obtained with the plot-based method have greater applicability to fire behavior and fire effects modeling. Results to date suggest that either method can be used to estimate total woody fuel loading (especially if the fuels are dry), but that squared averaged quadratic mean diameters specific to masticated fuels should be used in calculations with the planar intercept method. So far we have only made measurements of fuel particle size at one site and additional measurements are being made to determine if average particle size differs among sites.

While the plot-based sampling method appears to be useful for estimating loading of masticated fuels, several disadvantages exist. The plot-based method is time intensive and therefore, more costly and doesn't evaluate enough area to appropriately account for relatively uncommon 1000 hr fuels, compared to the planar intercept method.

Fuel depth was not found to be a significant predictor of total woody fuel loading possibly because of differences among sites caused by masticator type, operator experience, mastication effort, and vegetation type. It may therefore, not be feasible to create a universal equation relating depth to loading for this type of masticated fuel. While a relationship across all sites was not observed, all but one site's total woody fuel loading was significantly related to fuel depth. Relationships between fuel depth and woody loading may aid in determining simpler and faster means to calculating woody fuel loading within masticated sites. Surrogate measures of total woody fuel loading have been established for other areas (Fulé and Covington 1994) and deserve further investigation in masticated fuel beds.

The quantification and characterization of fuel loading in masticated sites have ramifications for the prediction of fire behavior and effects. Managers and researchers (Bradley and others 2006; Knapp, personal observation) report a high degree of variability in fire behavior with prescribed burning in masticated fuels, which may partially be related to variations in fuel loading. Differences in loading have additionally been shown to influence depth and duration of lethal soil temperatures during burning (Busse and others 2005). In spite of the growing popularity and use of mastication, many unknown factors still exist in characterizing this novel fuel type. The level of variation encountered within our study suggests that several custom fuel models may be necessary to adequately predict fire behavior and effects. Additional work to determine if differences in average particle size exist among sites, how these differences relate to site parameters, and the extent to which mastication alters the surface area to volume ratio of fuel particles, is in progress.

Acknowledgments

These preliminary results are a part of a larger study investigating the development of custom models for masticated fuel beds. Funding for this project was provided by the Joint Fire Science Program. Earlier drafts of this report were improved with the help of Emily Orling. This project was greatly advanced by Elishau Dotson and Emily Orling, who assisted with field data collection.

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Creating a Fuels Baseline and Establishing Fire Frequency Relationships to Develop a Landscape Management Strategy at the Savannah River Site

Bernard R. Parresol[1], Dan Shea[2], and Roger Ottmar[3]

Abstract—*The Savannah River Site is a Department of Energy Nuclear Defense Facility and a National Environmental Research Park located in the upper coastal plain of South Carolina. Prescribed burning is conducted on 15,000 to 20,000 ac annually. We modified standard forest inventory methods to incorporate a complete assessment of fuel components on 622 plots, assessing coarse woody debris, ladder fuels, and the litter and duff layers. Because of deficiencies in south-wide data on litter-duff bulk densities, which are the fuels most often consumed in prescribed fires, we developed new bulk density relationships. Total surface fuel loading across the landscape ranged from 0.8 to 48.7 tons/ac. The variables basal area, stand age, and site index were important in accounting for variability in ladder fuel, coarse woody debris, and litter-duff for pine types. For a given pine stand condition, litter-duff loading decreased in direct proportion to the number of burns in the preceding thirty years. Ladder fuels for loblolly and longleaf increased in direct proportion to the years since the last prescribed burn. The pattern of fuel loading on the SRS reflects stand dynamics, stand management and fire management. It is suggested that the Forest Inventory and Analysis Program can easily modify sampling protocols to incorporate collection of fuels data.*

Introduction

The Savannah River Site (SRS) is a 198,344 ac land base controlled by the Department of Energy. The SRS is a Nuclear Defense Facility and a National Environmental Research Park. The SRS is located on the Upper Coastal Plain and Sandhills physiographic provinces, south of the city of Aiken, South Carolina (figure 1). Created in 1951, the SRS today contains approximately 182,420 ac of forested landscape divided into 6,009 stands across six expansive management areas.

When the SRS was established, approximately 80,000 acres were in old-fields and the balance consisted of cut over forest land with low stocking (Kilgo and Blake 2005). The planting of the old fields and cutover forests with (non-native) slash pine (*Pinus echinata*), loblolly pine (*P. taeda*) and longleaf pine (*P. palustris*) created a large block in a narrow age class and a dynamic fuel loading problem. Approximately 14 wildfires, primarily surface fires, occur each year. An effective prescribed burning program was not initiated until the mid 1970's. Today prescribed burning is conducted on 15,000 to 20,000 acres annually to reduce fire hazards and to enhance ecological communities associated with longleaf fire savannas. The SRS has also utilized herbicides to reduce mid-story vegetation, primarily for management of the endangered

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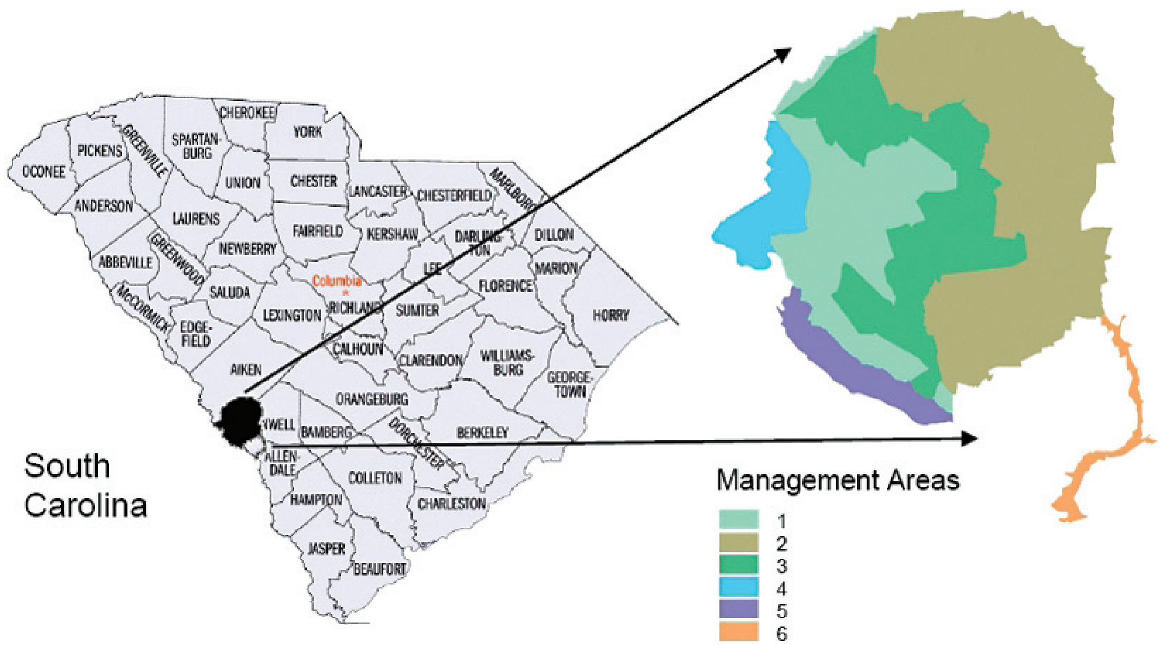


Figure 1—Location of the Savannah River Site in Aiken, Barnwell, and Allendale counties, South Carolina. The six expansive management areas are shown.

red cockaded woodpecker (*Picoides borealis*), and mechanical shredding. More recently sub-merchantable woody fuels are being considered as a fuel supply for a bioenergy fired power facility on-site. However, prescribed burning is the most cost effective technique on per acre basis. Because of smoke management constraints, which limits prescribed burning and the high costs of alternative fuel treatments, there was an identified need to optimize fuels management, including the types of stands to be treated, their location on the landscape, and the frequency of treatment.

The Need for Fuels Inventory

There are currently no periodic regional or national fuels inventories being conducted. The lack of periodic field inventories makes it impossible to gauge the effectiveness of national, regional or local fuels and fire management policies and strategies. Remote sensing methods are largely unable to accurately estimate surface fuels (Keane and others 2000) that are the main contributors to fire behavior in the South. Because of the identified need to optimize fuels management at the Savannah River Site, the periodic inventories conducted on-site were modified to include measurement of forest floor fuel variables. Small mid-story trees that contribute to ladder fuel were being captured by the existing design. Our objective was to establish a fuel loading baseline as a function of stand variables as a reference for Site management, to allocate fuel treatment strategies, and to estimate the prescribed burning frequency needed to achieve wildfire behavior objectives.

Inventory Design and Fuels Sampling

A systematic layout of sample points was installed using an approximate 1000- by 1000-meter grid over the entire SRS land base, except for the narrow corridor along the Lower Three Runs Creek that extends from the southeast boundary to the Savannah River. This resulted in approximately one sample plot per every 250 acres of the SRS, or 773 plot locations. This plot density is high from the traditional inventory perspective. Of the 773 plots, only 657 fell on forested areas. An additional data source of 62 plots that fall on the SRS from the Forest Inventory and Analysis (FIA) regional inventory (conducted by the USDA Forest Service) are included in the plot database. Combining the 62 regional inventory plots that fall on the SRS with the 657 new SRS plots produces a potential sample of 719 points (figure 2).

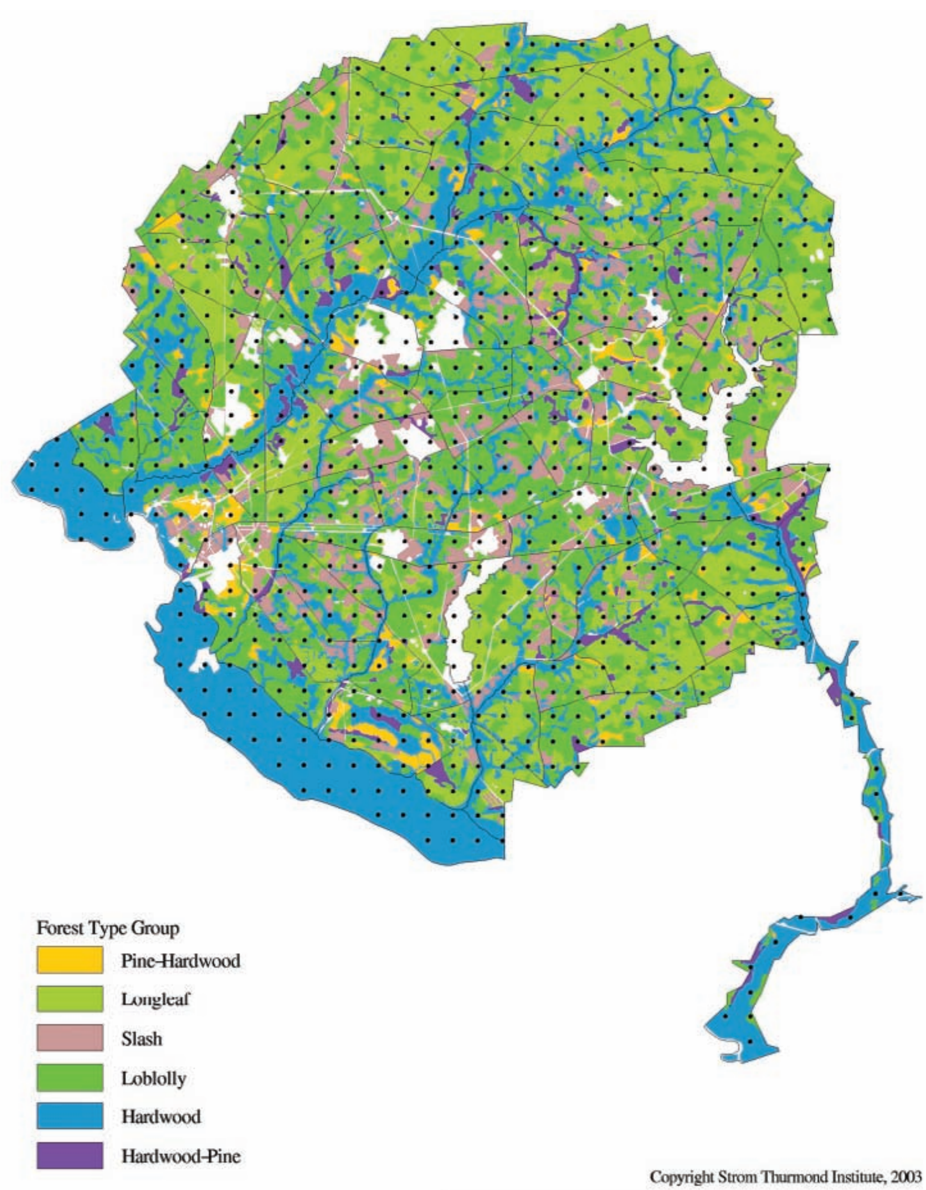


Figure 2—Systematic layout of inventory plots on the Savannah River Site and spatial distribution of the broad forest type groups.

The plot design used is a standard FIA design commonly used in the southeastern U.S. It consists of a cluster of five subplots, 70 feet between points, which are normally laid out in the scheme shown in figure 3. Two nested plot-types are established at each of these five subplot center points. One of these plot-types is a variable-radius plot using a 37.5-factor angle prism for sampling trees that are 5-inches or larger in diameter at breast height (dbh). Nested at the same point is a circular fixed-radius 1/300th-acre plot for sampling trees from 1- to 5-inches in diameter. All sampled trees from the five subplots are combined, meaning that the operative prism factor for the sample location (that is, the 5 subplots) is 7.5, and the cumulative area of the fixed-radius plots is 1/60th of an acre. The pattern shown in figure 3 is the standard subplot layout, but the arrangement was altered when necessary to insure that all subplots fall within the same stand or forest condition found at subplot 1. It was necessary to alter this arrangement in about a third of the plots on the SRS. Subplot 1 is never moved from the initially selected point location. Rotation only occurs on subplot 2 to 5, for the purpose of matching their forest condition with that of subplot 1.

In-between the five subplots are four planar transects used for measuring coarse woody debris (CWD) forest floor fuel (figure 4). These measurements are on dead woody material that has separated from the plant (trees and shrubs) that produced it, or from main stems of dead trees that have fallen down. The method for measuring CWD uses a vertical-plane-intersect plot that either counts by size class for smaller material or measures the individual diameters for diameters greater than 3 inches the pieces of CWD material that break the plot plane (Brown 1974). As shown in figure 4, counts were made along a 10-foot section of the transect line of dead downed material with diameters of 0-0.25 inches (1-hour fuels). Counts of pieces with diameters in the 0.25-1.0 inch range (10-hour fuels) were made at the same time along the same 10-foot section of the transect line. Counts were made of pieces with diameters of 1.0-3.0 inches (100-hour fuels) along a 20-foot transect. Dead downed material larger than 3 inches diameter encountered along the full 70-foot transect had their individual diameters at the point of intersection measured, and their condition was classed as either solid or

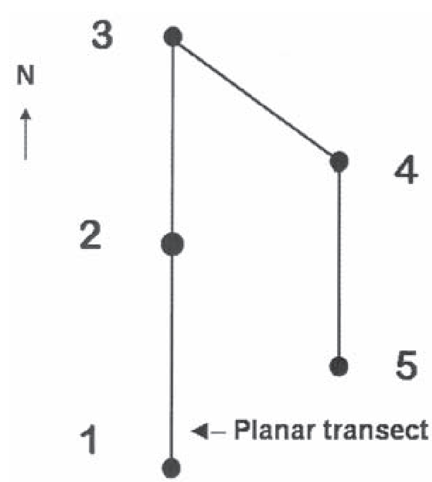


Figure 3—Plot design used at the Savannah River Site showing standard orientation of the 5 subplots and the 4 planar transects.

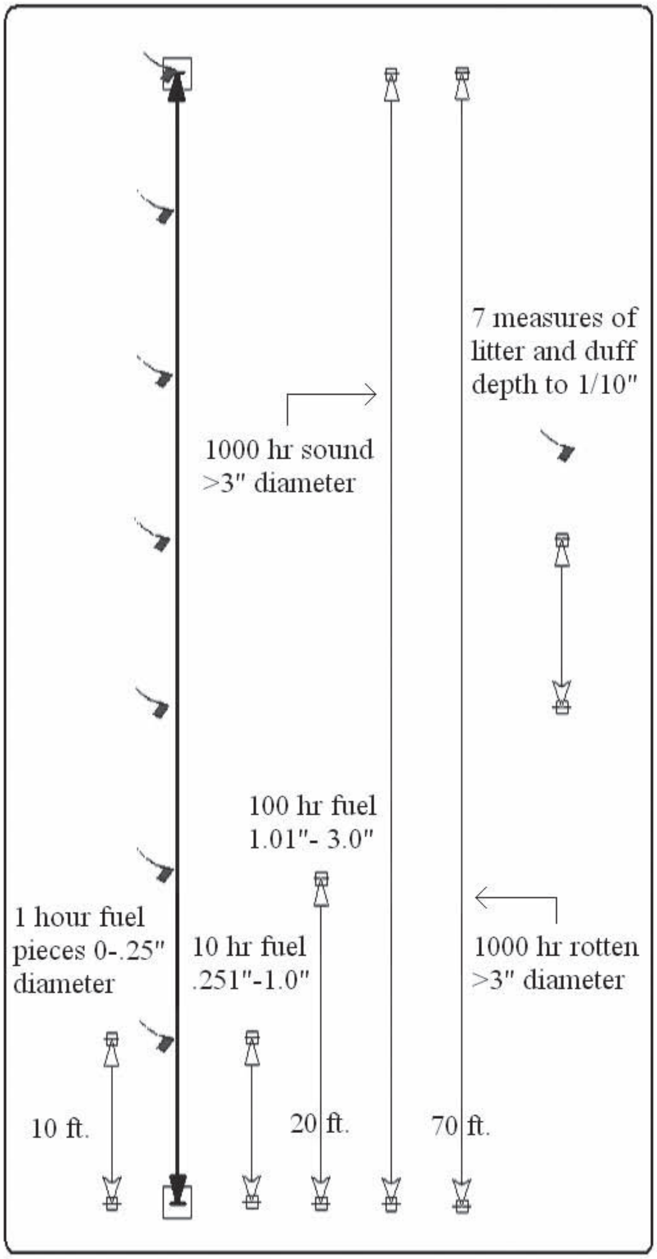


Figure 4—Design of the Brown's planar transect for measuring coarse woody debris and litter and duff depths.

rotten. Seven measurements of litter and duff depth to the nearest $1/10^{th}$ inch were taken at ten-foot intervals along each of the 70-foot transect lines. An inventory of 622 plots (from the 719 possible) was started in March 1999 and completed in January 2002.

Bulk Density Study

Because of deficiencies in south-wide data on litter-duff bulk densities, which are the fuels most often consumed in prescribed fires, a study was undertaken to develop new bulk density relationships. There have been several studies in the past to collect bulk density values for forested areas of the south. However, these studies were very limited in scope (Scholl and Waldrop 1999) or were completed at locations other than at the Savannah River Site (Ottmar and Vihnanek 2000; Ottmar and others 2003; McNab and others 1978). The primary objective for the study was to determine bulk density conversion factors to convert litter and duff depth values in inches to forest floor fuel values in tons per acre. This was done for combinations of four common forest types (loblolly/slash pine, longleaf pine, pine and hardwood mix, upland hardwood), 3 age classes (5-20, 20-40, 40+ years old) and 3 categories of burning history (0-3, 3-10, 10+ years since last burn).

Bulk density sampling points were randomly selected from the 622 inventory plots of the 1999-2002 inventory period. Random points were selected from groups of plots based on the aforementioned stand type, stand age, and rough age. Within each sample site, subplot 1 was designated as the plot center. The lower left bulk density sample square point was established 33 feet from the plot center at each of the four cardinal directions (figure 5). A 12-inch beveled steel square was positioned on top of the forest floor. Twelve markers (6 inch gutter nails) were then placed in a grid pattern evenly within the square (figure 5). The nails were tapped downwards until the top of the

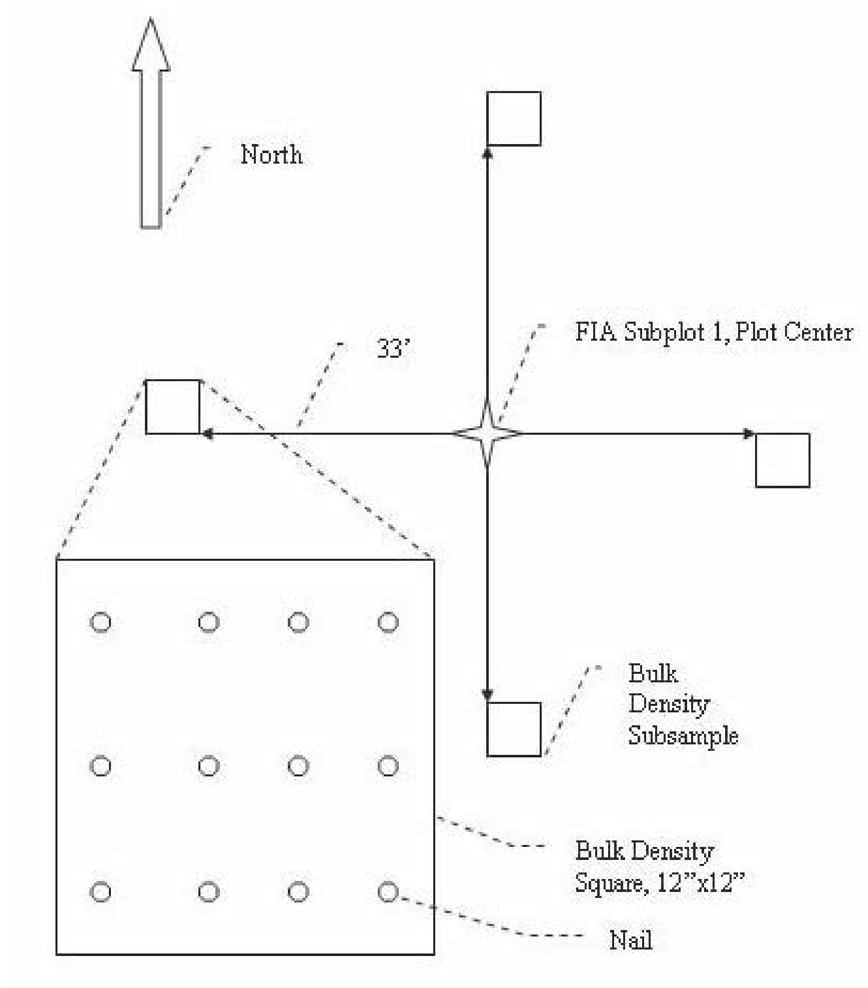


Figure 5—Sample plot layout for the Savannah River bulk density project.

nail was flush with the top of the litter layer. Litter was then carefully removed from the square and placed within a labeled bag. The distance between the top of each marker and the top of the duff layer was measured and recorded. The average of these twelve depth measurements represents the litter depth for the sample. After measurements were recorded, the markers (nails) were again tapped down so that the tops were all flush with the top of the duff layer. The duff layer was then carefully removed, placed in a labeled bag, and the distance between the top of the marker and the substrate was measured, the average of these twelve measurements represents the duff depth for the sample. All litter and duff samples were taken to the lab and oven dried for 48 hours. Litter samples were dried at 70 degrees Celsius and duff samples at 100 degrees Celsius. For further details and results see Maier and others (2004) and Parresol (2005).

Fuels Computation

Computation of biomass for each fuel component was done in a different fashion. For ladder fuels (i.e., non-merchantable arborescents of *Pinus*, *Juniperous*, *Taxodium* < 5" dbh and hardwoods < 6" dbh) biomass equations were utilized (Brown and others 1997). The coarse woody debris subcomponents were converted to biomass using formulas from Brown (1974). These formulas to compute tons/ac are:

$$\text{0- to 3-inch material:} \quad = \frac{11.64 \times n \times d^2 \times s \times a \times c}{L}$$

$$\text{3+-inch material} \quad : \quad = \frac{11.64 \times \Sigma d^2 \times s \times a \times c}{L}$$

where n is number of particles counted in each size class along a line transect, d is average particle diameter for the 0- to 3-inch size classes and d is measured diameter for pieces 3"+, s is wood specific gravity, a is the nonhorizontal angle correction factor (the correction factor adjusts weight estimates for the fact that all particles do not lie horizontally as assumed in the planar intersect theory), c is the slope correction factor for converting weight/ac on a slope basis to a horizontal basis, and L is the transect length in ft. The percent slope was measured at each inventory plot and the slope correction factor was calculated as $c = \sqrt{1 + (\text{percent slope}/100)^2}$. The following values for average d^2, s, a, and L were used:

Size class	d^2	s	a	L
0 – 0.25"	0.0151	0.7	1.13	40
0.25" - 1"	0.289	0.7	1.13	40
1" - 3"	2.76	0.58	1	80
3"+ sound	—	0.58	1	280
3"+ rotten	—	0.3	1	280

For the litter and duff calculations subplots were averaged for a combined average litter-duff depth for each inventory plot. Bulk density conversion factors determined from the bulk density study were applied to the averaged depth value for each plot to compute litter-duff tons/ac. See Parresol (2004) for a detailed description of the fuel loading computations.

Broad Species Groups

The SRS contains 25 naturally occurring mixtures of species or stand types (see Hansen and others 1992). For analysis purposes we grouped the 25 stand types into seven broad species composition groupings defined on the basis of the forest types as given in table 1. For each of the 622 inventory plots, a forest type was assigned based on each individual plot species make-up, by applying the following Forest Service definitions:

1) to be assigned to one of the three yellow pine forest types, 70% or more of the total basal area of the stand must be in yellow pine, and then it is assigned to a particular yellow pine species based on the species (loblolly, longleaf, or slash pine) with the largest basal area component,
2) to be assigned to the pine-hardwood type the plot must have ≥50% and <70% of the total basal area in yellow pines species,
3) to be assigned to the hardwood-pine type the plot must have >30% and <50% of the total basal area in yellow pines species, and
4) to be assigned to the hardwood type, < 30% of the total stand basal area must be in yellow pine species.
5) to be assigned to the cypress/tupelo type, ≥50% of the total stand basal area must be in baldcypress (*Taxodium distichum*)and/or tupelo (*Nyssa* sp.).

The inventory plots were grouped into the broad categories previously identified in table 1 based on their observed species make up derived from applying the above definitions. Examples of forest types are shown in figure 6. This resulted in the distribution of inventory plots into the forest type groups as given in table 1. The cypress/tupelo stands are set-aside areas and are not considered further.

Analysis

For analysis purposes we combined litter and duff, and added all components for total fuel. For each broad species group we ran a factorial analysis of variance (ANOVA) on 5 factors, site index class (SIC) where site index (SI) is stand height in ft at 50 years, basal area class (BAC) where basal area (BA) is measured in ft^2/ac, age class (AC) where age is years, number of burns class (NBC) where number of burns (NB) is a count of prescribed burns in a stand,

Table 1—The forest stands on the Savannah River Site categorized into seven broad species composition groups linked with the relevant Forest Service forest types.

Group	Group Name	Forest Types Included	# Stands	Acres	Percent	# Plots
1	Loblolly pine	25, 31, 32	1897	62,602	34.32	277
2	Longleaf pine	21, 26, 34	1151	43,294	23.73	129
3	Slash pine	22	618	17,716	9.71	58
4	Pine-Hardwood mix	12, 13, 14, 35	272	5,340	2.93	23
5	Hardwood-Pine mix	44, 46, 47, 48, 49	214	5,355	2.94	27
6	Hardwoods	51, 52, 53, 54, 56, 57, 58, 61, 62, 63, 64, 68, 72, 82, 98	1739	41,436	22.71	103
7	Cypress/Tupelo	67	118	6,677	3.66	5
			6,009	182,420	100.00	622

a

b

Figure 6—Examples of forest types occuring on the Savannah River Site: a) longleaf pine plantation, b) natural stand of mixed hardwoods.

and number of years since last burn class (YSBC) where years since last burn (YSB) is time in years or fraction thereof from the most recent prescribed burn. The definition of SIC is: if SI < 70 ft then SIC=1, if 70 < SI ≤ 80 then SIC=2, if SI > 80 then SIC=3. The definition of BAC is: if plot BA ≤ 82.5 ft^2/ac then BAC=1, if 82.5 < BA ≤ 111.5 then BAC=2, if plot BA > 111.5 then BAC=3. The definition of age class (AC) is: if age ≤ 4 then AC='A, if 5 ≤ age ≤ 17 then AC='B', if 18 ≤ age ≤ 35 then AC='C', if age ≥ 36 then AC='D'. Number of burns class is 0, 1, 2, 3+. Years since last burn class is defined as: if YSB ≤ 3 then YSBC=1, if 4 ≤ YSB ≤ 9 then YSBC=2, if YSB ≥ 10 then YSBC=3. We also examined the impact of the 5 analysis variables through running a series of stepwise linear least squares regressions by broad species group. To examine trends in more detail, that is, to investigate the role of stand dynamics and effect of prescribed burning, we present a series of regression response surfaces using longleaf pine to illustrate.

Results

Bulk Density Study

Bulk density conversion factors are given in table 2. Average litter bulk densities ranged from 1.5 tons/ac/in for mixed pine and hardwood stands between 5-20 years old without fire for over 10 years to 2.4 tons/ac/in for loblolly and slash pine sites between 5 and 20 years in age and more than 3 years since fire. Average duff bulk densities ranged from 2.6 tons/ac/in on mixed upland hardwood stands between 5 and 20 years in age with greater than 10 years since fire to 9.0 tons/ac/in for loblolly and slash pine greater than 40 years in age and 3 to 10 years since fire.

Fuel Loading

Fuel loading weight in tons across the entire SRS are given in table 3 by broad forest type. Fuel weights are displayed by the fuel categories conifer fuel trees, hardwood fuel trees, CWD, and litter-duff. Table 4 has the same structure as table 3 except average fuel weight in tons per acre is given in

Table 2—Litter and duff bulk densities (tons/acre/inch) for forest types by age class (years) and rough age (years).

		Forest Type							
Age	Rough	Lob/Slash		LL		PH Mix		UH Mix	
Class	Age	Litter	Duff	Litter	Duff	Litter	Duff	Litter	Duff
	0-3	—	—	1.8	3.8	—	—	—	—
5-20	3-10	2.0	4.4	1.6	4.5	—	—	—	—
	10+	1.9	4.8	1.8	4.1	1.5	3.9	1.8	2.6
	0-3	2.4	6.0	2.6	8.2	2.8	6.7	—	—
21-40	3-10	2.4	6.4	2.9	6.3	1.6	5.3	1.9	5.1
	10+	1.9	5.9	2.7	8.6	1.7	4.0	2.1	5.7
	0-3	1.9	6.4	2.2	8.2	2.1	8.8	2.2	6.6
40+	3-10	2.3	9.0	2.1	7.0	2.2	7.0	1.9	6.2
	10+	2.3	7.2	2.5	8.2	2.0	5.3	2.0	7.1

Note: Lob is loblolly pine, LL is longleaf pine, PH Mix is mixed species pine-hardwood stand, UH Mix is mixed species upland hardwood stand, and rough age is number of years since last burn.

Table 3—Fuel loadings in tons from the 1999-2002 Savannah River Site inventory of 622 plots.

	Forest Type						
Fuel Type	**Loblolly**	**Longleaf**	**Slash**	**Pine-Hdwd**	**Hdwd-Pine**	**Hdwd**	**All Types**
	Tons						
Conifer trees	160,949.2	86,854.5	36,242.4	1,821.3	15.5	4,120.8	290,003.7
Hdwd trees	232,256.3	80,439.4	50,093.5	34,619.4	40,828.3	314,243.7	752,480.6
CWD	233,994.5	150,301.2	79,926.2	28,655.6	22,147.1	149,620.5	664,645.1
Litter-duff	93,503.5	58,705.5	31,645.3	6,476.7	5,402.6	36,668.3	232,401.9
						Overall Total:	1,939,531.3

Note: Hdwd is hardwood, CWD is coarse woody debris.

Table 4—Average fuel loadings in tons/ac from the 1999-2002 Savannah River Site inventory of 622 plots.

	Forest Type						
Fuel Type	**Loblolly**	**Longleaf**	**Slash**	**Pine-Hdwd**	**Hdwd-Pine**	**Hdwd**	**All Types**
	Tons						
Conifer trees	2.571	2.006	2.046	0.357	0.003	0.107	1.684
Hdwd trees	3.710	1.858	2.828	6.784	8.109	8.167	4.369
CWD	3.738	3.472	4.512	5.615	4.399	3.888	3.859
Litter-duff	1.494	1.356	1.786	1.269	1.073	0.953	1.349
						Average:	11.261

Note: Hdwd is hardwood, CWD is coarse woody debris.

the table cells. The overall fuel tonnage for the 172,228 acres covered in the fuels inventory is 1,939,531 tons giving an average per acre value of 11.3 tons. This average breaks down as follows: 1.7 tons/ac in conifer fuel trees, 4.4 tons/ac in hardwood fuel trees, 3.9 tons/ac in CWD, and 1.3 tons/ac in litter/duff.

Analysis of Variance

The results of the ANOVAs are outlined in table 5. All factors shown in table 5 were significant at the $\alpha = 0.05$ level. As can be seen in this table, loblolly and longleaf pine had a number of significant factors. Our explanation for the nonsignificance with slash involves land-use history. Slash is an off-site species, planted primarily in old-fields with a small range in age, BA and SI, so there is very little variability among the stands. However, using stand variables as a continuum in the linear regressions shows significant effects despite the small range in values, as seen in the next section. The ANOVAs indicate the complex interplay of factors involved in trying to understand fuel loadings.

Table 5—Significant (P<0.05) class variables and interactions by forest type.

Forest Type	Ladder Fuel	CWD	Litter-Duff	Total Fuel
Loblolly	BAC, AC, SIC×YSBC, NBC×YSBC	AC	BAC, AC, SIC×BAC	None
Longleaf	SIC, BAC, AC BAC×AC SIC×YSBC	BAC, SIC×AC, SIC×NBC	None BAC×AC	SIC, BAC, AC
Slash	None	None	None	None
Pine-Hdwd	BAC, NBC	None	None	None

Note: Hdwd is hardwood, CWD is coarse woody debris, BAC is basal area class, AC is age class, SIC is site index class, YSBC is years since last prescribed burn class, and NBC is number of prescribed burns class. Please see text for definitions of classes.

Stepwise Linear Least Squares Regressions

More informative than the ANOVAs are the inferences from the linear regressions. The significant variables from the linear regressions are given in the table 6. Basal area and age are important explanatory variables for estimating fuel loading in loblolly pine stands. In terms of prescribed burning, loblolly ladder fuel and CWD were affected by years since last burn, while the litter-duff layers were affected by number of burns. Site index, basal area and stand age were all critical in determining longleaf pine stand fuel loadings. For longleaf, ladder fuel was affected by years since last burn, but burning in this linear context did not seem to affect the CWD or litter-duff layers. Because of the importance of longleaf pine management at the SRS, response was examined more closely using nonlinear models and log-transformed models. Those results are given in the next section. For slash pine, years since the last burn was correlated with CWD and number of burns affected the litter-duff layers. Finally for the pine-hardwood mix, the CWD was correlated with years since last burn. While stand characteristics play a major role in overall fuel loads, the prescribed burning program is having significant impacts on reducing fuel components.

Response Surfaces

To more fully understand the effects of stand variables and the impact of the prescribed burning program, a series of best-fit empirical regression relationships for longleaf pine were developed to generate response surfaces. Equations for ladder fuel (equation 1), litter-duff (equation 2), 1 hour fuel

Table 6—Signicant variables (P<0.05) from the stepwise linear least squares regressions.

Forest Type	Ladder Fuel	CWD	Litter-Duff	Total Fuel
Loblolly	BA, A, YSB	A, YSB	BA, A, NB	BA
Longleaf	SI, BA, A, YSB	SI, BA, A	BA	SI, BA, A, YSB
Slash	SI, BA	YSB	BA, NB	BA
Pine-Hdwd	SI, BA	SI,YSB	None	BA

Note: Hdwd is hardwood, BA is basal area in ft^2/ac, A is age in yeasrs, SI is site index in ft base age 50, YSB is years since last prescribed burn, and NB is number of prescribed burns.

(equation 3), 10 hour fuel (equation 4), and the 100+ hour fuel (equation 5) are given below.

$$\widehat{ladder\ fuel} = 50.217\,exp\left(-0.036SI + 0.014BA - 0.033Age + 0.00102YSB^2\right) \quad (1)$$
$$R^2 = 0.51, RMSE = 3.50$$

$$\widehat{litter\text{-}duff} = 0.598 + 0.0127BA - 0.374 / YSB \quad (2)$$
$$R^2 = 0.45, RMSE = 0.57$$

$$\widehat{\ln 1\,hour\ \ fuel} = 4.082 - 0.206\ln Age - 1.659\ln SI - 0.257\ln NB \quad (3)$$
$$R^2 = 0.084, RMSE = 0.966$$

$$\widehat{\ln 10\,hour\ \ fuel} = -1.429 + 0.272\ln Age + 0.075\ln YSB \quad (4)$$
$$R^2 = 0.11, RMSE = 0.836$$

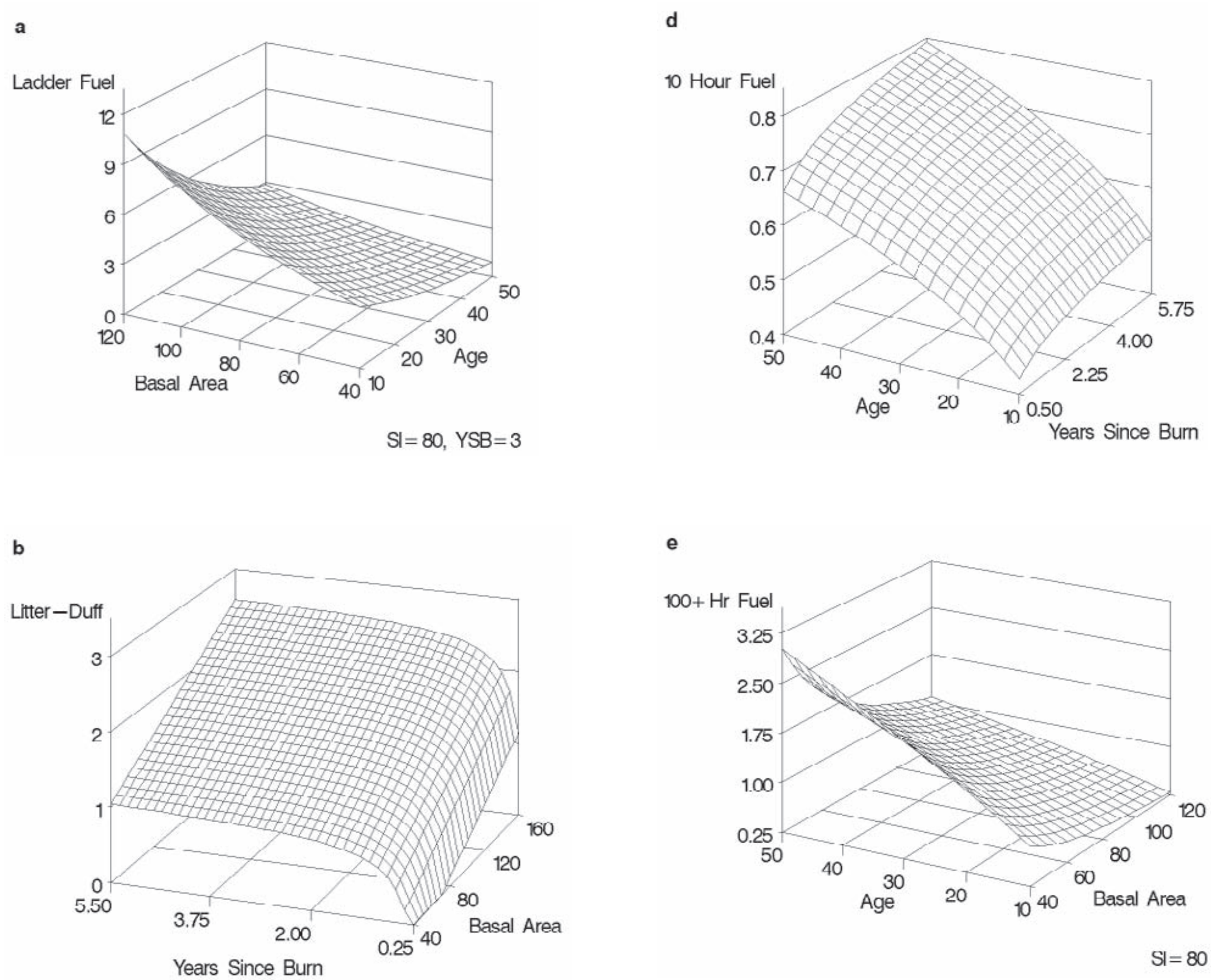
$$\widehat{\ln 100 + hour\ \ fuel} = -6.071 - 0.939\ln BA + 0.803\ln Age + 1.710\ln SI \quad (5)$$
$$R^2 = 0.15, RMSE = 1.373$$

Figure 7 shows the response surfaces generated from these equations. Figure 7a shows that ladder fuels are generally determined by BA and age, decreasing as BA decreases and age increases. Equation 1 shows that YSB has a small but statistically significant effect in reducing ladder fuels. Figure 7b shows the dramatic effect both YSB and BA has on determining litter and duff fuel loading. It is clear that litter-duff loadings recover quickly, in as little as two to three years after a burn. Figure 7c shows that the 1 hour fuel is reduced through repeated burning and that SI also plays a role. Figure 7d indicates that recency of burn has some impact on the 10 hour fuel but that age is the main factor determining fuel load. Finally, equation 5 and figure 7e reveal that burning has no detectable effect on the 100+ hour fuel, but rather the interplay of age, BA and SI.

Discussion

Field fuel inventories are generally not available at local, regional or national scales. At the SRS managers identified the need for such information to help guide decision making concerning fuels management. We easily modified standard forest inventory methods to incorporate a complete assessment of fuel components on the SRS. The FIA program of the USDA Forest Service inventories the entire U.S. forest resources periodically and is moving towards an annual multi-resource inventory system. A suite of habitat and environmental variables are collected along with the more traditional tree measurements. From our experience with this project, we were able to easily incorporate fuel variables into our inventory design and we strongly believe and recommend that the FIA program nationally can achieve the same objective. The average number of man days per plot was equal to the expected productivity without the fuel loading modification.

Due to the paucity of forest floor bulk density information for southeastern forests, new bulk density conversion factors for the dominant forest types on the SRS were developed to compute litter and duff fuel loading in tons/ac/in.



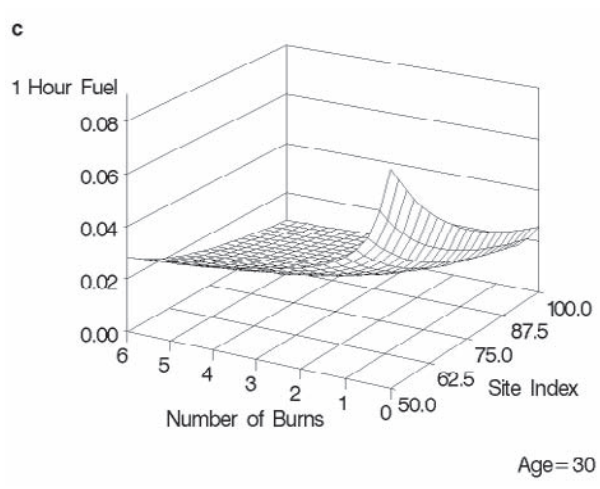


Figure 7—Response surfaces illustrating trends in fuel levels as a function of stand variables and burning history: a) ladder fuel based on equation 1, b) litter-duff fuel based on equation 2, c) 1 hour fuel based on equation 3, d) 10 hour fuel based on equation 4, and e) 100+ hour fuel based on equation 5.

These conversion factors should prove useful for similar forest types of the upper coastal plain and piedmont forests of the Southeastern U.S.

The pattern of fuel loading across the forest types, age, stocking and fire frequency reflects land use history, stand dynamics, stand management and fire management. For the major forest types (loblolly, longleaf, slash, pine-hardwood, hardwood-pine, and hardwood) stand variables generally explained the larger fraction of the variability in the fuel components. Age, BA, and SI explained a large proportion of the variability in individual components, but particularly ladder fuels and 100 hour+ fuels. Natural stand dynamics even in these highly disturbed systems dominated the observed relationships. Ladder fuels decreased with age probably as a result of two factors. Small trees and shrubs are predominant in young stands simply as a result of early succession. As the stands age, the mid-story shrub component is suppressed by the overstory. In addition, land use history also plays a role on these sites. The older pine types were generally planted on old-fields established during the 1950's. These stands had most of the hardwood shrub component eliminated through farming. Later plantations were established in cut-over lands with little effected control of the competition. More recent stands were established on an array of sites with a wide range in ladder fuel species development.

In contrast, stand management probably has a major influence on the relationship between BA and ladder fuels for the managed pine types. The lower BA stands have reduced ladder fuels and mid-story components as a result of disturbance from mechanical harvesting through repeated thinning operations, coupled with prescribed fire. The only fire variable affecting ladder fuels was YSB, but the impact was relatively small. Restriction on environmental conductions during prescribed burning, particularly wind, humidity, and fuel stick moisture, probably limits the fire intensity such that only smaller diameter woody trees and shrubs are killed or controlled. Most prescribed fire activities have also historically been applied during the dormant season, in contrast to the growing season. The latter period is recommended for burning when the objective is to control mid-story shrubs and ladder fuels.

The major fuel type controlling surface fire rate of spread in these stands is the litter and duff and the 1 hour fuel components. Numerous studies of prescribed burning fuel consumption at the SRS demonstrated that these components are the largest fraction contributing to fuel consumption following burning (Kilgo and Blake 2005). Using longleaf pine as an example, it is clear that the previous dominant management paradigm that stands should be burned every five to seven years may not be an effective frequency to reduce hazard fuels within stands. Not withstanding the influence of the spatial distribution of fuel treatments on the rate of spread of catastrophic large wildfire, it appears that a two-to three year burning cycle is critical to effectively reduce these fuels (Outcalt and Wade 2004). This study has established a baseline for future fuels management and policies and provides insight into factors contributing to fuel dynamics for upper coastal plain forests.

Acknowledgments

The authors wish to thank Dr. John Blake, Assistant Manager Research, of the Savannah River Site for his peer review of this manuscript. Funding was provided by the Department of Energy-Savannah River Operations Office through the U.S. Forest Service Savannah River under Interagency Agreement DE-AI09-00SR22188.

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Variation in Surface and Crown Fire Hazard With Stand Age in Managed Coastal Western Hemlock Zone Forests in Southwestern British Columbia

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***Abstract**—Surface and crown fuels were measured in 186 stands ranging in age from 0 years after clearcutting to old-growth forests > 300 years old in Douglas-fir (*Pseudotsuga menziesii*) – western hemlock (*Tsuga heterophylla*) – western redcedar (*Thuja plicata*) – dominated forests in southwestern British Columbia. Indexes of surface fire hazard based on woody debris loads, and of crown fire hazard based on 5 factors (canopy foliar bulk density, height to live crown, woody debris loads, ladder fuels, and snag quantities), were developed. Using the indexes developed, surface fire hazard followed a U-shaped trend with stand age, being highest for the first few years after clearcutting, declining to a minimum 20 to 40 years after harvesting before increasing. Crown fire hazard was lowest for the first few years after clearcutting, rose to a maximum 20 to 90 years after harvesting and then declined to low values in 100 to 150 year old forest, before rising to higher values in old-growth. In the absence of fuel reduction treatments, some post-harvesting age classes of forests will have higher surface or crown fire hazards than old-growth forests.*

Introduction

Fuel management in forests of southern coastal British Columbia, dominated by Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and western redcedar (*Thuja plicata*), in the recent past has been characterized by a dichotomy. On the one hand, in active forest harvesting areas, strips of old-growth forest were left between clearcut blocks partly because it was believed that the old-growth strips could serve as fuel breaks as they presented a lower fire hazard than the clearcuts (Grant 1984). On the other hand, in the water supply watersheds for the city of Vancouver, management involved clearcutting old-growth forests to produce younger plantations with a perceived lower fire hazard state (Economic and Engineering Services 1991). This raised the question of how fire hazard varied with forest age.

Forest fire hazard (a fuel complex defined by volume, type, condition, arrangement, and location, that determines the degree both of ease of ignition and of fire suppression difficulty (Forest Resources Development Branch 1986)) can be broken into two components – surface fire hazard and crown fire hazard – which are not necessarily correlated. Assuming surface fire hazard is directly related to surface fuel quantity, different trends with stand age in surface fire hazard have been reported. Brown and See (1981) described three different trends for lodgepole pine (*Pinus contorta*) as well as for subalpine fir (*Abies lasiocarpa*) forests in the U.S. Rocky Mountains – i) a general increase with age, peaking in old-growth, ii) an inverse U-shaped curve with a peak occurring in mature (110 – 160-year old) forests, and iii) a U-shaped curve

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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with maximum values occurring in the youngest as well as the oldest forests. Most studies have found U-shaped curves (Feller 2003), particularly in B.C. and the adjacent U.S. Pacific Northwest (Agee and Huff 1987; Fahnestock 1976; Spies and others 1988; Wells and Trofymow 1997).

In areas subjected to forest harvesting, surface fire hazard for the first few years after harvesting can be greater than at any other time in the life of a forest due to inputs of logging slash (Feller 2003; Wells and Trofymow 1997). Feller (2003) considered that a U-shaped curve could be the normal trend in surface fire hazard with forest age after harvesting, with deviations from this occurring for different reasons. For example, initial hazard may not be particularly high if initial post-disturbance inputs are low as a result of a severe fire, slow collapse of snags, or low pre-disturbance vegetation or surface fuel biomass. An inverse U-shaped curve may occur if thinning occurs or if tree mortality is particularly high during the mid-life period of a forest as a result of high tree densities, insects, disease or blowdown.

Surface fire hazard is likely to depend not only on the total surface fuel load, but also on the distribution of size classes and decay states of surface fuels (Baker 2003; Van Wagner 1983). Baker (2003) considered that large sound fuels are relatively unimportant to fire behaviour since they are usually not consumed, while large well-decayed fuels and fine fuels were considered important. Fine fuels may increase slowly after a fire for 150-200 years, and then decline, while large sound fuels, legacies of the pre-disturbance forest, generally decrease with time for long periods until they are replenished again (Baker 2003; Harmon and others 1986; Romme 1982). Van Wagner (1983) proposed that surface fire hazard in northern coniferous forests peaked before canopy closure and again in old-growth forests, primarily due to fluctuations in the quantity of fine fuels present.

Crown fire hazard depends on the ease of initiation and of propagation of crown fires. Van Wagner (1977) developed conceptual models of both initiation and propagation, and most subsequent work on crown fire hazard has used these models (for example, Cruz and others 2003; Scott and Reinhardt 2001). According to Van Wagner (1977), ease of initiation depends on the intensity of the surface fire, the height above the ground of the base of the live canopy, and foliar moisture content. Ladder fuels can be considered to either increase the surface fire intensity or increase flame length (Alexander 1988), or decrease canopy height (Van Wagner 1993), facilitating crown fire initiation. Once in the crowns, ease of propagation depends on the bulk density of available fuel in the canopy as well as rate of spread of the fire which in turn, depends on wind speed. Scott and Reinhardt (2001), using Van Wagner's (1977) conceptual models, developed a quantitative Torching Index and Crowning Index, but did not sample surface and crown fuels across all forest ages. The Canadian Fire Behavior Prediction System indicates that crown fire intensity and spread rate are greater in immature than in mature lodgepole pine forests for a given set of fuel moisture conditions (Forestry Canada Fire Danger Group 1992). No study, however, appears to have determined an index of crown fire hazard for an entire range of age classes of a forest, although Van Wagner (1983) has proposed that crown fire hazard was greatest in young stands with closed canopies, then decreased before increasing again in old-growth stands. Fahnestock (1976), using fire hazard keys, reported a similar trend in subalpine fir – false box (*Pachistima myrsinities*) forests in north central Washington, but Hawkes (1979), using Fahnestock's keys, found little difference in crowning potential between young and old-growth stands in Canada's southern Rocky Mountains in Alberta.

Due to the contrasting beliefs about the fire hazard in old-growth versus managed forests and the lack of quantitative data on successional changes in forest fire hazard in southwestern British Columbia, this study was begun in 1994 with the objective of determining the relative surface and crown fire hazards of old-growth forests, and those arising from a forest harvesting regime.

Study Area

The study occurred in the Coastal Western Hemlock biogeoclimatic zone of southwestern British Columbia, within 50 km from the city of Vancouver, specifically in the dry maritime (CWHdm) and very wet maritime (CWHvm) biogeoclimatic subzones (Meidinger and Pojar 1991).

A total of 186 study plots, each approximately 0.5 to 1 ha in size, were located in old-growth forests and adjacent areas that had been clearcut up to 80 years previously, or burned from 80 to 150 years previously. No stands aged 151 to 250 years old were sampled due to their unavailability. All stands older than 250 years, regardless of their actual age, were classed as old-growth. Clearcuts up to 60 years old had not been subjected to any slash disposal treatment and had mostly been planted with Douglas-fir. All forests were dominated by western hemlock, western redcedar, and Douglas-fir and, at higher elevations, Pacific silver fir (*Abies amabilis*) as well. All study plots were located on sites intermediate in moisture and nutrient status to avoid the confounding factor of site variability.

The CWHdm and CWHvm subzones have wet mild climates, with mean annual precipitation of 1800 to 2800 mm, most of which is rain, and mean annual temperatures of 8 to 10° C. All months have mean temperatures > 0° C. Due to the high forest productivity resulting from this climate, relatively long intervals between fires, and the presence of slowly decaying western redcedar, old-growth CWH forests generally contain the greatest surface fuel loads of all B.C. old-growth forests (Feller 2003).

Methods

Field Measurements

Within each study plot, 3 surface fuel plots and 3 crown fuel plots were randomly located. Each surface fuel plot consisted of an equilateral triangle with 20 m or 30 m sides, depending on fuel load and spatial orientation of the study plot. The mass of all surface woody fuels > 1 cm diameter was determined using the line intersect technique (Van Wagner 1968) measuring along the sides of the triangles. Each piece measured had its species or decay state recorded. Volumes calculated from the line intersects were converted to masses using relative densities determined for each size class (1.l-3.0, 3.1-5.0, 5.1-7.0, 7.1-12.0, and > 12 cm) for each species and decay class present. Nine to 32 samples per size class for each species or decay class were cut from randomly chosen woody materials and taken to the laboratory for density analysis. Fine fuels (≤ 1 cm diameter) were collected from nine 1 m^2 plots, each located 2 m away from each triangle apex along a line projected outwards from the centre of the triangle.

Each crown fuel plot consisted of a 20 x 20 m or 20 x 10 m plot, depending on spatial orientation of the study plot. Within each crown fuel plot, the species and d.b.h. of every tree present was measured. The dominance class and state of decay of each snag present were also recorded. Canopy volume was estimated by multiplying surface area by crown length, which was measured as the difference between the height to the base of the live crown and the height to the top of the tree canopy, with 1 to 3 measurements per crown fuel plot. Relative ladder fuel amount was estimated visually using a 6 category system. Ladder fuel was considered to be any dead woody material or small conifers occurring between the surface fuel bed (up to 1.5 m above the ground) and the live canopy.

Stand age was determined from forest cover maps where known, or from counting rings in cores extracted from 2 to 3 of the largest trees in each crown fuel plot.

Laboratory Procedures

Surface fuel materials—Relative densities of all woody materials were measured using a water displacement technique and an average value calculated per size class and species or decay class. Fine fuel samples were dried at 100 °C for 24 to 48 hours, then weighed. An average fine fuel mass was calculated from each of the nine samples collected per study plot.

Crown fuel data—For each study plot, an average canopy foliar bulk density, height to the base of the live crown, and relative ladder fuel quantity were calculated from the 3 crown fuel plot values. Canopy foliar bulk density was calculated by dividing the total foliage mass in a plot by the measured crown volume. Foliage mass was estimated by applying foliar biomass equations to the d.b.h. values of all trees measured in a plot. These equations had either been developed by M. Feller or were obtained from Gholz and others (1979).

Development of a surface fire hazard index (SFHI)—Surface fire hazard was considered to depend on the quantity of surface fuels present, particularly on fine fuels (≤ 1 cm diameter). It was assumed that a surface fire was unlikely to start if no fine fuels were present. The surface fire hazard index (SFHI) chosen was

$$\text{SFHI} = \text{FF}\ (1 + \text{CWD})$$

where FF is the quantity (kg/m^2) of fine fuels present, and CWD is the quantity (kg/m^2) of coarse woody debris (materials > 1 cm diameter). The study plots were placed into different age classes then the average SFHI was calculated for each age class. To test the sensitivity of the changes in SFHI with age to different age class groupings and different relative weighting of FF and CWD, the average SFHI was calculated for combinations of six different age class groupings (table 1) and nine different FF/CWD weightings. Thus, for SFHI = FF [1 + a(CWD)], "a" varied from 10 to 0.01.

Development of a crown fire hazard index (CFHI)—Crown fire hazard indexes which combined both initiation and propagation were developed. It was considered that a crown fire would not occur if it could not be initiated or if it could not propagate. Thus -

Crown Fire Hazard Index (CFHI) = (ease of propagation) x (ease of initiation).

Ease of initiation was considered to depend on surface fire intensity, ladder fuels, and height to the live crown, while ease of propagation was considered

Table 1—Different age class groupings used to calculate the Surface and Crown Fire Hazard Indexes and relative weightings of FF and CWD used to calculate the Surface Fire Hazard Index.

Groupings	A	B	C	D	E	F
Age class (years)	0-3	0-2	0-3	0-3	0-2	0-4
	4-9	3-5	4-10	4-9	3-6	5-10
	10-15	6-10	11-18	10-16	7-12	11-20
	16-29	11-20	19-30	17-25	13-20	21-30
	30-40	21-39	31-45	26-35	21-35	31-50
	41-61	40-60	46-65	36-55	36-50	51-70
	62-81	61-80	66-85	56-75	51-70	71-90
	82-105	81-100	86-105	76-100	71-90	91-110
	106-150	101-150	106-150	101-150	91-150	111-150
	>150*	>150	>150	>150	>150	>150

* All forests > 150-years-old were actually > 250 years old and could be considered old-growth.

to depend on canopy foliar bulk density. It was assumed that foliar moisture content would not vary with stand age and could be ignored. Surface fire intensity would depend on surface fire rate of spread and fuel consumption. It was then assumed that rate of spread would be similar beneath forests of different ages and that fuel consumption would depend on surface fuel load. The presence of tall snags (codominant to dominant in canopy height status) with rough surfaces, implying a high probability of blowing embers, was also considered as a factor which might enhance the likelihood of a crown fire.

Therefore, CFHI α [f(FD)] [f(SFL, LF, HC, SD)]

where FD is the canopy foliar density (kg/m^3), SFL is the surface fuel load (kg/m^2), LF is the relative ladder fuel quantity (dimensionless, with scale = 0-5), HC is the height to the live canopy (m), and SD is the density of tall, rough snags (no. snags/ha).

In its simplest form, this equation is CFHI = (FD) (SFL + LF – HC + SD).

The study plots were placed into different age classes then the average CFHI was calculated for each age class. Due to missing tree data, canopy foliar bulk densities could not be calculated for seven plots, so the analyses were conducted using 179 plots. To test the sensitivity of the changes in CFHI with age to different age class groupings and different relative weighting of SFL, LF, HC and SD, the average CFHI was calculated for combinations of six different age class groupings (the same as those used for SFHI (table 1)) and different SFL, LF, HC and SD relative weightings in the CFHI equation. The weighting given to each of these factors was increased or decreased by up to 6-10 times (table 2).

To determine which weighting factors might be most appropriate to use, the outputs from these equations were correlated with the Crowning Index (CI) of Scott and Reinhardt (2001), calculated for drought summer conditions using their figure D-1 for each of the study plots except those aged 0-3 years (table 2). This left 154 study plots for which the CI was calculated. The CI decreases as the ease of crowning increases, whereas the CFHI of the present study increases as the ease of crowning increases. Consequently, equations which produced CFHIs which were positively or weakly negatively ($r > -0.1$) correlated with CI values, were not considered to be appropriate.

Table 2—Pearson correlation coefficients (r) between the CFHI of the present study and the CI of Scott and Reinhardt (2001) for different weightings of SFL, LF, HC, and SD used in the equation CFHI = FD (SFL + LF – HC + SD).

	r			
Weighting	**SFL**	**LF**	**HC**	**SD**
10.00	--	–0.55	--	–0.18
6.00	–0.41	--	0.57	--
5.00	--	–0.61	--	--
4.00	–0.36	--	0.51	–0.16
3.00	–0.31	--	--	--
2.50	--	–0.36	--	--
2.00	–0.22	--	0.31	–0.13
1.67	--	–0.24	--	--
1.33	--	–0.17	--	--
1.00	–0.06	–0.06	–0.06	–0.06
0.67	--	0.07	--	--
0.50	0.03	0.14	–0.38	--
0.40	--	--	--	–0.06
0.33	0.07	0.22	--	--
0.25	0.08	--	–0.53	--
0.20	--	--	--	–0.05
0.17	0.10	0.30	–0.56	--
0.13	--	--	–0.58	--
0.10	--	--	–0.59	–0.05
0.07	--	0.33	--	–0.04

-- not calculated
The equation in which each of SFL, LF, HC, and SD has an equal weighting (1) is CFHI = FD (SFL + 6LF – HC + SD/20)

SFHIs and CFHIs, determined for the 6 different age class groupings were compared using a Kruskal Wallis test to identify significantly different ($P < 0.05$) values. All statistical analyses were conducted using SYSTAT 11 software (SYSTAT 2004).

Results and Discussion

Surface Fire Hazard

Average fine fuel and coarse fuel loads each varied approximately three fold from 0.1 to 0.3 and from 4.2 to 15.2 kg/m^2, respectively (table 3). The SFHI suggested that the surface fire hazard in old growth forests was less than in recently harvested areas, regardless of the relative weighting given to coarse fuels, which varied over 3 orders of magnitude (figure 1). Since the surface fire hazard in old-growth forests, relative to that in recently harvested areas, varied little with the magnitude of the coefficient "a" in SFHI = FF[(1 + a(CWD)], it was decided to use the simplest form of this equation, with a = 1, to express the relative surface fire hazard. When this equation was applied to different age groupings, the general trend in hazard with age was an initial very high hazard (up to five years post-harvest) which declined to

Table 3—Average values, with standard errors in parentheses, of each of the variables used in the SFHI and CFHI equations for each of the age classes assessed in age class grouping F.

Age class	Number of plots	FF	CWD	SFL	FD	LF	HC	SD
(years)		*- - - - - - (kg/m²)- - - - - -*			*(kg/m³)*		*m*	*(no./ha)*
0 - 4	16	0.29	13.45	13.74	0.00	3.3	0.0	0
		(0.03)	(1.56)	(1.56)	(0.00)	(0.6)	(0.0)	(1)
5 - 10	17	0.10	15.15	15.25	0.03	3.9	0.2	4
		(0.03)	(1.73)	(1.74)	(0.01)	(0.4)	(0.1)	(3)
11 - 20	14	0.12	9.51	9.63	0.05	3.3	1.4	0
		(0.03)	(1.62)	(1.64)	(0.01)	(0.4)	(0.7)	(0)
21 - 30	24	0.12	4.81	4.93	0.13	3.4	7.4	16
		(0.01)	(0.52)	(0.52)	(0.02)	(0.2)	(0.8)	(14)
31 - 50	17	0.24	5.64	5.88	0.10	3.6	10.3	150
		(0.03)	(0.60)	(0.62)	(0.01)	(0.3)	(1.0)	(44)
51 - 70	19	0.29	6.54	6.83	0.13	2.5	15.9	54
		(0.05)	(0.74)	(0.77)	(0.01)	(0.3)	(1.1)	(22)
71 - 90	15	0.23	7.48	7.71	0.13	1.9	17.7	54
		(0.03)	(1.62)	(1.62)	(0.01)	(0.3)	(1.5)	(19)
91 - 110	7	0.26	6.93	7.19	0.09	1.4	14.9	69
		(0.03)	(0.60)	(0.60)	(0.01)	(0.2)	(2.0)	(12)
111 - 150	18	0.20	4.19	4.39	0.10	1.6	18.8	23
		(0.03)	(0.53)	(0.53)	(0.01)	(0.2)	(1.1)	(8)
> 150	32	0.21	10.00	10.21	0.12	2.4	18.9	23
		(0.02)	(0.94)	(0.94)	(0.01)	(0.1)	(1.0)	(4)

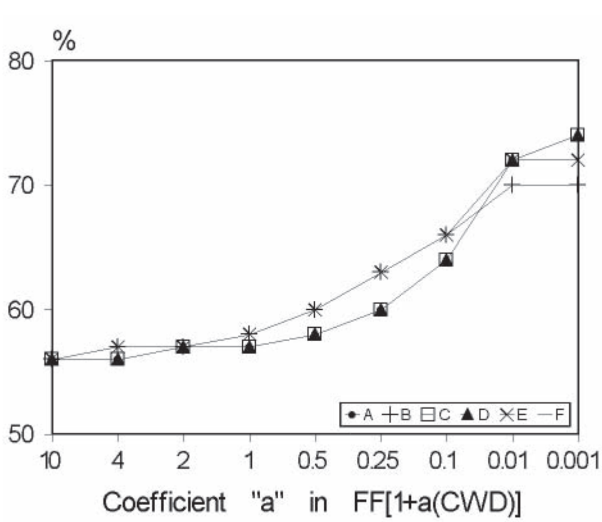

Figure 1—Surface Fire Hazard Index in old-growth forests as a percentage of that in the youngest post-harvesting forests for six different age class groupings (A-F).

a minimum around 20 to 40 years post harvest, followed by an increase to around 50 to 70 years post harvest, a decrease to around 100 to 150 years post harvest, then an increase again in old-growth (figure 2). Old-growth forests, however, generally had a lower surface fire hazard than forests 0 to 5 and 50 to 70 years old (figure 2), although the difference between the old-growth SFHI and the greatest SFHI was statistically significant for age class groupings A, C, D, and F, but not B and E (figure 2). The only age classes which had a statistically significantly lower SFHI than that of old-growth were those in the range of 16 to 35 years (figure 2).

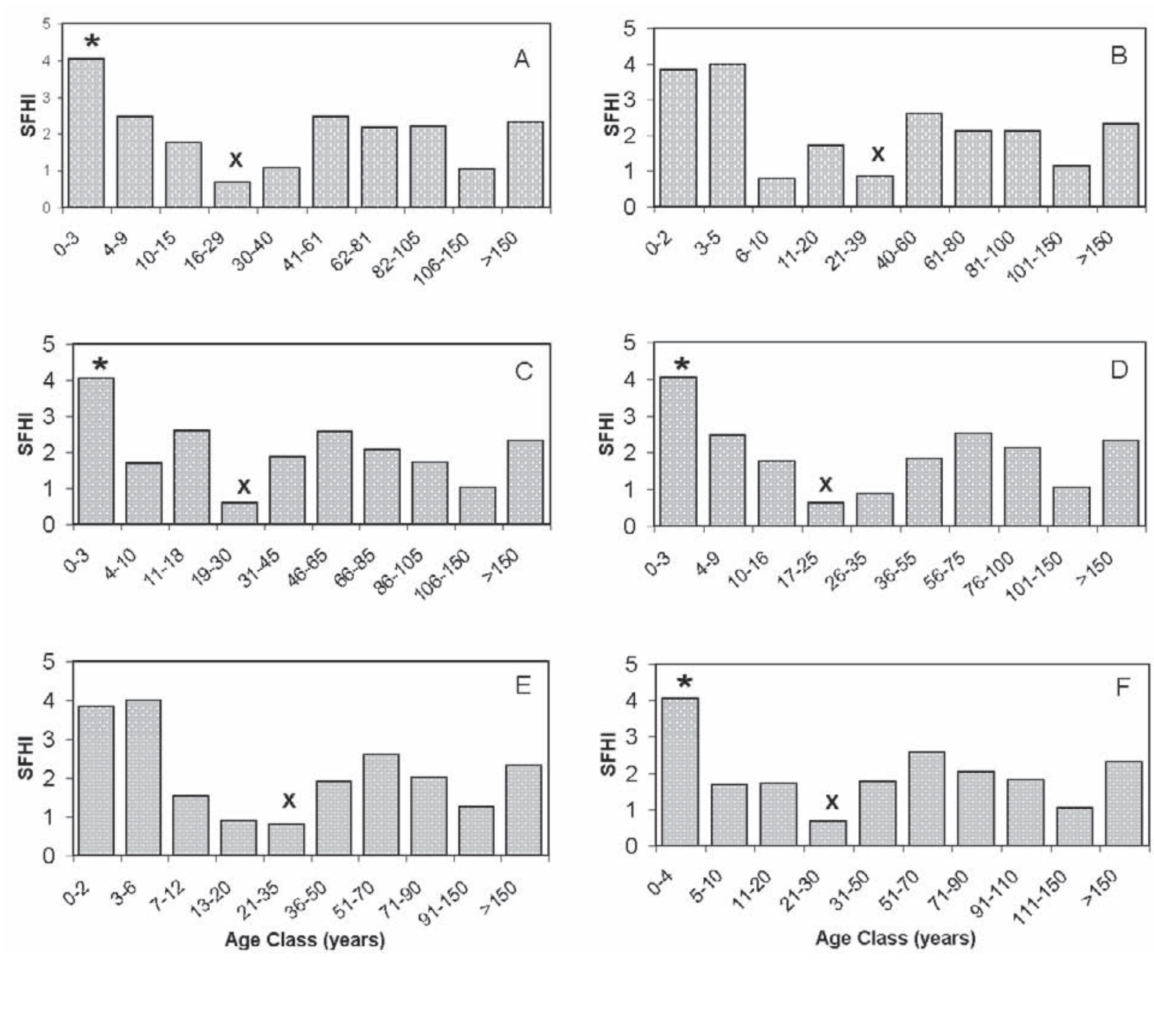

Figure 2—Average Surface Fire Hazard Indexes for different aged forests using six different age class groupings (A-F) and the equation SFHI = FF(1 + CWD).* designates a SFHI which is significantly higher ($P < 0.05$) than that of old-growth. x designates a SFHI which is significantly lower ($P < 0.05$) than that of old-growth.

The SFHI used total CWD and not just well decayed CWD, which has been considered more important in determining surface fire hazard (Baker 2003). Quantitative data to support this do not appear to be available, however. Furthermore, several studies in coastal western hemlock forests have found that well decayed materials constitute a greater proportion of total CWD mass in younger than in old-growth forests (Spies and others 1988; Wells and Trofymow 1997; Feller 2003). Consequently, if the SFHI had given greater weight to well decayed CWD than to less well decayed CWD, the differences in SFHI between old-growth and the youngest forests would likely have been greater. It was also assumed that wind speed was unaffected by forest age. This is unlikely to be correct as wind speed near the ground surface is usually greater in the open than beneath forests (Spittlehouse and others 2004), so fire forward rates of spread, and hence fire hazard would also be greater in the open. Tanskanen and others (2005) have also found that surface fire likelihood in Finnish conifer forests was greatest in recent clearcuts and declined with increasing age up to age 60 years, the oldest forest studied, due to increasing surface fuel moisture content. Consequently, microclimate differences even further emphasize the difference in surface fire hazard between old-growth and the youngest forests. Thus, it can be concluded that the surface fire hazard of the old-growth forests in the study area was less than that of recent clearcuts and was only greater than that of forests around 16 to 35 years old.

Crown Fire Hazard

Average surface fuel loads were greatest in 0 to 10 year old stands and least in 111 to 150 year old stands; average canopy foliar bulk densities increased with age up to 20 years, then remained relatively constant thereafter; ladder fuels were greatest in 0 to 70 year old stands; canopy heights tended to increase with stand age; and the density of dominant rough snags was least in the youngest stands and greatest in stands aged 31 to 110 years (table 3). Canopy foliar bulk densities may be overestimated in some old-growth stands as some of the tallest trees had dead tops and the foliar biomass regression equations used, which had been developed for trees up to 1.6 m d.b.h., were applied to trees up to twice this size.

Although the influence on the CFHI of variations in the weighting given to individual factors was assessed, the influence of variations in the weighting given simultaneously to 2 or more factors was not fully analyzed. Consequently, the appropriate CFHI equations chosen must be considered a first approximation. When the different crown fire initiation variables (whose range in values between individual plots were - SFL = 0.4 to 30.2 kg/m^2, LF = 0 to 5, HC = 0 to 32 m, and SD = 0 to 592 stems/ha) were given equal weight, the CFHI equation became CFHI = FD (SFL + 6LF – HC + SD/20). The weighting given to SFL had a major impact on the relative CFHI of old-growth versus younger forests. As the weighting increased, so did the CFHI of old-growth compared to that of younger forests (figure 3). Correlations between the CFHI and the CI of Scott and Reinhardt (2001) were > -0.1 for weightings of one or less (table 2). Consequently, an appropriate weighting factor would be > 1.

Regardless of the weighting given to LF, HC, or SD, the CFHI always remained lower in old-growth than in younger forests (figure 3). This applied even for weighting factors substantially greater or less than those given in figure 3. Based on correlations between the CI and CFHIs, appropriate weighting factors would be > 1 for LF and SD, and < 1 for HC (table 2).

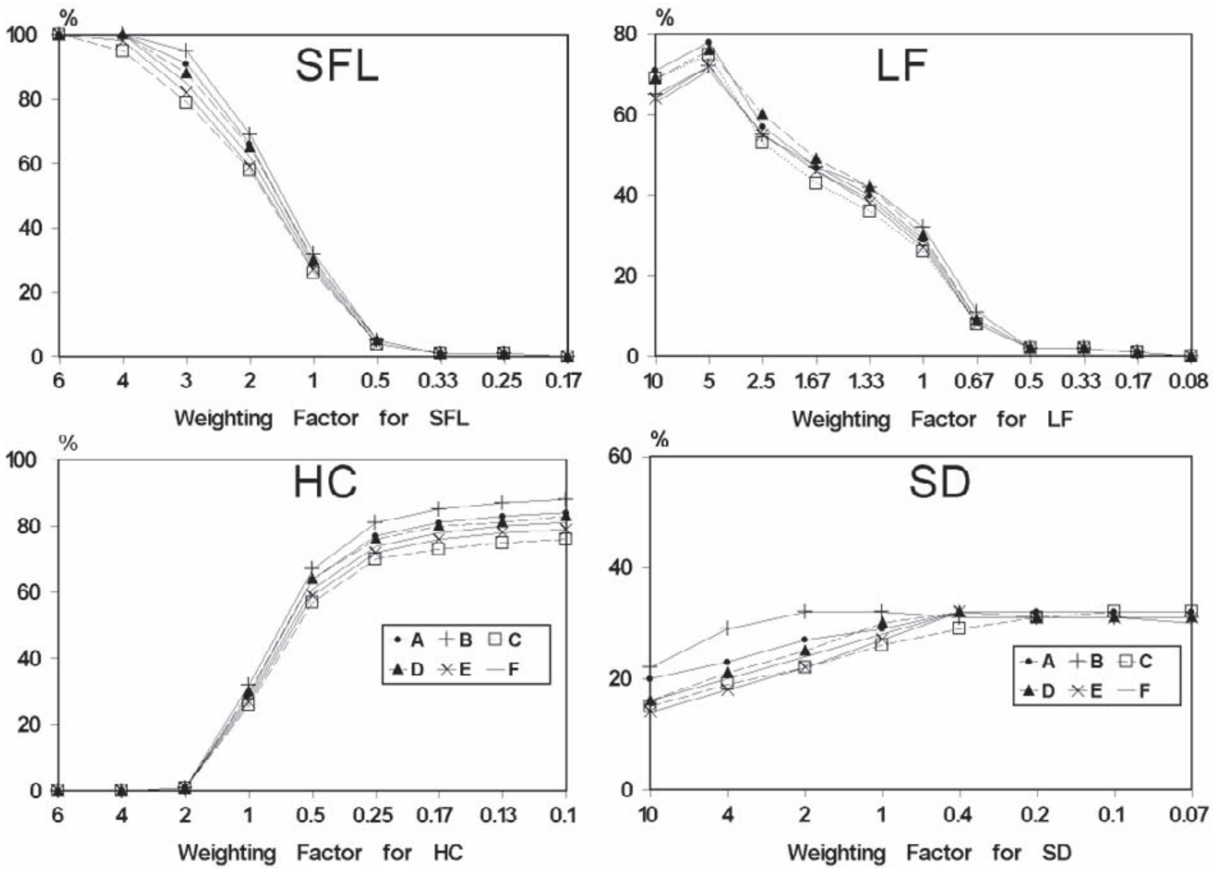

Figure 3—Crown Fire Hazard Index in old-growth forests as a percentage of the highest CFHI in all age classes of forests, using six different age class groupings (A-F) and different weightings for SFL, LF, HC, and SD.

Many possible equations could be chosen using different appropriate weighting factors. All equations with SFL preceded by a coefficient of 4 or less resulted in CFHIs being lower in old-growth than in some younger forests. For simplicity, several equations were chosen for use, using weighting factors that were not too extreme. Due to the lack of data or even theoretical models which link snag abundance to crown fire hazard, the weighting given to snag density was kept relatively low. It is currently unclear which equation best predicts crown fire hazard as none have been tested with real fires. CFHIs calculated from a sequence of equations with increasing weight being given to SFL from equation 1 through equation 4 are given in figure 4. The indexes calculated from the equations CFHI = FD(aSFL + bLF + cHC + dSD), with varying a-d, were multiplied by either 25, 10, or 8 to convert the index to a scale of 1 to 100. The CFHIs calculated from all 4 equations were significantly negatively correlated with the CI of Scott and Reinhardt (2001). These correlations progressively improved from r = –0.30 for equation 1 to r = –0.60 for equation 4, suggesting that as the relative weighting of SFL increases, the CFHI becomes a better predictor of crown fire propagation. This only occurs up to a weighting factor of 8, however, after which the closeness of the correlation declines.

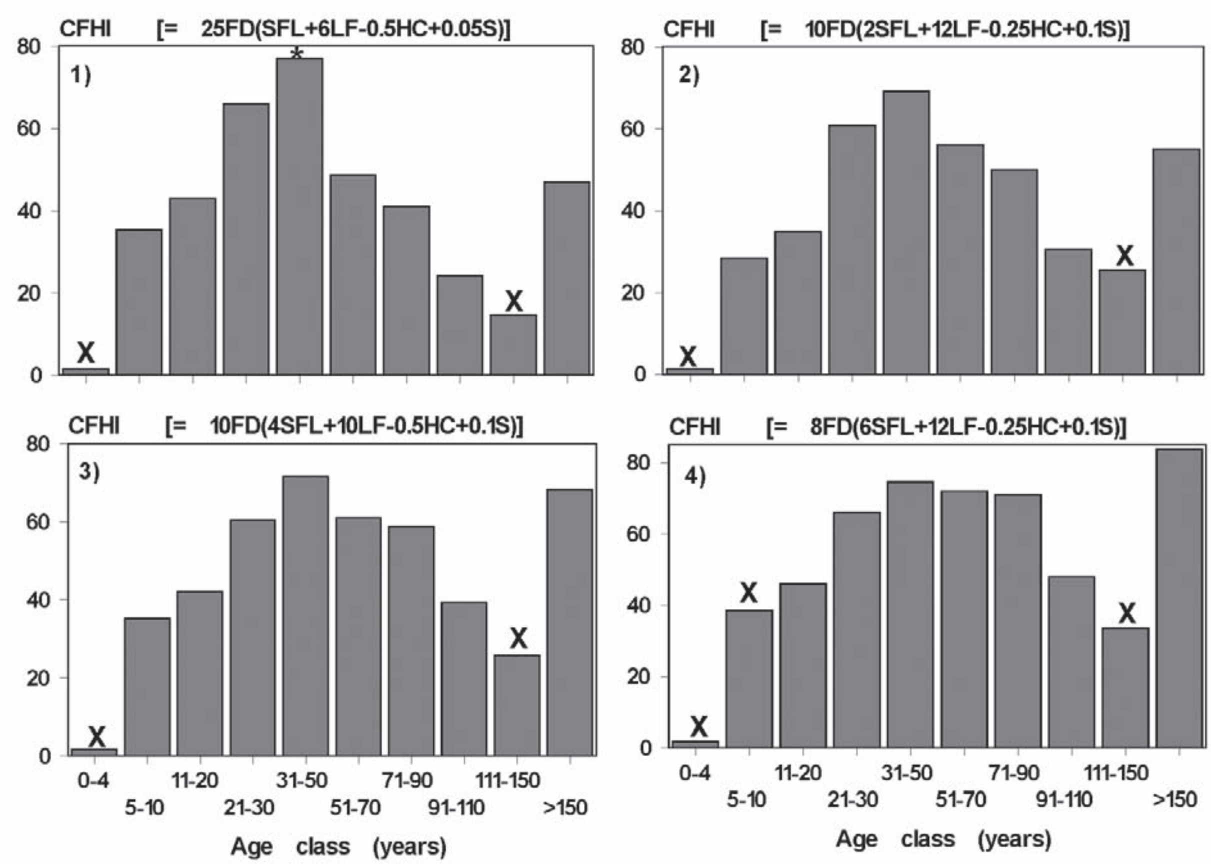

Figure 4—Average Crown Fire Hazard Indexes for different aged forests, calculated using four different CFHI equations and age class grouping F. * designates a CFHI which is significantly higher (P < 0.05) than that of old-growth. x designates a CFHI which is significantly lower (P < 0.05) than that of old-growth.

The CFHIs in figure 4 are shown only for one grouping of age classes as there were no substantial differences between the six different age groupings in the relative rankings of old-growth versus younger forests. The CFHI was always lowest for 0 to 5 year old age classes, then increased to peak values in 20 to 90 year old age classes, before declining in 100 to 150 year old age classes then rising again in old-growth. The CFHI for old-growth was lower than that of a younger age class forest for all equations in which SFL had a weighting factor < 5. However, it was statistically significantly lower (Kruskal Wallis tests, P = 0.05) only when the SFL weighting factor was < 2, as in equation 1 (figure 4). The CFHI for old-growth was also significantly higher than that for 0 to 4 and 111 to 150 year old stands (figure 4).

It can be concluded that whether or not younger forests have a higher crown fire hazard than old-growth in the study area depends primarily on the weighting given to surface fuel load. As the weighting given to this factor increases, the relative crown fire hazard of old-growth forests increases. However, as no reasonable equation could be found which resulted in old-growth forests having a statistically significantly higher crown fire hazard than all younger forests, it can also be concluded that simply clearcutting old-growth will not produce younger forests that always have a lower crown fire hazard than old-growth forests. Following clearcutting, fuel abatement treatments, such as slash reduction and thinning, would be necessary to significantly reduce crown fire hazards. Slash reduction would definitely be required to reduce post clearcutting surface fire hazard below that of old-growth forests. These conclusions are consistent with those of DellaSala and Frost (2001), who reported that old-growth forests in the western U.S. were less likely to burn catastrophically than younger forests.

Guidelines for fuel reduction treatments which lower fire hazards in forests are becoming available (for example, Keyes and O'Hara 2002; Peterson and others 2005). The present study suggests that both surface and crown fire hazard reduction would benefit from an emphasis on reducing surface fuels. However, the ecological benefits of surface fuels (Brown and others 2003; Feller 2003) as well as their influence on fire hazard must be considered.

Acknowledgments

B. Ford, D. Leard, R. Lehmann, P. Olanski, E. Pierce, and M. Råberg as well as many students have assisted with field work and data analysis. We thank the staff of the University of B.C. Malcolm Knapp Research Forest, and the Greater Vancouver Watershed District for permission to work within their areas and for facilitating this work. Funding for the study has come from the University of B.C. Research Forest, the government of B.C., and the Canada-B.C. FRDA research program. We thank B. Hawkes and C. White for helpful reviews of an earlier version of this paper.

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Evaluation of a Dynamic Load Transfer Function Using Grassland Curing Data

Patricia L. Andrews[1], Stuart A.J. Anderson[2], Wendy R. Anderson[3]

Abstract—*Understanding and calculating fire behaviour in various fuel types is essential for effective fire management, including wildfire suppression and fuels management. Fire spread in grassland fuel is affected by the curing level, the amount of dead fuel expressed as a percentage of the total (live and dead fuel combined). The influence of live fuel is included in various fire models in different ways. U.S. fire behavior prediction systems are based on Rothermel's fire spread model, which uses the load of live and dead fuel and the moisture content of each. Dynamic fuel models include a transfer of fuel load from the live to dead class as a function of live fuel moisture. Australian and New Zealand grassland fire behavior models rely heavily on the curing level as a major determinant of the ability for a fire to develop and spread, and place greater direct emphasis on both the proportion and moisture content of the dead fine fuels. A joint Australian and New Zealand study under the Australian Bushfire Cooperative Research Centre (CRC) is addressing various methods of assessing curing levels in grasslands. Data from that study are used to evaluate the dynamic fuel load transfer function used in fuel models developed for the Rothermel spread model. Results showed that live fuel moisture is not an indicator of level of curing. A significant difference is demonstrated in calculated rate of spread using the load transfer model versus direct entry of live fuel moisture and level of curing.*

Introduction

Fuels management planning often involves modeling potential fire behavior to identify areas of risk, assess hazard, and evaluate the effectiveness of various fuel treatment options. Fire behavior for a given fuel type can be modeled under a range of weather conditions and seasonal changes. Fire behavior modeling supports other aspects of fire management including suppression, prevention, and prescribed fire.

Fire behavior is influenced primarily by the fuel type (grass, shrub, etc.), fuel condition (moisture content, percentage of dead fuel), wind speed, and slope. The moisture content of fine dead fuel varies diurnally in response to changes in temperature, humidity, solar radiation, and rainfall. Live fuel moisture changes seasonally due to the physiology of the plant and its response to seasonal weather conditions. Seasonal curing of live herbaceous plants leads to a change in the ratio of dead to live material in the fuel complex, commonly referred to as level of curing. Live fuel plays an important role in determining the behavior of grassland fire (Cheney and Sullivan 1997, Cheney and others 1998). The level of curing has a major effect on grass fire behavior, in particular fire spread (Alexander 1993, Anderson and Pearce 2003).

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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The influence of live fuel is incorporated into fire behavior models in several ways. The fire models used in New Zealand and Australia place the emphasis on level of curing, whereas U.S. models utilize live fuel moisture. New Zealand uses the Canadian grassland fire behavior models from the Canadian Fire Behavior Prediction System based on data collected in Australia (Forestry Canada Fire Danger Group 1992). There are models for cut or matted grass and for natural standing grass.

In Australia a fire model has been developed for grassland (three defined pasture types) by Cheney and others (1998) to replace existing models based on the McArthur Mark 3 and Mark 5 Fire Danger Meters (McArthur 1966, McArthur 1977) and provided in equation form by Noble and others (1980). Although the fire models used in New Zealand and Australia are quite different, they both predict fire spread in grasslands from fine dead fuel moisture, wind speed, and degree of curing.

Fire behavior prediction systems in the U.S. are based on Rothermel's (1972) surface fire spread model. Calculations are based on a description of the fuel, fuel moisture content of each size class of dead and live fuel, wind speed, and slope. The fire model itself does not include the influence of curing. Dynamic fuel models are used as a means of modeling changes in fire behavior that occur as herbaceous fuels cure and die.

In this paper we evaluate the dynamic load transfer function that is part of fuel models developed for use with Rothermel's surface fire spread model (Scott and Burgan 2005). We compare the load transfer model predictions with field sampled grassland curing data and we examine the influence of the load transfer function on rate of spread calculations.

Grassland Curing Study

Grassland curing data are being collected as part of an ongoing study under the Australian Bushfire Cooperative Research Centre (CRC): "Improved Methods for the Assessment and Prediction of Grassland Curing" (www.bushfirecrc.com). Grass curing describes the annual or seasonal cycle of grasses dying and drying out following flowering. Degree of curing refers to the proportion of cured (dead) material in grasslands, expressed as a percentage of the total grassland fuel complex (live and dead material). It is a critical input to grassland fire behavior and fire danger models used in Australia and New Zealand. Current curing inputs are often inaccurate, leading to incorrect determination of grassland fire danger levels and potential fire behavior. Many important fire management decisions and strategies are based upon this grassland fire behavior information, and fire managers need access to accurate and reliable information to protect life and property.

The degree of curing is currently assessed visually or by satellite remote sensing using an index based on the reflective properties of grasses at different wavelengths. Visual assessment is often inaccurate, sometimes differing vastly from the actual curing value obtained from destructive sampling. Problems include difficulties obtaining and extrapolating estimates over large areas, experience of observers, calibration of visual assessments, and timing and frequency of observations (Anderson 2005, Anderson and Pearce 2003, Millie and Adams 1999).

Remote sensing is used to assess curing levels in grasslands over parts of Australia (Paltridge and Barber 1988, Barber 1990, Allan and others 2003). However, the algorithms developed have had little validation outside of southern Australia, and there are issues with the accuracy of the technique due to atmospheric conditions and lack of uniformity of grasslands within pixels.

The Bushfire CRC project is examining improved remote sensing approaches, and will also include evaluation and modification of agricultural pasture growth models for curing determination. These models account for environmental and physiological factors regulating grass growth. An Australasian-wide field sampling program is providing data for development and validation of techniques. We used preliminary field data for this analysis.

Destructive sampling of grasses is the most accurate method of collecting curing data, but is not practical to implement on a large scale. It is labor-intensive to collect and process destructive samples, and there are further issues with obtaining spatially-representative samples of curing across the landscape.

Curing data in the CRC study were obtained by destructive field sampling. Sampling quadrats were located along two transects at right angles to each other and a total number of approximately five samples were collected. For each sample, all the vegetation from within a 0.25m^2 frame was clipped with shears to the ground level and removed and placed in a bag. In the laboratory, the samples were then separated into live and dead material, oven dried at 100°C for 24 hours and then weighed. The degree of curing was then determined by calculating the percentage of dead material expressed as a percentage of the total (live and dead) material.

Samples of live, dead, and combined fuel moisture were also collected in the field, to investigate the feasibility of using grass fuel moisture data to calculate curing percentage, assuming that the moisture status of the grasses represents a live or dead state. Live and dead fuel moisture samples were collected randomly from within the curing sampling area, sealed in tins, weighed, oven-dried for 24 hours at 100°C and reweighed. The moisture content of the combined (live and dead) fuel was calculated using the material collected as part of the destructive sample from the 0.25m^2 sampling frame. Collecting representative fuel moisture data in the field can be difficult. Live moisture varies by the part of the plant and the stage of growth as well as by grass species. For example on the same date and location Australian native grass may have a moisture content of 125% while improved pasture has a moisture content of 250%.

Table 1 shows the data from the grassland curing study used in this analysis. There are ten sites, three in New Zealand and seven in Australia. The type of grass and level of grazing is noted for each. The grass is characterized by loading and height. The date of each of the fourteen sample data points is given with the live fuel moisture and level of curing.

Dynamic Load Transfer Function

The dynamic load transfer function is part the of dynamic fuel models developed for use with Rothermel's (1972) surface fire spread model. Dynamic fuel models are used as a means of modeling changes in fire behavior that occur as herbaceous fuels cure and die. The fire model itself does not include the influence of curing. Calculations in Rothermel's fire model are based on fuel model, fuel moisture content of each size class of dead and live fuel, wind speed, and slope. A fuel model is a set of intrinsic fuel parameters that are required by the fire model.

Table 1—Data from the Australian Bushfire Cooperative Research Centre (CRC) study: "Improved Methods for the Assessment and Prediction of Grassland Curing."

	Site description				Sample data		
Location*	Grass type**	Grazing***	Total fuel load	Grass height	Date	Live fuel moisture content	Level of curing
			(ton/acre)	(ft)		---------(%)---------	
Monaro	IP	UG	3.8	1.1	8/8/2005	211	93
Monaro	IP	UG	3.6	1.1	9/6/2005	270	91
Fisher	IP	LG	1.4	1.5	8/18/2005	315	87
Majura	IP	UG	1.5	2.3	1/16/2006	92	79
Majura	IP	UG	1.2	2.3	2/22/2006	113	71
Umbigong	NG	LG	2.2	0.8	8/30/2005	124	92
Tidbinbilla	IP	HG	0.6	0.7	1/24/2006	152	99
Braidwood	IP	LG	1.0	0.7	1/5/2006	142	80
Braidwood	IP	LG	0.7	0.7	2/14/2006	192	84
Milton	IP	UG	7.0		9/12/2005	331	72
Darfield	IP	LG	1.1	0.5	9/16/2005	292	58
Darfield	IP	LG	0.7	0.5	2/20/2006	320	86
Godley Head	IP/NG	UG	4.1	1.0	9/17/2005	234	80
Lake Lyndon	IP/NG	UG	2.3	0.8	2/14/2006	165	70

*Darfield, Godley Head, and Lake Lyndon are in New Zealand; the rest are in Australia.
**IP = Improved Pasture; NG = Native Grass.
***UG = Ungrazed; LG = Lightly Grazed; HG = Heavily Grazed.

The standard set of 13 fire behavior fuel models, which has been widely used since 1976, are static; fuel model parameters do not change (Albini 1976, Anderson 1982). Dynamic fuel models, on the other hand, include the dynamic load transfer function which changes the fuel description by moving some of the load from the live category to dead. Although rarely used, the option of developing dynamic custom fuel models was available in the BEHAVE fire behavior prediction and fuel modeling system (Burgan and Rothermel 1984). Seventeen of the recently developed set of 40 standard fuel models are dynamic (Scott and Burgan 2005). These 40 fuel models were designed to represent a wider range of fuel types than the set of 13, and have been implemented in the BehavePlus fire modeling system (Andrews and others 2004), the FARSITE fire area simulator (Finney 1998), and other fire behavior prediction systems in the U.S.

The dynamic fuel load transfer function is shown in figure 1. Load is transferred from the live herbaceous class to dead as a function of live fuel moisture. The same relationship is used for all dynamic fuel models.

- For live herbaceous fuel moisture content of 120 percent or higher, most of the herbaceous fuels are assumed to be green, and the initial live herbaceous load for the fuel model stays in the live category.
- For live fuel moisture of 30 percent or lower, the herbaceous fuels are considered fully cured, and all live herbaceous load is transferred to the dead category.
- For live fuel moisture between 30 and 120 percent, part of the live herbaceous load is transferred to dead. For example, if live fuel moisture is 75 percent (halfway between 30 and 120 percent), half of the initial live herbaceous load is transferred to dead herbaceous, the remainder stays in the live herbaceous class.

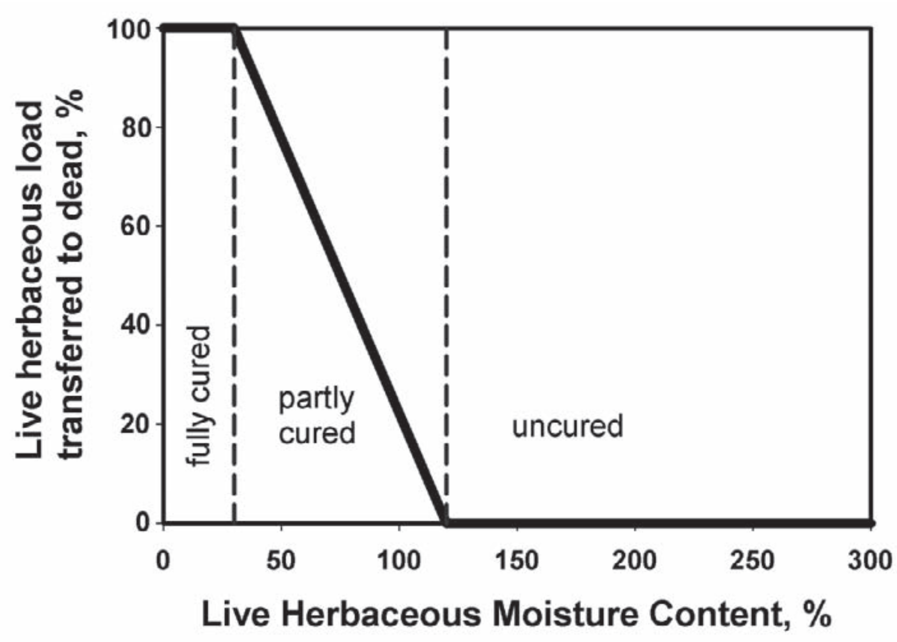

Figure 1—Percent of the live herbaceous fuel load that is transferred to the dead category (Burgan 1979). There is dead fuel in the fuel model when the percent is zero, for the section of the graph labeled "uncured."

Table 2 gives the parameters for the standard fire behavior fuel models applicable to grasses. Fuel models 1, 2, and 3 are from the original set of 13 and are static. Fuel models GR1 through GR9 are dynamic fuel models from the set of 40. The listed fuel loadings for the dynamic fuel models are the values before the fuel load transfer function is applied. The percentage of the total load that is dead fuel prior to load transfer is also given on the table. Scott and Burgan (2005) refer to the percent load transferred as *curing percent*, and say that the parameters on the table are for *uncured* fuel. There is, however, dead fuel in the fuel models even before any load is transferred from live to dead. As an illustration of the difference between percent load transferred and percent dead, table 2 gives the percent dead at 50 percent load transferred. Fuel model GR2 is 63 percent dead (63 percent cured) when 50 percent of the load is transferred from live to dead. In Australasian and Canadian fire behaviour models, degree of curing in grasslands is defined as percent dead. For this paper, we use the terminology "percent load transferred" where Scott and Burgan used the term "percent cured".

As an illustration of the effect of live fuel moisture for static and dynamic fuel models, the BehavePlus fire modeling system was used to compare calculated rate of spread using Rothermel's fire spread model for seven fuel models under the same wind and fuel moisture conditions (5 percent dead fuel moisture, 5 mi/h wind, no slope) (figure 2). Fuel models 1 and 3 have no live fuel, so rate of spread is not affected by a change in live fuel moisture. Fuel model 2 is a static model with a live fuel component. The effect of live fuel moisture is therefore limited to the relationships in the original formulation of the Rothermel (1972) fire model. Fuel models GR1, GR2, GR4, and GR7 are dynamic. Live fuel moisture is not only used in the rate of spread

Table 2—Load and depth for grass fire behavior fuel models. Percent dead for no load transfer and for 50% load transfer from live herbaceous to dead are given to illustrate the difference between percent load transferred and percent dead.

		Fuel model parameters						
		Fuel load (ton/ac)				Depth	Percent dead fuel	Percent dead at
Fuel model		1-h	10-h	100-h	live herb	(ft)	prior to load transfer	50% load transfer
1	Short Grass	0.74				1.0	N/A	N/A
2	Grass and timber understory	2.0	1.0	0.5	0.5	1.0	N/A	N/A
3	Tall Grass	3.0				2.5	N/A	N/A
GR1	Short, Sparse, Dry climate	0.1			0.3	0.4	25.0	63
GR2	Low Load, Dry Climate	0.1			1.0	1.0	9.1	55
GR3	Low Load, Very Coarse, Humid Climate	0.1	0.4		1.5	2.0	6.3	63
GR4	Moderate Load, Dry Climate	0.25			1.9	2.0	11.6	56
GR5	Low Load, Humid Climate	0.4			2.5	1.5	13.8	57
GR6	Moderate Load, Humid Climate	0.1			3.4	1.5	2.9	51
GR7	High Load, Dry Climate	1.0			5.4	3.0	15.6	58
GR8	High Load, Very Coarse, Humid Climate	0.5	1.0		7.3	4.0	6.4	59
GR9	Very High Load, Humid Climate	1.0	1.0		9.0	5.0	10.0	59

calculations according to the fire spread model, but also to change the fuel model according to the fuel load transfer function. For fuel model GR7 under the specified dead moisture and wind conditions, there is a four-fold increase in calculated rate of spread as live fuel moisture decreases from 100 to 75 percent; and rate of spread increases by a factor of 2.4 for the very small change in live fuel moisture from 100 to 95 percent. In his paper "Sensitivity of a fire behavior model to changes in live fuel moisture" Jolly (2005) found that the grass fuel models within the set of 40 new fuels showed the highest sensitivity to live fuel moisture changes. They were most sensitive to changes in live fuel moisture from 90 to 100%.

The fuel load transfer function was developed as part of a live fuel moisture model developed by Burgan (1979) for use in the U.S. National Fire Danger Rating System (Deeming and others 1977). The load transfer function is a conceptual model; development was not based on live fuel moisture and

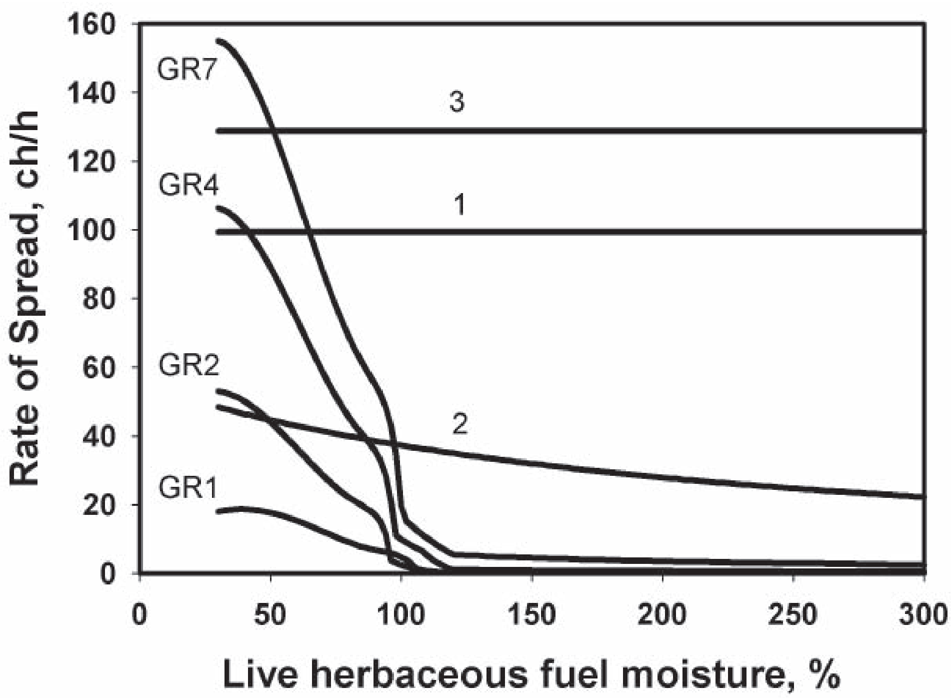

Figure 2—Comparison of calculated rate of spread for seven fuel models to illustrate sensitivity to live fuel moisture for static (1, 2, 3) and dynamic (GR1, GR2, GR4, GR7) fuel models. Dynamic fuel models include the use of the load transfer function.

curing data. The live fuel moisture range of 30 to 120 percent was defined as the transition stage because 120 percent "roughly defines the moisture content at which new growth is complete and the foliage is mature." Thirty percent was defined as the minimum moisture for transition because "that is the approximate fiber saturation point, below which plants are assumed to be dead." The fuel load transfer function has not previously been evaluated using field data.

Results

Table 3 gives the sample data for live fuel moisture and level of curing, and the model values for percent load transferred and percent dead calculated from the sampled live fuel moisture. We compare the sampled and modeled level of curing (percent dead). A fuel model was assigned to each sample site based primarily on the fuel loadings of the sample data in table 1. The Milton site in coastal Australia was the only one designated as humid. Only three of the fourteen sample points had live fuel moisture content below 120 percent. According to the dynamic fuel load transfer function, moisture above 120 percent indicates no load is transferred from live to dead. The modeled percent dead for the fuel models is calculated from the percent dead for the fuel model before the load transfer (see table 2) and the percent transferred from live to dead according to the dynamic load transfer function.

Table 3—Fuel models were assigned to each site primarily based on fuel loading. Field data includes live fuel moisture and level of curing (percent dead). The fuel load transfer function is used to calculate percent load transferred for the associated live fuel moisture value. Percent dead is affected by the fuel model (see table 2).

		Sample data		Model values	
Location	Fuel model	Live fuel moisture content	Level of curing	Percent load transferred live to dead	Percent dead
		- - - - - - - - - (%) - - - - - - - - -			
Monaro	GR7	211	93	0	15.6
Monaro	GR7	270	91	0	15.6
Fisher	GR4	315	87	0	11.6
Majura	GR4	92	79	34.5	42.1
Majura	GR4	113	71	12.1	22.3
Umbigong	GR4	124	92	0.5	12.0
Tidbinbilla	GR1	152	99	0	25.0
Braidwood	GR1	142	80	0	25.0
Braidwood	GR1	192	84	0	25.0
Milton	GR8	331	72	0	6.4
Darfield	GR2	292	58	0	9.1
Darfield	GR2	320	86	0	9.1
Godley Head	GR7	234	80	0	15.6
Lake Lyndon	GR4	165	70	0	11.6

Figure 3 is a plot of the sample data, level of curing (percent dead) vs. live fuel moisture, with an indication of the assigned fuel model. The dynamic fuel load transfer function is used to plot percent dead for each fuel model. Figure 4 is a plot of predicted and observed level of curing (percent dead). The lowest observed curing level was 58 percent while the highest predicted value was 42 percent. A simple look at the plots precludes the need for a statistical analysis.

The load transfer function is based on the assumption that fuel is "uncured" when live fuel moisture is over 120 percent. Note that a significant amount of the grass fuel load is dead at high live fuel moisture values. For example, the live fuel moisture content was 315 percent for the Fisher site, corresponding to a measured 87 percent curing level. The load transfer function gives no load transfer and 11.6 percent dead fuel for fuel model GR4 and live fuel moisture 315 percent.

It is apparent that there is no useful relationship between live fuel moisture and curing level for this data. We conclude that for this data set, live fuel moisture is not an indicator of level of curing.

Influence on Rate of Spread Calculations

The dynamic load transfer model is an intrinsic part of dynamic fuel models. Given that we have shown that live fuel moisture may not be an indicator of curing, we examine the option of independent specification of live fuel moisture and curing level.

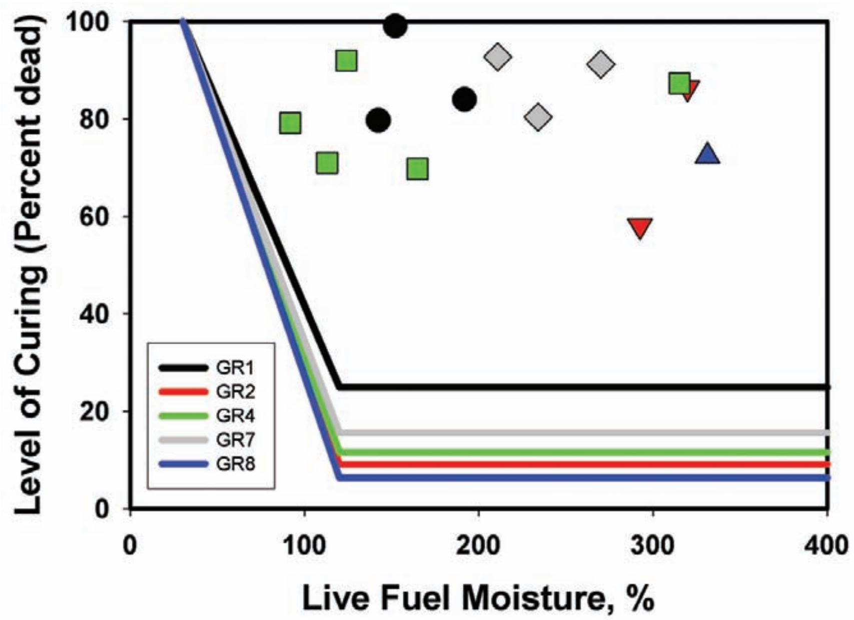

Figure 3—Australian and New Zealand live fuel moisture and curing data compared to the dynamic load transfer function. There is a different curve for each fuel model because of the dead fuel in the fuel models when there is zero load transferred from live to dead. The sample data points are from table 3.

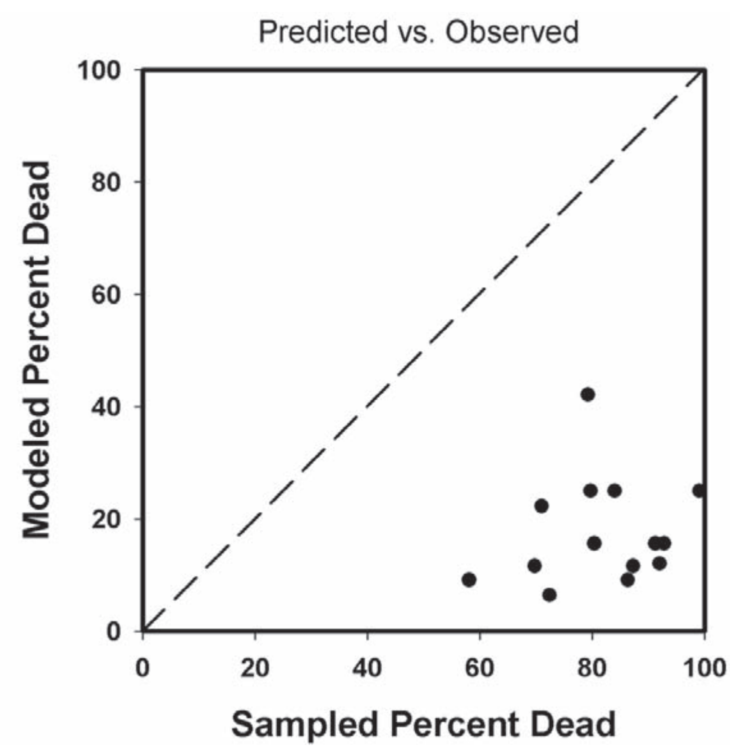

Figure 4—Predicted vs. observed level of curing (percent dead). Data are from table 3.

As a means of dealing with the required relationship between curing and live fuel moisture, Scott and Burgan (2005) give the following guidance in use of the dynamic fuel models: "It will often be preferable to estimate live herbaceous moisture content by working backward from observed or estimated degree of herbaceous curing. For example, if the fuelbed is observed to be 50 percent cured, use a value of 75 percent for live herbaceous moisture content." A user who knows both live fuel moisture and curing level must choose which to use. It is not possible, for example, under the current formulation, to calculate rate of spread for live fuel moisture of 200 percent and 50 percent cured. (Recall that Scott and Burgan use the term percent cured for the percent load transferred from live to dead rather than the percent dead.)

Table 4 shows the live fuel moisture values that correspond to 100, 75, 50, 25, and 0 percent load transferred according to the function. The calculated rate of spread for fuel model GR4 (5 percent dead fuel moisture, 5 mi/h wind, and no slope) is given for each and indicated on the curve in figure 5. For example, live fuel moisture of 75 percent and a 50 percent load transfer gives rate of spread of 53 ch/h. These calculations are as implemented in the BehavePlus fire modeling system using the dynamic fuel models as described by Scott and Burgan.

Consider the effect of not using the dynamic load transfer function, but rather directly supplying values for live fuel moisture and load transfer percent. Table 5 shows calculated rate of spread for a range of live fuel moisture values and load transfer levels. The highlighted values in table 5 correspond to those in table 4 and are indicated on figures 6 and 7. Figure 6 is rate of spread for five levels of load transfer for a range of live fuel moisture. The curves in figure 6 correspond to the columns in table 5. For a fixed load transfer of 50 percent, live fuel moisture from 30 to 300 percent results in rate of spread from 11 to 90 ch/h. Similarly, figure 7 is rate of spread for seven levels of live fuel moisture for a range of load transfer values. The curves in figure 7 correspond to the rows in table 5. For a fixed live fuel moisture of 75 percent, load transfer from 0 to 100 percent results in rate of spread from 2 to 110 ch/h. There is a significant difference between the results using the dynamic load transfer function and specifying live fuel moisture and curing independently.

Table 4—Live fuel moisture and percent load transferred from live to dead according to the dynamic load transfer function. Associated calculated rate of spread for fuel model GR4, 5 percent dead fuel moisture, 5 mi/h midflame wind, and no slope. The five highlighted rate of spread values are shown in figure 5.

Live fuel moisture	Load transferred live to dead*	Rate of spread
(%)	*(%)*	*(ch/h)*
30	100	**110**
53	75	**87**
75	50	**53**
98	25	**11**
120	0	**1**
200	0	1
300	0	1

*Referred to as percent cured by Scott and Burgan (2005).

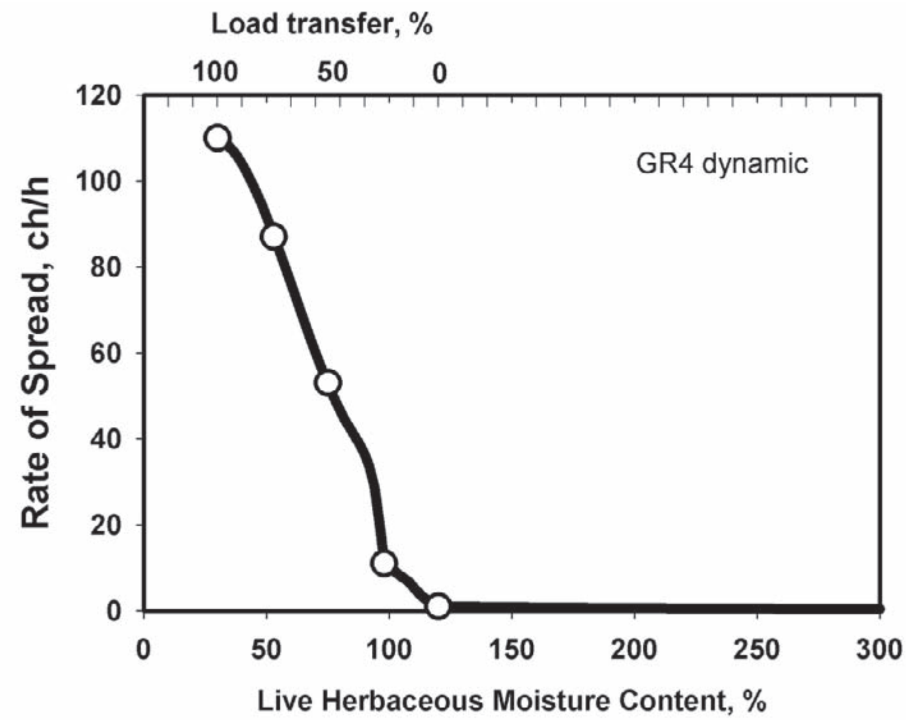

Figure 5—Calculated rate of spread for dynamic fuel model GR4, which incorporates the fuel load transfer function. Load is transferred from the live to the dead class as a function of live fuel moisture. The data points on the curve are given in table 4.

Table 5—Calculated rate of spread for a range of live fuel moisture and load transfer values. The highlighted values correspond to those in table 4 and are plotted on the curves in figures 6 and 7. The curves in figure 6 correspond to the columns of this table. The curves in figure 7 correspond to the rows.

Live herbaceous moisture (%)	Rate of spread (ch/h)				
	Load transferred from live to dead*, %				
	100	75	50	25	0
30	**110**	103	90	69	3
53	110	**87**	66	49	2
75	110	76	**53**	33	2
98	110	66	44	**11**	1
120	110	59	38	10	**1**
200	110	43	24	6	1
300	110	32	11	5	1

*Referred to as percent cured by Scott and Burgan (2005)

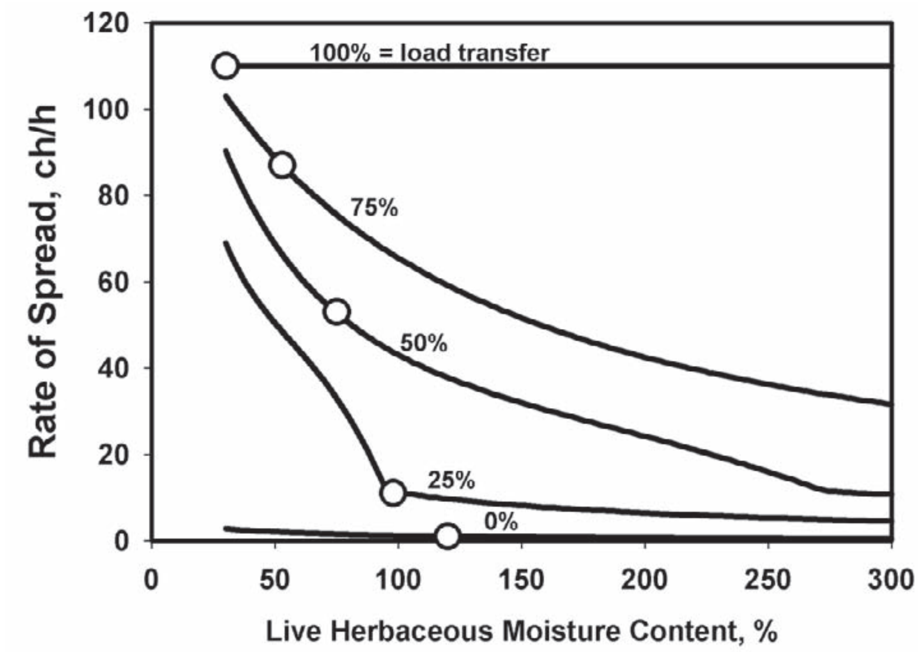

Figure 6—Rate of spread is calculated for several levels of load transfer for a range of live fuel moisture. Use of the load transfer function results in only the single indicated point on each curve. The curves correspond to the columns in table 5.

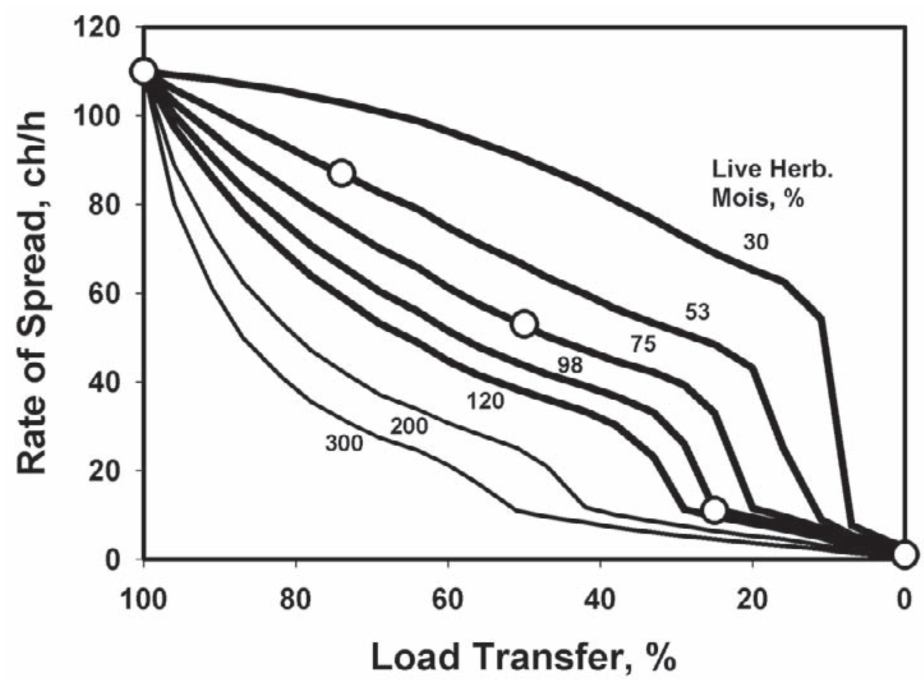

Figure 7—Rate of spread is calculated for several values of live herbaceous moisture for a range of load transfer percentage. Use of the load transfer function results in only the single indicated point on each curve. The curves correspond to the rows in table 5.

Discussion

It is recognized that curing level is an important factor in determining fire behavior in grass fuel types. Because the Rothermel (1972) fire spread model does not include the influence of curing, fuel models that incorporate a dynamic load transfer function have been developed by Scott and Burgan (2005) to reflect seasonal curing. Live fuel moisture is used to estimate the load that is transferred from the live to dead class in the fuel model. Evaluation of the dynamic load transfer function using field sampled data from Australia and New Zealand showed that the assumption that level of curing is related to live fuel moisture needs to be questioned.

An examination of the use of the dynamic load transfer function compared to the option of independent specification of live fuel moisture and curing level showed a significant difference in rate of spread calculations using Rothermel's model. Although both live fuel moisture and degree of curing are currently difficult to determine, we suggest that the required use of the dynamic load transfer function be reconsidered in anticipation of improved models and methods of assessment.

There is a need for longer term research on the curing process, a description of the seasonal changes in the grasslands for fire modeling, and on the combustion processes involved in the burning of a mixture of live and dead fuel. It is imperative that fire researchers and fire managers continue to question, validate, and refine fire behavior models and their underlying assumptions for effective fire and fuel management.

Acknowledgments

The authors wish to thank the Australian Bushfire Cooperative Research Centre (CRC) for permission to use the curing data for this paper.

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Foliar Moisture Contents of North American Conifers

Christopher R. Keyes[1]

***Abstract**—Foliar moisture content (FMC) is a primary factor in the canopy ignition process as surface fire transitions to crown fire. In combination with measured stand data and assumed environmental conditions, reasonable estimates of foliar moisture content are necessary to determine and justify silvicultural targets for canopy fuels management strategies. FMC values reported in research publications are best used for this purpose. This paper summarizes the results of 11 studies on the FMC values and trends for 16 North American conifers. FMC values ranged from 73 to 480 percent but varied by species, foliage age, and season. FMC values presented here and the references associated with them will be helpful to managers engaging in canopy fuels planning with the use of popular fire behavior and fuels management software (e.g. NEXUS, Fuels Management Analyst, and the Forest Vegetation Simulator's Fire and Fuels Extension).*

***Keywords**: crown fire, fire surrogates, wildfire hazard, canopy ignition, shaded fuelbreak*

Introduction

The relationship of stand structure to fire behavior, and the basis for silviculturally modifying stands to reduce crown fire susceptibility, have been well established (Graham et al. 2004, Agee and Skinner 2005). In planning silvicultural treatments to achieve crown fire resistance, assumptions must be made about uncontrolled parameters that are beyond the scope of manipulation (Keyes and O'Hara 2002). One of these is the percent foliar moisture content (FMC) of overstory and midstory trees.

The quantitative basis for prescribing silvicultural treatments (such as thinning and pruning) to the aerial fuel complex is Van Wagner's (1977) model of the relationships among crown fire behavior, surface fire behavior, and canopy fuel structure. Since its inception as a tool to predict the occurrence and behavior of crown fires, Van Wagner's model has since been refined and adapted in formats useful for fuels planning (Alexander 1988, Scott and Reinhardt 2001, Keyes and O'Hara 2002). It is currently utilized by virtually all decision-support software currently used in fuels planning in North America, including FARSITE (Finney 1998), NEXUS (Scott 1999), the CrownMass program of the Fuels Management Analyst tool suite (Fire Program Solutions 2003), and the Forest Vegetation Simulator's (FVS) Fire and Fuels Extension (Reinhardt and Crookston 2003).

Using one or more of those simulation programs, fuels planners identify structural targets that can reduce a stand's susceptibility to crown fire initiation, crown fire spread, or both, and then propose fuels treatments to achieve these targets. Ideally, the effects of proposed silvicultural fuels treatments on fuel dynamics are also considered (Keyes and Varner 2006). To decrease

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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susceptibility to torching or canopy ignition, a target canopy base height is determined on the basis of anticipated surface fireline intensity and foliar moisture content. For the former parameter, measured surface fuelbed properties are utilized in combination with a worst-case fire weather scenario to determine the most intense surface fire behavior that is likely to occur. But fuels planners lack a standard basis for determining appropriate values for FMC. This paper reviews relevant literature to address that need.

Variability in Foliar Moisture Content

Fuels treatments are expected to be effective over a range of temporally changing conditions, so estimates of FMC are best drawn from published studies that document changes in foliar moisture content over seasons or years. A list of these is given in table 1 for 16 common North American conifer species. The table reveals a wide range of moisture content values based on species, period of measurement, and foliage age. These values are drawn from the primary literature; in some cases values have been visually approximated to the nearest 5 percent from published graphs.

Table 1—Published percent foliar moisture content (FMC) values for North America forest conifers. In some cases values are visually approximated to the nearest 5 percent from graphs.

Species	New foliage[1]	Old foliage[2]	Period[3]	Reference
Abies balsamea – balsam fir	180-230	130-150	Jul-Sep	Kozlowski and Clausen 1965
	130-220	110-150	Jul-Oc	Little 1970t
	143-356	75-140	Jan-Dec	Chrosciewicz 1986
Abies grandis – grand fir	167-313	112-138	Jun-Oct	Agee et al. 2002[4]
	140-310	110-150	Jun-Sep	Agee et al. 2002[4]
Abies lasiocarpa – subalpine fir	150-225	110-125	Aug-Sep	Agee et al. 2002[4]
	115-312	—	Jun-Sep	Agee et al. 2002[4]
Abies magnifica var. *shastensis* – Shasta red fir	170-310	—	Jun-Sep	Agee et al. 2002
Picea glauca – white spruce	146-480	78-139	Jan-Dec	Chrosciewicz 1986
Picea engelmanii – Engelmann spruce	(mixed	100-130)	Jul-Oct	Gary 1971
Picea mariana – black spruce	131-349	73-126	Jan-Dec	Chrosciewicz 1986
	—	75-115	Jan-Dec	Springer and Van Wagner 1984
Pinus banksiana – jack pine	130-190	105-120	Jul-Oct	Johnson 1966
	137-288	79-129	Jan-Dec	Chrosciewicz 1986
Pinus clausa – sand pine	195-210	145-150	Jul-Oct	Hough 1973
Pinus contorta – lodgepole pine	117-148	96-118	Late Aug	Hartford and Rothermel 1991
Pinus edulis – pinyon pine	(mixed	95-130)	Jul-Oct	Jameson 1966
Pinus ponderosa – ponderosa pine	125-210	95-115	Jul-Oct	Philpot and Mutch 1971
	149-275	85-120	Jun-Oct	Agee et al. 2002[4]
	115-340	85-135	Jun-Sep	Agee et al. 2002[4]
Pinus resinosa – red pine	160-250	120-140	Jul-Sep	Kozlowski and Clausen 1965
	135-200	110-130	Jul-Oct	Johnson 1966
Pinus strobus – eastern white pine	150-230	130-140	Jul-Sep	Kozlowski and Clausen 1965
Pseudotsuga menziesii – Douglas-fir	120-200	80-120	Jul-Oct	Philpot and Mutch 1971
Tsuga canadensis – eastern hemlock	170-280	120-150	Jul-Sep	Kozlowski and Clausen 1965

[1]Range of percent FMC values for first-year leaves.
[2]Range of percent FMC values for second-year leaves or older.
[3]Month(s) comprising the study duration.
[4]Two separate studies for each species in same publication.

Foliar moisture content varies seasonally. Lowest foliar moisture contents typically occurring during late spring (Philpot and Mutch 1971), rapidly increase to an annual maximum shortly therafter, and then steadily decline through summer to fall (Kozlowski and Clausen 1965). This trend is physiologically based, and is more a function of the leaf's changing carbohydrate content than its water content. For example, an analysis of young red pine (*Pinus resinosa*) foliage revealed a seasonally declining FMC even as the actual water content increased (Kozlowski and Clausen 1965).

Like other fuel properties, the moisture content of foliage also varies on a diurnal basis. Philpot's (1965) study of ponderosa pine (*Pinus ponderosa*) summertime FMC revealed diurnal fluxes of 26 to 34 percent. FMC roughly tracked ambient relative humidity measured over the same period. More modest fluxes of 4 to 12 percent for ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), and grand fir (*Abies grandis*) were observed during a late August day in Washington by Agee et al. (2002).

The occurrence of worst-case fire weather and lowest foliar moisture content are usually asynchronous. For conifers such as ponderosa pine and Douglas-fir, old foliage FMC drops below 100 percent, but generally ranges between 100 percent and 130 percent during the summer months when ignitions are most frequent and fires most intense. In fuels planning, assumed FMC values should be kept seasonally consistent with the fire weather scenario used to predict surface fireline intensity.

Foliage age is another primary determinant of variation in FMC. Moisture content of first-year leaves is typically higher than older leaves by a substantial margin. For the species in table 1, the range of FMC values for new foliage is 120 to 480 percent, versus a range of 73 to 150 percent for older foliage (2^{nd} year or later). In a study of eastern white pine (*Pinus strobus*), FMC values between July and September ranged from 130 to 140 percent for old foliage, but ranged from 150 to 230 percent for new foliage on the same trees (Kozlowski and Clausen 1965). Although studies have identified FMC differences in foliage age, none have demonstrated FMC differences in tree age. Until this relationship is further examined, values in Table 1 should be applied regardless of stand or cohort age.

No reports have addressed FMC among stands of variable densities or other attributes of stand structure. Therefore, fuels planners must assume that stand structure or treatment history has no bearing on the FMC assumption. Differences between species and regions are apparent (table 1), but not with any obvious relationships to shade tolerance, latitude, or other useful ordinal characterizations that might suggest a need for regionally explicit assumptions, or that would allow extrapolation to other species not represented in table 1.

The case of mixed-species stands introduces additional complexity. In stratified even-aged mixtures or mixed multi-cohort stands, it is most appropriate to use the FMC value of the species relegated to the lower-most stratum (the stratum that will initiate the crown ignition process). For unstratified even-aged mixtures, it is suggested that the lowest FMC value be adopted among those species constituting at least 10 percent the stand's basal area.

Conclusion

Whenever possible, all assumptions in silvicultural fuels management should be supported on the basis of best available scientific information.

The foliar moisture content values summarized here should be utilized in the fuels planning process, and their supporting documentation cited in justifying silvicultural treatments of forest fuels. Alexander (1988) lists several additional studies of FMC that are more obscure but that could also prove useful. For species lacking published FMC data, a low default value of 90 or 100 percent is a prudently conservative assumption (e.g. Scott 2003). For this review, additional details that are present in the original research (table 1) were by necessity omitted in order to present all species together in one common tabular format. Additional information beyond the values presented here is available from the primary literature, and should be consulted and cited as necessary to establish the scientific basis for value assumptions used in fuels planning.

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Mapping the Relationship Between Wildfire and Poverty

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Abstract*—Wildfires and related government roles and responsibilities for federal wildland management are prominent in our national consciousness because of the increased severity in the last decade of fires on and around public lands. In recent years, laws, strategies, and implementation documents have been issued to direct federal efforts for wildfire prevention, firefighting, and recovery. Reliable national-level information and monitoring are essential to ensure good decision-making and agency accountability. Social and economic information about communities at risk from wildfire is critical to these decisions. Despite the indispensable nature of this information for understanding communities, wildfire risk, and cooperative efforts, there is a void in policy direction within the federal agencies to collect, understand, and use social and economic information in wildfire management programs. This study addresses community capacity and examines socioeconomic indicators as elements of wildfire risk. The study investigates whether communities most at risk from wildfire are able to access and benefit from federal programs established to serve these communities. In other words, are the dollars, assistance, and fuels-reduction projects hitting the ground in the areas throughout the country that are most at risk to wildfire? This presentation will provide a forum to discuss the needs of rural and underserved communities in relationship to fire and fuels management programs.*

Introduction

Wildfires and the related government roles and responsibilities for federal wildland management are prominent in our national consciousness because of the increased severity in the last decade of fires on and around public lands. In recent years, numerous laws, strategies, and implementation documents have been issued to direct federal efforts for wildfire prevention, firefighting, and recovery. Reliable national-level information and monitoring are essential to ensure good decision-making and agency accountability.

Social and economic information about communities at risk from wildfire is critical to these decisions. Despite the indispensable nature of this information for understanding communities, wildfire risk, and cooperative efforts, there is a void in policy direction within the federal agencies to collect, understand, and utilize social and economic information in wildfire management programs.

This research project uses the concept of community capacity – a community's ability to protect itself, respond to, and recover from wildfire – and examines socioeconomic indicators (one component of community capacity) as elements of wildfire risk. Utilizing socioeconomic information, as well as ecological factors, this study set out to investigate, through a geographical-information-systems approach, whether communities most at risk from

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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wildfire are able to access and benefit from federal programs established to serve these communities. In other words, are the dollars, assistance, and fuels-reduction projects hitting the ground in the areas throughout the country that are most at risk?

This research project found that federal agencies do not have the information and data necessary to answer this question. Spatial data to inform every aspect of this research – including data regarding the ecological conditions of federal lands, wildfire protection capability in and around communities, and the federal expenditures under the national fire plan – are unavailable and/or inadequate.

Using the limited data that are currently available, this research focused primarily on the relationship between poverty and populated areas at risk to wildfire. Our research indicates that there is a relationship between poverty and federal land ownership, and that more poor households are located in close proximity to federal lands. Perhaps more significant, the research shows a higher percentage of poor households in inhabited wildland areas that are not considered part of the Wildland Urban Interface – the areas that federal agencies and Congress have prioritized to receive the majority of funds for activities under the national fire plan. The research also indicates that, in the one state analyzed, poor households are more likely in areas with low or no fire response capabilities than are non poor households.

This research should be seen as a first step to document the importance of social and economic information and community capacity in wildfire policy and implementation. The lack of information about wildfire risk, including ecological conditions, socioeconomic indicators, and resource allocation convinced us to focus our recommendations on improving federal agency understanding and use of social and economic factors through national inventory and monitoring efforts. Specific recommendations include developing a method for measuring community capacity in the context of wildfire and using this methodology to redefine the concept of risk for implementation priorities at the national level and in state, regional, and local planning and risk assessment. Federal land management agencies must also improve systems for monitoring national fire plan expenditures and the datasets that support the prioritization of these funds.

Understanding the social and economic dynamics of communities is critical for providing federal assistance that will help communities protect themselves from wildfire and respond to and recover from an event. We encourage others to build on this effort to understand the complex social, economic, and ecological factors that influence wildfire risk. Specifically, we encourage federal agencies to take steps to understand the social and economic indicators that are necessary to understand and serve our nation's communities.

Research Methods

This study examines the relationship between wildfire and community risk through the concept of community capacity. The research also attempted to analyze federal resource allocation in conjunction with data indicating relative risk. To examine these issues, the project team conducted background research to identify indicators and nationally consistent data for each element of the project. The team also facilitated internal and external data review, mapped indicators once data had been collected, and reexamined and reported findings through the mapping process.

To illustrate the study elements, we sought data to use as indicators of community capacity and wildfire risk. This process was iterative, investigating potential datasets, summarizing the benefits and drawbacks of each, and obtaining feedback from an advisory committee. We also presented preliminary findings of the study at two community meetings in southern Oregon and central Oregon.

This section provides a description of the data we initially sought to examine community capacity, wildfire risk, and federal resource allocation. It includes the limitations of the best available data, and a summary of how we use the data in this study.

National-Level Data

This report is a national-level analysis that seeks to provide information on a national scale. The spatial information included in this report is provided at the county and census-block levels. Therefore, the visual analysis is, in many cases, more meaningful on a state level. Consequently, the researchers have included more detailed maps and analysis for the states of Washington and Oregon, as state-level examples. The maps and analysis shown for these two states are also available, upon request, for other states.

Identifying indicators that provide consistent and meaningful information for a nationwide study became the first challenge. Although some poverty data exist on a national scale (from the Census and Department of Housing and Urban Development), it was more difficult to find consistent national data on community capacity, protection capacity, wildfire risk, and federal resource allocation. The researchers encountered major challenges in finding spatial data, especially in a format conducive to national-level modeling. Specifically, there is a lack of suitable data in the areas of: (1) community capacity/protection capability (2) ecological conditions on federal lands/populated areas at risk from wildfire; and, (3) federal resource allocation.

Indicators and Data

The following section provides information about the purpose of each indicator, the data initially sought, the limitations encountered, and the data ultimately selected.

Community Capacity

Examining community capacity requires understanding a complex set of issues and indicators that are not easily summarized by a single set of data. Below, we explain the purpose for using the concept of community capacity, existing definitions of community capacity found in published research, the limitations we encountered in identifying data, and the indicators we ultimately chose for this research.

Community capacity can be used to assess the relative risk that a community faces from wildfire. Well defined, community capacity will provide the social information to tell us which communities are at a greater risk—less ready to protect themselves from wildfire, and less able to recover from the impacts of a fire. Understanding the capacity of a community to address the economic, social, and environmental costs of wildfire will lead to more directed policies and programs and a more efficient use of resources. Following are two definitions of capacity that we used to help frame the study and the indicators we sought to use for the research.

- Kusel (1996) defines community capacity as "the collective ability of residents to respond…to external and internal stresses; to create and take advantage of opportunities; and to meet the needs of residents, diversely defined."
- A response by American Forests to the 2001 Federal Register notice *Urban Wildland Interface Communities within the Vicinity of Federal Lands that are at High Risk from Wildfire*, defines community capacity as the collective ability of residents in a community to respond to external and internal stresses, to create and take advantage of opportunities, and to meet local needs. Community capacity in relation to wildfire addresses a community's ability to mitigate wildfire threats, respond to active wildfire, and mitigate post fire damage. This includes the ability to implement risk-reduction strategies, including hazardous fuels reduction, firefighting, and restoration activities (American Forests 2001).

For purposes of this research (and because of limited data), two indicators were used as a first step to measure community capacity as it relates to wildfire: (1) socioeconomic elements that influence a community's ability to respond to and recover from wildfire and (2) protection capability - systems that are in place that influence a community's ability to protect itself from an actual wildfire. As previously stated, a true assessment of community capacity would include a much broader array of social and cultural information; however, this information was not readily available at the time that this research was undertaken.

The study uses 2003 Housing and Urban Development (HUD) Income Limits, at a comparable census block group level, as the primary layer for poverty. HUD Income Limits reflect income, earnings and employment, and housing affordability. The Median Family Income Limit estimates are based on the U.S. Census Bureau median family income estimates with an adjustment using a combination of earnings and employment data, median family income data, and fair market rents. Data are available nationally. HUD Income Limits describe family sizes of one to eight persons, and a formula is provided to calculate income limits for larger family sizes. Income limits are adjusted for family size and areas with unusually high or low family income or housing-cost-to-income relationships (Housing and Urban Development). Income limit groups include families whose incomes do not exceed 80 percent of the median family income for the area *(low-income)*, families whose incomes do not exceed 50 percent of the median family income for the area *(very low-income)*, and families whose incomes do not exceed 30 percent of the area median income *(very, very low-income)*.

This report also utilizes fire hazard ratings, used by both public and private sector organizations around the nation, as indicators of the capabilities of fire districts to protect their communities from wildfire. The Fire Suppression Rating Schedule is a common method used by the insurance industry in reviewing the firefighting capabilities of individual communities. The schedule measures the major elements of a community's fire suppression system and develops a numerical grading called a "Public Protection Classification." Ten percent of the overall grading is based on how well the fire department receives and dispatches fire alarms. Fifty percent of the overall grading is based on the number of engine companies and the amount of water a community needs to fight a fire. Forty percent of the grading is based on the community's water supply, which focuses on whether the community has sufficient water supply for fire suppression beyond daily maximum consumption.

This report uses data from the Washington State Independent Fire Hazard Rating Bureau to assess the relationship between fire hazard ratings, poverty, and potential wildfire risk. The Washington State Rating Bureau provides data for all of the fire protection ratings for fire districts in Washington State.

Ecological Risk/ Populated Areas at Risk from Wildfire

The research intended initially to examine ecological wildfire risk—the likelihood of fire occurring in different areas and the potential damage such a fire would pose—through spatial data that would indicate, on a national level, the relative risk status of wildlands across the country. This indicator was intended to provide information about the ecological condition of lands. When it became apparent that there was insufficient consistent and up-to-date data on the ecological conditions of lands, we focused the study on the potential risk of fire to populated areas.

This study focuses on two distinct elements of the Forest Service study and data on wildland urban interface. The first data set that we examine is the *Wildland Urban Interface* as defined above. The second set of data that we use is the *Wildland Intermix* —less densely populated areas in wildlands, which enabled the study to include significant portions of inhabited land in areas vulnerable to wildfire.

Federal Resource Allocation

Initially, this study intended to include data detailing all federal expenditures under the National Fire Plan, including grants to communities and hazardous fuel reduction projects on private and public lands and spatial information that would indicate where the activities took place. These data would provide a roadmap to track where federal funding was being spent, which would allow researchers to examine these data with the data layers indicating capacity and wildfire risk. The combination of these layers would provide information about how well the federal agencies were serving the areas most at risk from wildfire.

National Fire Plan Grants—National Fire Plan data for Region 6 are available in a multi-agency database (projects funded by BLM, Bureau of Indian Affairs, USDA Forest Service, and Fish and Wildlife Service). They include zip code and latitude/longitude information for each grant, based on the location of the grant recipient, and a designation for the type of project funded (fuels reduction, fire prevention, planning and education, small-diameter marketing and utilization). Because of the limitations of the grants data, the decision was made not to analyze the data numerically. This report does include maps that illustrate the allocation of National Fire Plan Community Assistance grants in Oregon and Washington in comparison with poverty and WUI and Inhabited Wildland areas.

Findings

When we began this study, we anticipated that findings would focus on the provision of services (or gaps in services) to at-risk communities. Actual findings are considerably different from this original intent, due largely to the limited availability of data and lack of monitoring information.

Overall, the findings indicate that using national datasets to illustrate the complex social and ecological factors influencing wildfire risk is limited by the very nature of these elements. Datasets available for social, economic and ecological factors are more refined and meaningful on smaller scales. Locally specific data and information provide a better indication of the relationship between wildfire and poverty and how well services for fire protection are being provided to at-risk communities. This is apparent in the data we reviewed, as well as from comments from public meetings held in southwest and central Oregon and through dialogue with national partners. Despite these challenges, specific research findings include:

1) a slightly higher percentage of poor households in inhabited wildland areas that are not considered part of the WUI;
2) poor households in Washington State are more likely to be in areas with low or no fire response capabilities than are non poor households;
3) federal land management agency information about grants to communities and hazardous fuels reduction projects is insufficient to allow an analysis of areas served or improved.

The following section describes these findings in more detail.

Poverty and Wildland Urban Interface and Inhabited Wildland Areas

The first set of findings is related to the incidence of poverty in the wildland urban interface and other inhabited forested land areas. Initial analysis using the WUI dataset resulted in maps that showed a small portion of the total forested land area, particularly in the western United States. Further investigation indicated that the federally defined "*Wildland Urban Interface*" is based on residential density that excludes many inhabited forest areas. Expanding the analysis to include wildland intermix, the less densely populated areas that are not included in the WUI, which we refer to from here on as "*Inhabited Wildlands,*" allowed us to include significant portions of rural, inhabited land in areas vulnerable to wildfire.

Table 1 illustrates the percentage of households in Oregon, Washington, and nationally in WUI and Inhabited Wildland areas and compares non-poor, poor, and very poor households. These percentages illustrate a trend in the Northwest and nationally of a greater number of poverty areas in inhabited wildland areas than in the states or nation as a whole, or in WUI areas or non-forested areas.

Results from this analysis indicate that, in general, there are more households in poverty in inhabited wildland areas than there are in the Wildland Urban Interface or in areas outside of the vegetated wildlands in the rest of the state. The researchers held regional meetings to share preliminary findings with community organizations, agencies, and citizens in poor areas to examine data at a local level. These meetings reinforced the finding that the inhabited wildland areas that do not fall within the federal WUI definition are areas with a greater number of households in poverty.

Maps of Oregon, Washington, and the United States on the following pages illustrate the data described above and provide a visual representation of the relationship between wildfire and poverty. The maps illustrate HUD units where 20% of households or more are low-income households in Wildland Urban Interface and Inhabited Wildland areas.

The study maps of Oregon and Washington clearly indicate a tremendous amount of inhabited wildland, particularly in the western United States,

Table 1—Household Location by Poverty Level and Wildland Urban Interface Designation.

Income level	Location	Overall	Fire hazard Designation		Inhabited
			Not vegetated	WUI	wildlands
Non Poor	National	77%	79%	81%	76%
	Oregon	79%	78%	83%	77%
	Washington	79%	79%	83%	78%
Poor	National	23%	21%	**19%**	**24%**
	Oregon	21%	21%	**17%**	**23%**
	Washington	21%	21%	**17%**	**22%**
Very Poor	National	12%	10%	**9%**	**12%**
	Oregon	10%	10%	**8%**	**11%**
	Washington	11%	10%	**8%**	**11%**

that is not considered part of the WUI under the Federal Register definition (figures 1, 2, and 3). There is a relatively high level of poverty in the non-WUI rural areas (areas where the housing density is too low to be included in the WUI).

The maps of Oregon and Washington illustrate a strong relationship between poor areas and the communities in the Inhabited Wildland areas. The national numbers support this relationship as well. However, more detail is evident from the national map, which illustrates that, although there may be more poverty in the inhabited wildlands in some regions, such as the western United States, other regions may have more households in poverty in the WUI, as appears to be the case in the Southeast.

If agencies are following the Federal Register definition, the strategy to prioritize WUI lands for hazardous fuels reduction work and the funding reserved for those areas means that fewer resources are being allocated in some regions to the poorest citizens in communities that may need the most assistance.

Poverty and Protection Capability

This study provides data about the level of fire district capabilities, which is only one indicator of the capacity of a community to reduce wildfire risk. This information is provided for the state of Washington.

Table 2 illustrates the percentage of poor and non-poor households in each of four fire response categories in Washington. A small area in the west-central portion of the state did not fall under a particular response category but showed that 33.1% of households are poor. Although there are low-income populations with all levels of fire protection, the map illustrates the visual relationship between the Wildland Urban Interface and Inhabited Wildland areas, as well as poverty and protection capability. In general, a higher percentage of poor households live in areas with no or low fire response capability than do non-poor households.

Figure 4 illustrates the level of fire protection capability in relation to the Wildland Urban Interface and poverty data in the state of Washington. The map shows a relationship between high poverty areas that overlap with areas with limited to no protection capability.

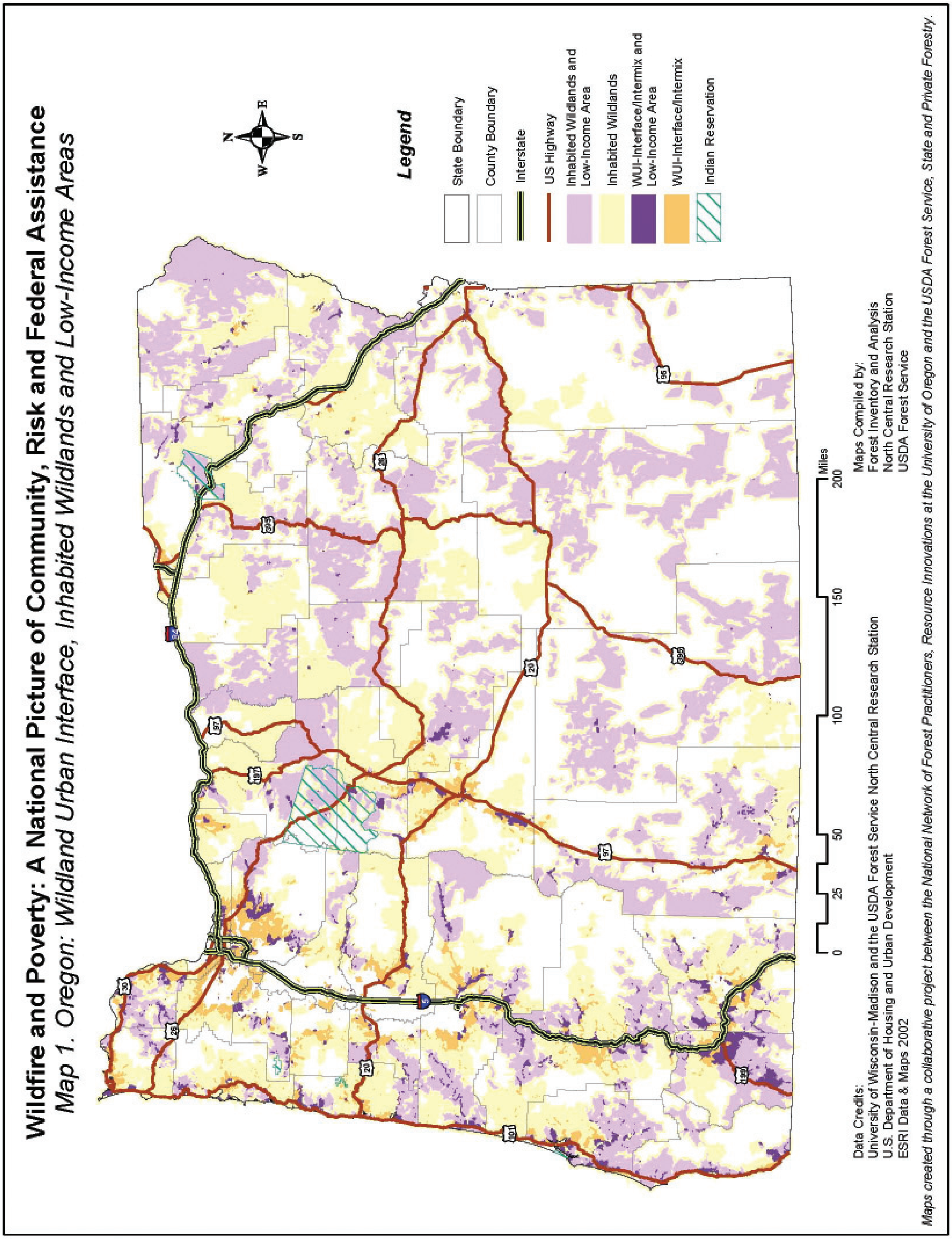

Figure 1—Oregon: Wildland Urban Interface, Inhabited Wildlands, and Low-Income Areas.

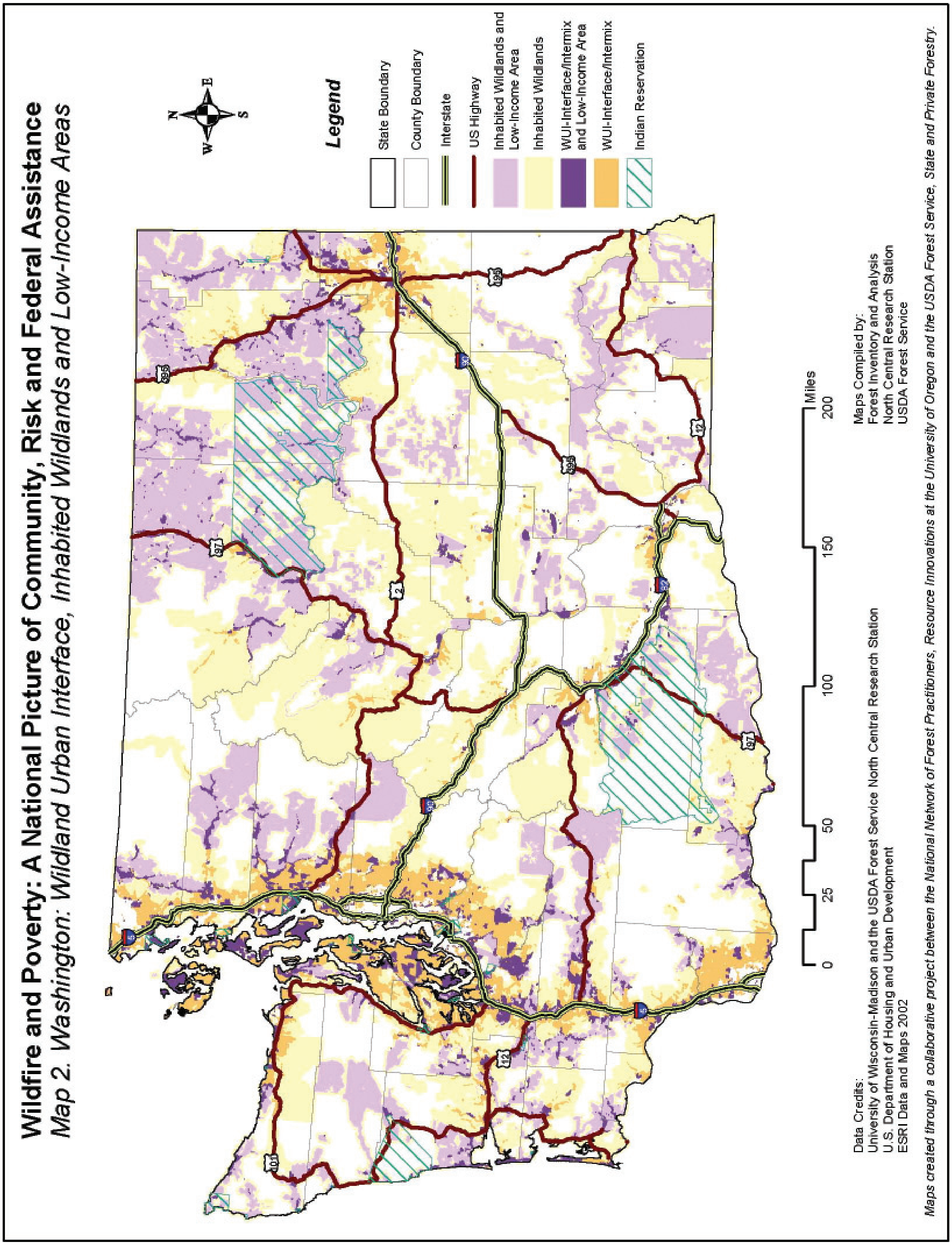

Figure 2—Washington: WUI, Inhabited Wildlands, and Low-Income Areas.

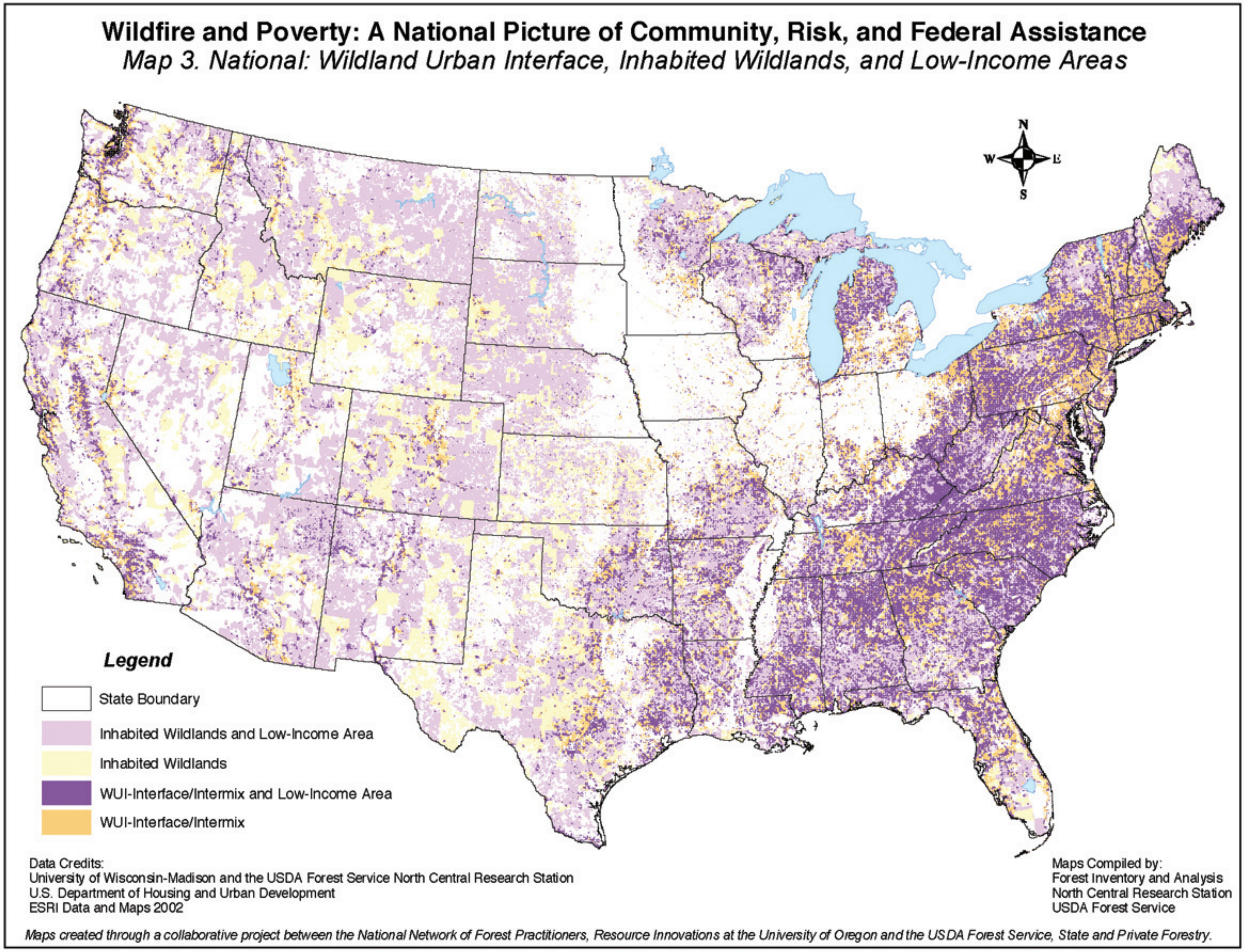

Figure 3—National: WUI, Inhabited Wildlands, and Low-Income Areas.

Table 2—Washington Households, Poverty Level and Fire Protection Capability.

Income Level	High Fire Response	Medium Fire Response	Low Fire Response	No Fire Response
Non-Poor	82%	85%	79%	77%
Poor	18%	16%	**21%**	**23%**
Very Poor	8%	7%	**10%**	**12%**

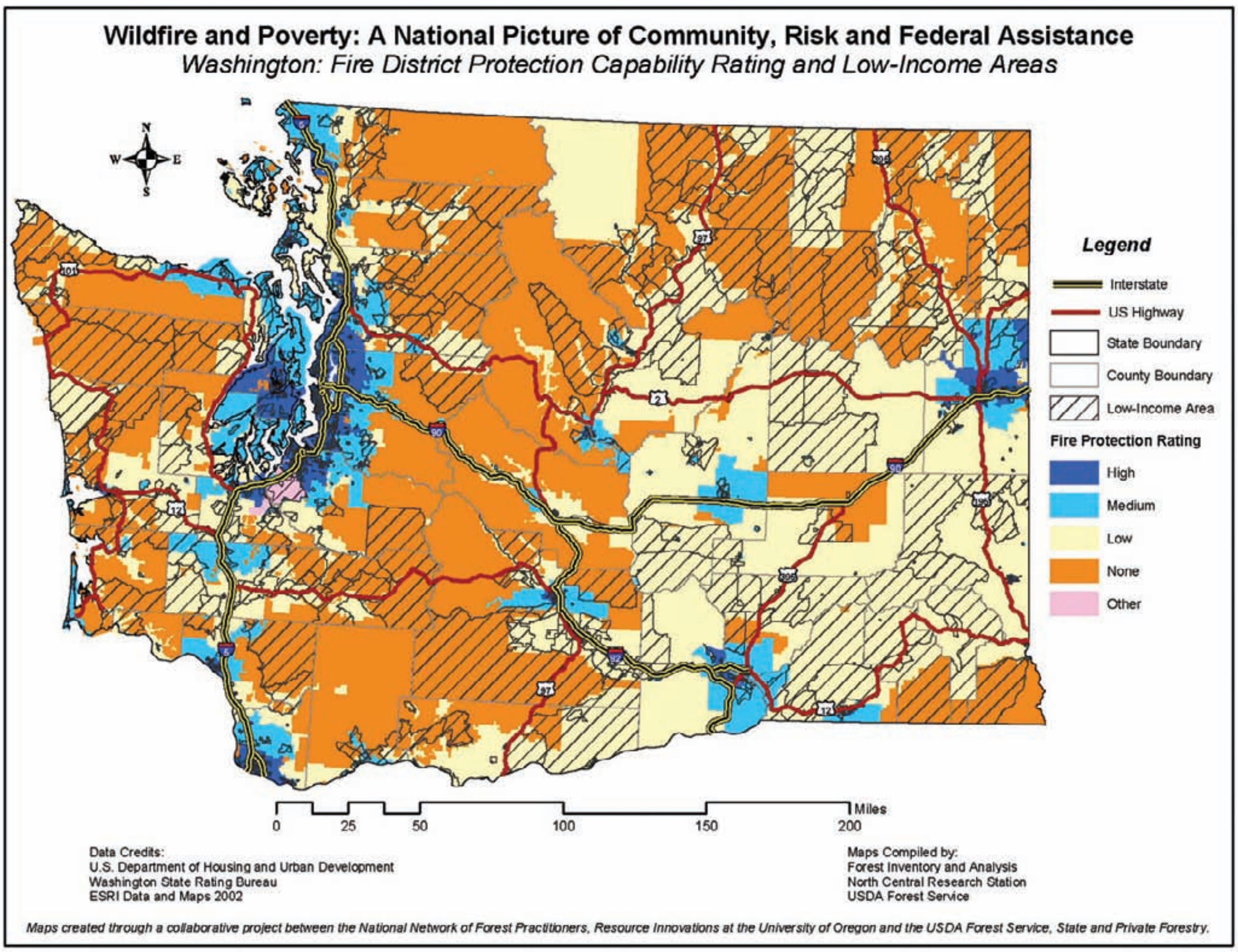

Figure 4—Washington: Fire District Rating and Low-Income Areas.

Federal Resource Allocation and Grants

The original goal of this study was to examine the provision of fire-related services and resources to low-income, low capacity communities in high-risk wildfire areas. Because of limited data about actual grant and resource allocation, it is not possible to draw reliable conclusions about resource allocation in and around poor communities. Consequently, our findings are limited to the discovery that there is inadequate monitoring of NFP expenditures and program implementation at the national level to ensure the accountability of federal programs to the goals and priorities set forth in the National Fire Plan, Healthy Forest Restoration Act, and related wildfire programs.

National Fire Plan Grants—Data about fire and aviation community assistance grants obtained through the National Fire Plan office in Region 6 (Oregon and Washington), produced maps that reflect areas that have received grants that relate to the poverty data in WUI and Inhabited Wildland areas.

The limitations of these data, as described in the research methods section, above, restricted our ability to provide percentages of poor communities that have received (or benefited from) National Fire Plan grants. The points on the map illustrate where grant funds have been received, not where grants were actually expended. In some cases, grants may have been received by agencies and organizations in county seats or municipalities that have higher income levels than the more rural areas where the funds were expended. The point data also lack information on the type and amount of treatment that occurred and the extent to which fire and fuel conditions, and community capacity have changed in low-income areas.

Recommendations

Due to the limited availability of data and the limitations of the existing data, we have focused our recommendations on improving federal agency understanding and use of social and economic factors through national inventory and monitoring efforts, and on increasing and improving assistance for low-income and low capacity communities. A summary of recommendations is provided below.

1. Redefine the areas prioritized for federal assistance to include rural areas with lower residential density (e.g., inhabited wildlands).
2. Improve systems for monitoring and evaluating the National Fire Plan and other federal fire-related program implementation by including social and economic, as well as ecological, information.
3. Immediately develop nationally consistent standards for monitoring National Fire Plan expenditures that will enable assessment of outcomes over time.
4. Develop a method for measuring community capacity in the context of wildfire.
5. Provide clear direction to federal and state land management agencies for determining "at risk" communities, giving significant consideration to social and economic factors. Target assistance and federal programs based on community needs.
6. Integrate indicators of community capacity into state, regional, and local planning and risk assessment.

7. Increase federal support and funding to programs that target assistance to "at risk" communities.
8. Conduct case studies in high wildfire risk areas to gain more in-depth knowledge about the relationship between wildfire, poverty and community capacity.

Acknowledgments

Several individuals were instrumental to this research. Special thanks to Dacia Meneguzzo and Ron McRoberts from the Forest Inventory and Analysis, North Central Research Station, USDA Forest Service. Dacia provided the mapping expertise and labor, and Ron provided knowledge and advice regarding spatial mapping and datasets. Krista Gebert, Rocky Mountain Research Station, USDA Forest Service and Susan Odell, National Rural Community Assistance Coordinator, USDA Forest Service bridged the gap between the authors and the Forest Service, providing support and assistance. Bonnie Wood and Lauren Maloney assisted in obtaining data about community assistance grants from the Region 6 National Fire Plan office.

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Fuel Treatment and Prescribed Fire

Fire Severity and Intensity During Spring Burning in Natural and Masticated Mixed Shrub Woodlands

Tim Bradley[1], Jennifer Gibson[2], and Windy Bunn[3]

***Abstract**—Fire risk is an ever present management concern in many urban interface regions. To mitigate this risk, land management agencies have expanded their options beyond prescribed fire to include vegetation mastication and other mechanical fuel treatments. This research project examined fire severity and intensity in masticated and unmanipulated units that were burned in spring in a Northern California mixed shrub woodland. Mastication treatments significantly altered the fuel profile, resulting in an approximate 200 percent average increase in woody fuel cover for 1-hr and 1000-hr TLFM size classes, and greater than 300 percent average cover increase in 10-hr and 100-hr TLFM size classes. The mean flame length (29 vs. 10 inches/ 74 vs. 25 cm) and flame zone depth (20 vs. 6 inches/ 51 vs. 15 cm) were significantly greater (P<0.001) in masticated units than in unmanipulated units as were the mean temperatures at the litter surface (657°F vs. 219°F/ 347°C vs. 104°C) and 1.64 ft (0.5 m) above the litter surface (277°F vs. 59°F/ 136°C vs. 15°C) (P<0.001). Greater flaming and heat release in the masticated units led to increased mortality of overstory and pole-sized oaks and conifers posing conflicts with the management objective of retaining overstory vegetation.*

Introduction

Land managers in the Western United States are increasingly faced with the challenge of implementing wildland fuel reduction treatments that are both effective and achievable within reasonable time frames. Traditionally, managers have relied on prescribed fire as the primary tool for landscape level risk reduction and ecosystem restoration in fire prone plant communities. However, a number of challenges complicate the achievement of fuel reduction goals using prescribed fire alone. These challenges include air quality restrictions, limited burn windows, insufficient staffing, and the liability associated with escaped burns. Due to these limitations, managers are increasingly turning to the use of mechanical treatments as a supplement to prescribed fire for the accomplishment of fuels management objectives.

One option that has gained popularity with land managers in Western states is vegetation mastication, which can allow managers to quickly and safely decrease shrub and other understory vegetation at a fraction of the cost of comparable manual thinning treatments. Tens of thousands of acres of shrubs and other understory species in fire-prone plant communities are being treated with vegetation mastication to reduce fire hazard. Most land management agencies prefer to leave masticated biomass on the ground to cycle nutrients, prevent soil erosion, and to impede the establishment of non-native and invasive plant species. However, since mastication does not remove

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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this biomass, but rather converts the standing brush to dead surface fuels, fire risk can still be high. Despite gaining acceptance as a landscape-scale treatment, significant uncertainty exists regarding the effects of these alterations on fire behavior in both prescribed fire and wildland fire scenarios.

Like many National Park Service units throughout the country, Whiskeytown National Recreation Area recently revised its Fire Management Plan (National Park Service 2003). This plan greatly expands the options available to park managers and includes a suite of mechanical treatments, such as manual thinning, small-scale logging, and vegetation mastication that have yet to be tested in the park or in similar habitat types elsewhere. With support funding from the Joint Fire Science Program, a research project was initiated in 2002 to provide managers with a better understanding of the effects of one of these treatments, vegetation mastication, on fire behavior and intensity.

Since fuel beds resulting from the mastication of shrubs and small trees are most similar to those of a logging slash fuel model, it is hypothesized that the increase in small-sized surface fuels would increase fire intensity and severity. The overall goal of this project was to evaluate key fire behavior indices and severity effects to vegetation in both masticated and unmanipulated vegetation during a spring prescribed burn. Specific objectives for the unmanipulated vegetation were consistent with prescribed burn treatments applied throughout the park, while separate project-specific objectives were developed for the application of fire to masticated vegetation (table 1). These objectives targeted the reduction in specific fuel classes and the retention of overstory trees.

Study Site

Whiskeytown National Recreation Area is located on the southeastern edge of the Klamath Mountains in Northern California. The climate is characterized as Mediterranean, with cool, wet winters and hot, dry summers. Temperature readings are often over 100°F (38 °C) from May through October and occasional sub-freezing temperatures occur from November through March. The annual precipitation averages 60 inches (152 cm) at

Table 1—Management objectives for the prescribed fire treatments in masticated and unmanipulated fuelbeds.

	Targeted percent change	
Objective	Masticated	Unmanipulated
Reduce surface fuel accumulation (litter, duff, 1, 10, 100, 1000 hr TLFM)	15 to 35	25 to 70
Reduce live density of small knobcone pine trees (<8 inch/20 cm d.b.h)	0 to 25	10 to 75
Reduce live density of all other small trees (<8 inch/20 cm d.b.h)	0 to 25	0 to 40
Limit mortality of overstory trees (>8 inch/20 cm d.b.h)	0 to 15	0 to 15
Reduce cover of live shrubs	0 to 25	15 to 75

park headquarters, most of which falls between November and April. The 45 acre study site is located in a low elevation (1,250 to 1,400 ft/380 to 460 m) area that has slopes less than 30 percent (the upper limit for the selected machinery). Overstory vegetation is dominated by black oak (*Quercus kelloggii*) and knobcone pine (*Pinus attenuata*), with limited presence of other species such as canyon live oak (*Quercus chrysolepis*), grey pine (*Pinus sabiniana*), and interior live oak (*Quercus wislizeni*). The understory vegetation is typically dense and dominated by whiteleaf manzanita (*Arctostaphylos viscida*), with toyon (*Heteromeles arbutifolia*) and poison oak (*Toxicodendron diversilobum*) also common.

Experimental Design and Treatments

The research site was stratified based on vegetation, slope, and aspect, resulting in the selection of ten different 1 to 2 acre (0.4 to 0.8 ha) treatment blocks. Each treatment block was divided into fourteen approximately equal-sized units, with two units from each block representing masticated (n=20) and unmanipulated (n=16) vegetation burned in the spring. The remaining experimental units are part of a separate long-term research project focusing on vegetation response to mastication and other fuels treatments.

Mastication treatments were completed in November of 2002 using an ASV Posi-Track™ with industrial brush-cutter. At least 90 percent of machine operations occurred over surfaces covered with chipped wood to limit soil disturbance and compaction (Poff 1996). To further minimize soil impacts, the tractor specifications required rubber tires or tracks, a vehicle no larger than 10,000 gross pounds (4,500 kg), an average of less than 3.5 pounds per square inch (0.25 kg/cm^2) ground pressure, and operation on dry soil (Windell and Bradshaw 2000). The goal of this treatment was to reduce understory bulk density by 60 to 95 percent by thinning shrubs and small trees less than four meters in height. In areas where overstory trees were absent, a limited cover of shrub species was maintained.

Prescribed burn treatments were designed to be representative of treatments typically applied within the park. All fires were backing with respect to slope and/or wind, utilizing drip torches and applying a combination of strip and spot ignition patterns. Ambient weather conditions were recorded on-site by fire effects monitors. During the burning period (April-May 2003), temperature extremes ranged from 59°F to 71°F (15°C to 22°C), relative humidity ranged from 34 to 73 percent, and wind speeds averaged 2 mph (3 km/h) with a maximum wind speed of 6 mph (9.5 km/h). Soil moisture readings were very high (0.3 to 0.4 kPa tension) as recorded by a Delmhorst KS-D1 soil moisture meter at reference locations 18 inches (45 cm) below the surface.

Fire behavior and effects measures were recorded for each burn unit in four 1 m^2 fire behavior plots (n=140). Within each fire behavior plot, pre- and post-burn measurements were collected for litter, duff, 1-hr (<0.25 inches or 0.6 cm), 10-hr (0.25 to 1 inch or 0.6 to 2.5 cm), 100-hr (1 to 3 inches or 2.5 to 7.6 cm) and 1000-hr (>3 inches or 7.6 cm) time lag fuel moisture (TLFM) cover. In addition, percent cover values for herbaceous vegetation and bare ground were recorded. Using a method similar to Hobbs and Atkins (1988), a garden stake with pyrometers was located at the center of each fire behavior plot to record maximum temperature. Pyrometers were constructed using brass tags painted with heat-sensitive paint (OMEGALAQ®, Omega

Engineering, Inc.), and were positioned in three strata: 1) between the duff and soil layers; 2) on top of the litter; and 3) 0.5 m (1.64 ft) above the litter surface. During the burn, fire behavior data were recorded on the maximum and average flame lengths, flame zone depths, rates of spread, and fire types (head, backing, or flanking). One month after the burn, scorch estimates for dominant trees and shrubs were recorded for each burn unit and tree and shrub mortality estimates were recorded approximately six months post-burn.

To examine potential patterns in fire behavior, severity, and surface fuels, all fire behavior plots were characterized through a Principal Components Analysis (PCA) (Tabachnick and Fidell 1996). A two-tailed t-test (Zar 1996) was used to determine the difference in the mean PCA factor scores for masticated and unmanipulated vegetation. Similarly, a two-tailed t-test was used to determine the mean difference in flame length and flame zone depth for masticated and unmanipulated vegetation. To ascertain differences in pyrometer temperature between masticated and unmanipulated vegetation, a two-tailed t-test was used. A multiple regression (Zar 1996) was used to model relationships for aerial and litter level pyrometers with surface fuels and fine dead fuel moisture.

Results and Discussion

The effect of the brush mastication treatment did not result in a reduction of fuels, but rather the rearrangement of standing live material into dead and small-sized surface fuels. Prior to implementation of the mastication treatment, the fuels at the site were best characterized as a mix of fuel models 4, 8, and 9 (Anderson 1982). After mastication, the fuel bed changed drastically, with post treatment conditions representative of fuel model 11 (logging slash). This conversion of standing vegetation into downed woody debris resulted in an approximate 200 percent average cover increase in woody fuel loading for 1-hr and 1000-hr TLFM size classes, and greater than 300 percent average cover increase in 10-hr and 100-hr TLFM size classes. In addition to a surface fuel quantity increase, average shrub canopy cover was reduced from 64% down to 2% by the mastication treatment. This removal of canopy cover can contribute to an increase in air circulation, surface temperature, and direct solar radiation (Aussenac 2000), which can dry fuels quickly and increase flammability (Weatherspoon 1996). The results from this research strongly suggest that the combination of rearranging the structure of fuels while simultaneously altering the site microhabitat characteristics, led to an increased potential for high intensity fire.

To examine potential patterns between surface fuels and indices of fire behavior and severity, a Principal Components Analysis (PCA) was used (figure 1). Positively skewed data were transformed using the square root and the Pearson's product moment correlation coefficient (Zar 1996) was used to eliminate variables that were highly correlated (>0.6). The PCA illustrated differences between masticated and unmanipulated plots for Factor 1 scores. A two-tailed t-test on the PCA scores demonstrated a difference in the amount of surface fuels, fire behavior, and fire severity variables with mean Factor 1 scores for masticated plots (0.480) significantly ($P<0.001$) greater than those for unmanipulated vegetation (–0.583). The high Factor 1 scores for masticated plots indicate a high amount of surface fuels (litter, 1-hr, 10-hr, and 100-hr fuels), wide flame zone depth, and greater aerial temperatures. Plots in unmanipulated vegetation had a high percent cover

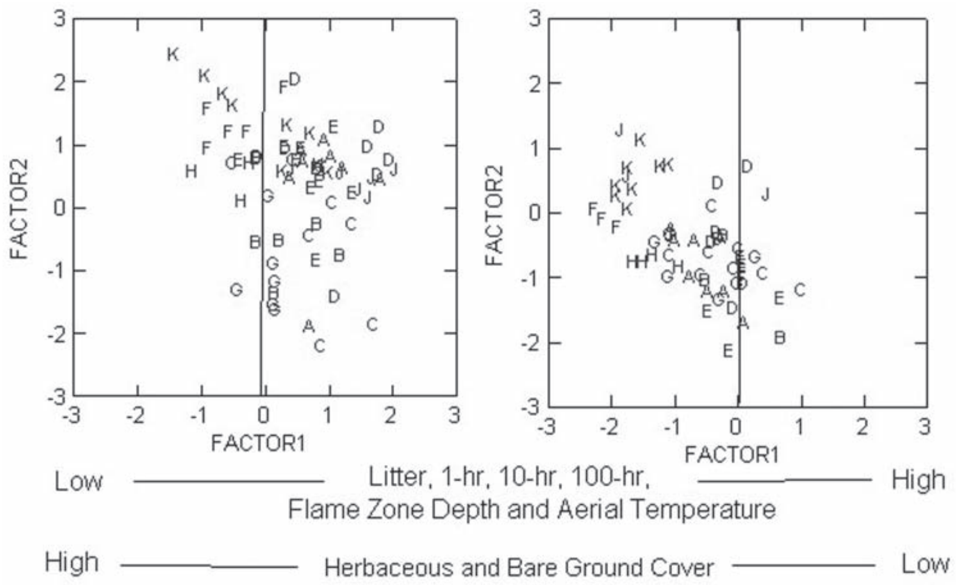

Figure 1—PCA scores for masticated (left) and unmanipulated (right) plots during the burn treatment.

of herbaceous species, bare ground, and low surface fuels, fire behavior and fire severity values.

A variety of fire intensity measures showed striking differences between the masticated plots and those in unmanipulated vegetation. A two-tailed t-test for both flame length and flame zone depth indicated greater values in masticated plots when compared to plots in unmanipulated vegetation. Mean flame length (29 inches/ 74 cm) and flame zone depth (19 inches/ 48 cm) were significantly greater ($P<0.001$) in masticated plots than mean flame length (10 inches/ 25 cm) and flame zone depth (6 inches/ 15 cm) in the unmanipulated plots. Two of the three strata tested with pyrometers also indicated significant temperature differences between masticated and unmanipulated plots (figure 2). A two-tailed t-test showed that mean temperatures for litter (657°F/ 347°C) and aerial (277°F/ 136°C) pyrometers in the masticated plots were significantly greater ($P<0.001$) than temperatures recorded for litter (219°F/ 104°C) and aerial (59°F/ 15°C) pyrometers in unmanipulated vegetation. While above ground temperatures were moderate to high, high duff and soil moistures moderated intensity effects to the soil, with only limited heating recorded by the lowest pyrometer. As a result of these conditions, duff reduction was not complete in either masticated (27 percent consumption) or unmanipulated (16 percent consumption) fuels.

The data for aerial and litter pyrometers were analyzed by multiple linear regression models to investigate the relationship among variables. With aerial pyrometer temperature as the dependent variable, the best fitting model ($P = 0.004$) included 100-hr fuels and fine dead fuel moisture as independent variables (table 2). With litter pyrometer temperature as the dependent variable, the best fitting model was also highly significant ($P = 0.026$) and included litter depth, 10-hr fuels, and 100-hr fuels as dependent variables (table 3). Despite their high significance, each of these models demonstrated relatively mediocre fit with $r^2 = 0.314$ for aerial pyrometers and $r^2 = 0.478$ for litter

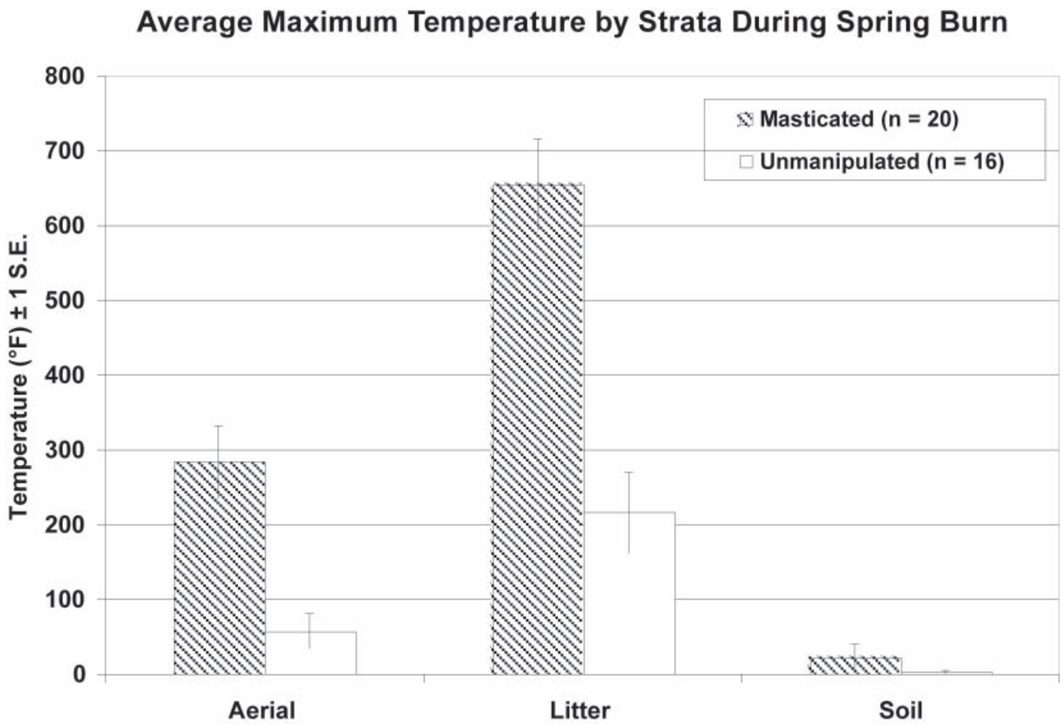

Figure 2—Average temperatures recorded by pyrometers during the burn treatment in masticated and unmanipulated plots. Aerial pyrometers were located 0.5 m/1.64 ft above the ground surface, litter pyrometers were located on the surface of the litter, and soil pyrometers were located between the duff and soil layers.

Table 2—Regression statistics for aerial (0.5 m/1.64 ft above ground surface) pyrometers

Model Term	Parameter estimate	SE	Pr(>|t|)
Intercept	357.9272	122.6933	0.0041
100 hr. Fuels[a]	14.4611	2.5365	0.0000
FDFM[b]	–28.1747	12.2782	0.0233

[a] 100 hour TLFM size class
[b] Fine dead fuel moisture

Table 3—Regression statistics for pyrometers placed at the litter surface.

Model Term	Parameter estimate	SE	Pr(>|t|)
Intercept	453.5598	201.7489	0.0262
Litter Depth	91.0512	21.3446	0.0000
10 hr Fuels[a]	8.6276	1.8347	0.0000
100 hr Fuels[b]	13.1951	4.0239	0.0013
FDFM[c]	–46.1797	19.2146	0.0176

[a] 10 hour TLFM size class
[b] 100 hour TLFM size class
[c] Fine dead fuel moisture

pyrometers. It is probable that a more accurate quantification of the fuelbeds would have improved our results, although at a significant increase in time. Regardless, given the high level of variability that existed within individual fuelbeds, such findings are not surprising and perhaps highlight the differences frequently found between laboratory and field experiments. Of note is the correlation shown by fine dead fuel moisture in both models. While a coarse value, fine dead fuel moisture is sensitive to changes in canopy cover and regularly recorded ambient weather conditions.

Based on the multiple regression analyses, surface fuel loading was a primary driver of fire behavior, with significant fuel consumption differences noted between treatments (figure 3). With the exception of 1-hr fuels, total percent consumption in the masticated fuelbeds was higher for all TLFM size classes. It is probable that the apparently low consumption of 1-hr size class fuels in the masticated fuels (17 percent) was actually much higher, and includes larger 10-hr and 100-hr fuels that were only partially consumed during the burns. Interestingly, an increase was noted in 100-hr and 1000-hr TLFM size classes following the burn treatment in unmanipulated vegetation. While only a marginal increase, this finding is consistent with other monitoring completed at the park, reflecting the addition of recently killed vegetation to the surface fuelbed.

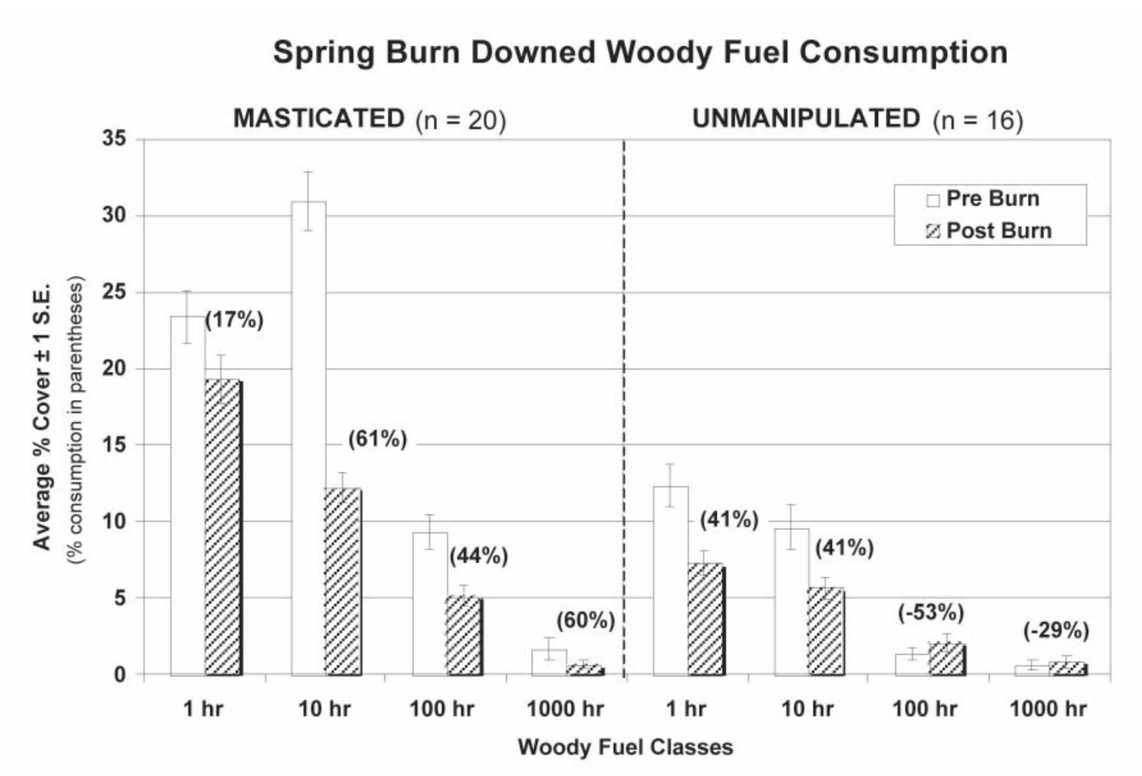

Figure 3—Consumption of downed woody fuels during the burn treatment in masticated and unmanipulated plots. Fuels are categorized as 1 hour, 10 hour, 100 hour, and 1000 hour time lag fuel moisture (TLFM).

The total surface fuel reduction objectives (table 1) were achieved in both masticated and unmanipulated vegetation, but the fire effects to live vegetation were more complex. In the unmanipulated units, reduction targets were met for pole-sized (<8 inches or 20 cm d.b.h.) trees and shrubs and there was no mortality of overstory (>8 inches or 20 cm d.b.h.) trees (table 4). However, in the masticated units, reduction and mortality targets were greatly exceeded for pole-sized trees, shrubs and overstory trees (table 4). Despite efforts by ignition crews to mitigate effects to overstory trees, the heat effects to these trees and to residual shrubs in the masticated units were severe. While applying prescribed fire during the early growing season was likely a contributing factor to this mortality, the increased fire intensity in masticated fuels was the primary cause.

Management Implications

Results from this study showed significant differences in fire behavior and effects during spring prescribed burns in units with masticated vegetation versus those with unmanipulated vegetation. These results strongly suggest that the differences were driven by the surface fuel conditions created as a direct result of the mastication treatment. Through time, decomposition and compaction of these materials may promote lowered fire intensity potential, but in the short term mastication appeared to contribute to an increase in fire severity and intensity.

While vegetation mastication followed by prescribed fire was a success from a fuel reduction standpoint, fire intensity in the masticated units was lethal for much of the residual vegetation. Since the mastication treatment had already eliminated shrubs and small trees, the effect of the prescribed burn on retained vegetation was undesirable. In natural areas the retention of overstory trees is a primary resource management concern during prescribed burns, and these results highlight the potential conflicts of burning in varied fuelbeds when objectives extend beyond surface fuel consumption.

While this study was restricted to one site, the results apply to many land management agencies that are interested in applying mastication treatments

Table 4—Average percent mortality of trees and shrubs during the spring burn treatment in masticated and unmanipulated plots.

	Overstory (>8 inch/20 cm d.b.h)		**Pole (<8 inch/20 cm d.b.h.)**	
	Unmanipulated	**Masticated**	**Unmanipulated**	**Masticated**
	percent mortality[a]			
Knobcone Pine (*Pinus attenuata*)	0	16	15	66
Black Oak (*Quercus kelloggii*)	0	23	17	47
Canyon Live Oak (*Quercus chrysolepis*)	0	49	21	98
Shrubs	**Unmanipulated**		**Masticated**	
	30		96	

[a]Mortality figures for resprouting oak species refers to top-killed individuals.

for reduction of understory vegetation. The following list highlights some of the management implications derived from this research:

1) Mastication of vegetation results in a short to medium-term increase in fire intensity and severity potential. Where utilized, mastication prescriptions should consider the need for greater canopy retention to increase shading at the soil surface, thus increasing fine dead fuel moisture and contributing to slower seasonal drying of fuels. In addition, lowering intensity of mastication will directly reduce total surface fuel load.

2) Mortality of remaining overstory vegetation may be high in areas where masticated treatments are followed by prescribed burning. Managers may be able to reduce this secondary mortality by:

   - Decreasing the level of mastication intensity. This will contribute to lower fire behavior indices and severity results by reducing surface fuel loading, increasing shading of fuels, decreasing wind circulation and thus, drying of surface fuels.
   - Applying fire during mild conditions. Mastication treatments significantly alter the fuelbed and result in significantly different fire behavior than in unmanipulated vegetation. Prescriptions must consider these differences in expected behavior and subsequent severity.
   - Avoiding spring or early growing-season burns when desirable species are in a susceptible period of development. The post green-up application of fire in this study coincided with a vulnerable phenologic period in plant development, when leaf, bud, and cambium tissues were particularly susceptible to thermal effects. Prescription windows that are scheduled during the dormant season would likely minimize severity effects to retained vegetation.

3) Short-term increases in fire intensity occur following mastication; however, long-term trends are still unknown. This study was conducted six months after mastication when the masticated fuelbed was still loosely arranged on the surface. Through time, it is expected that decomposition and compaction of the masticated fuels would occur, lowering the potential fire intensity, but the rate of change is not known. Research on assessing changes in masticated vegetation over time would provide valuable information for long-term management.

Acknowledgments

The authors would like to thank Whiskeytown NRA Fire and Resource Management personnel for assistance in all aspects of this project. In particular, we want to thank Jake Blaufuss for setting up the initial treatment polygons, and Justin Cully, Johanna D'Arcy, Ed Waldron, James Savage, Chris Sprague, Brian Rasmussen and Joe Svinarich for fire behavior data collection assistance. We also want to thank North Tree Fire International for assistance with the mastication treatment, and the California Conservation Corps, California Department of Forestry and Fire Protection, and USFS, Redding Hotshots and Redding Smokejumpers for assistance with the burn treatments. This project was made possible by funds provided by the Joint Fire Science Program.

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Assessing Mitigation of Wildfire Severity by Fuel Treatments — An Example From the Coastal Plain of Mississippi

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***Abstract**—Fuel treatments such as prescribed fire are a controversial tenet of wildfire management. Despite a well-established theoretical basis for their use, scant empirical evidence currently exists on fuel treatment effectiveness for mitigating the behavior and effects of extreme wildfire events. We report the results of a fire severity evaluation of an escaped prescribed fire that burned into an area previously treated with repeated prescribed fires. We observed significantly lower scorch heights, crown damage, and ground char in the treated area. We attribute the moderated fire severity in the treated area to a significantly altered fuel profile created by the repeated prescribed fires. Though our results represent just one treatment area in a single wildfire, they add to a depauperate database and bring us a step closer to defining the conditions under which fuel treatments are an effective pre-suppression strategy.*

Introduction

Fuel treatment effectiveness as a pre-suppression strategy is a controversial tenet of wildfire management with a strong theoretical foundation, but scant empirical evaluation. Several recent reviews provide a survey of the extant literature on the scientific justification for fuel treatment programs (Graham and others 2004; Carey and Schumann 2003; Fernandes and Botelho 2003). A perusal of the publications cited in these reviews and those published subsequently (prior to March 2006) reveals that much of the evidence of fuel treatment effectiveness comes from the results of simulations based on models of fire spread (Rothermel 1972) and crown fire potential (Rothermel, 1991). More than half (26 of 49) of the analytical studies conducted in North America rely on simulations and, of these, half (13) employ hypothetical treatments as well as hypothetical wildfires. Many questions related to fuel treatments can only be addressed in a modeling environment, such as optimal landscape placement (Finney 2001) or potential effectiveness under varying climate regimes. However, the ability of current fire behavior models to reflect reality has received little validation, particularly under the extreme conditions that produce large wildfire events (Cruz and others 2005). Thus, the results of modeling experiments are best viewed as hypotheses awaiting an empirical test.

Nonetheless, simulation experiments have been necessary to establish a scientific basis for the effectiveness of fuel treatments, given the obvious limitations on experimentation with actual wildfires. Just one study exists that tested the effectiveness of a fuel treatment under experimental conditions extreme enough to produce crown fire activity (Alexander and Lanoville 2004). This study was conducted in the boreal forest of the Canadian Northwest Territories and the authors conclude that thinning without treatment

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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of surface fuels is largely ineffective, though the sample size was very limited and no statistical analysis has been reported.

The remainder of the evidence of fuel treatment effectiveness in North American ecosystems relies on natural experiments in which an actual wildfire serendipitously encountered one or more fuel treatment areas. Though there have been recent efforts to collect fire behavior data *in situ* as wildfires encounter fuel treatments (Fites-Kauffman 2001), all 22 of the natural experiments published to date have relied on *post facto* analysis. However, just 11 of these studies included a statistical analysis of the treatment effect and only seven attempted to control for the influences of topography and weather, which along with fuels are the determinants of fire behavior. Rather incredibly, only four studies have been published that included both a statistical test and adequate control to discern a fuel treatment effect in an actual wildfire.

Pollet and Omi (2002) evaluated the severity of four wildfires that burned over treated areas in ponderosa pine forests in Oregon, Washington, California, and Arizona. One of the fires encountered a prescribed burn, while the other three encountered thinning treatments where the activity fuels were effectively removed, either by burning or whole-tree removal. The treatments were completed 1 to 11 years prior to wildfire and in all cases fire severity was found to be significantly lower in treated stands.

Raymond and Peterson (2005) evaluated the severity of a wildfire in mixed conifer forest of coastal Oregon that burned over four thinning treatments, one of which included subsequent underburning. All thinning was completed 6 years prior to the wildfire and the underburn was done 5 years later. Fire severity was found to be significantly greater in two of the three thinned areas that were not underburned, while the third showed no effect. However, the wildfire burned around the underburned treatment without entering.

Cram and others (2006) evaluated the severity of three wildfires that burned over treatments in ponderosa pine forests in Arizona and New Mexico. All of the wildfires included areas that were thinned followed by prescribed burns and one of them also included areas where the slash was scattered but left on-site. All treatments reduced wildfire severity, but the treatments that were not prescribe-burned were less effective.

Skinner and others (*in press*) evaluated the severity of a wildfire in ponderosa pine dominated forest in northern California that burned over five thinning treatments, all but one of which were subsequently treated with prescribed fire. Fire severity was found to be significantly lower in the thinned units where the slash was treated, but no effect was observed in the thin-only treatment.

This paper describes how the fuel treatment assessment methods followed by Pollet and Omi (2002) were applied again to provide much needed additional empirical information from a wildfire that burned into an area that had been previously treated with repeated prescribed burns in coastal Mississippi. We follow with a discussion of how our methods have since evolved to overcome certain limitations presented by this site.

Methods

Study Area

The study site is located on and adjacent to the Fontainebleau Unit of the Mississippi Sandhill Crane National Wildlife Refuge. The Refuge is approximately 8 km east of Ocean Springs in Jackson County, Mississippi in the Gulf Coastal Plain physiographic province. Topography is flat throughout at an elevation of 6m. Slash pine (*Pinus elliottii* Englem.) is dominant in the forest canopy with longleaf pine (*Pinus palustris* Mill.) also present. Sub-canopy species include persimmon (*Diospyros virginiana* L.) and black gum (*Nyssa sylvatica* Marsh). Vines (e.g., *Vitis* spp. and *Smilax* spp.), bays (*Persea* spp.), and gallberry (*Ilex coriacea* (Pursh) Chapm.) are abundant in the understory.

The US Fish and Wildlife Service established the Refuge in 1975 to protect the endangered Mississippi Sandhill Crane (*Grus canadensis pulla* Aldrich) and its wet pine savannah habitat. Management of the Refuge includes extensive use of prescribed fire to reduce hazardous fuels and restore the open structure of longleaf pine savannahs (Platt and others 1988). One such prescribed fire became the Fontainebleau wildfire at 1430 hours on April 18, 1999 when it spotted across a railroad and onto private property containing untreated fuels best characterized by Fuel Model 7 (Anderson 1982). The wildfire exhibited extreme behavior and at 1600 hours spotted back across the railroad and into a stand that Refuge managers had burned in 1988, 1992, and 1998 with the objective of converting fuels to approximate Model 2 conditions. The Fontainebleau fire grew to a final size of 142 ha including 36.5 ha on Refuge lands last treated in 1998. Hourly weather conditions from an on-site Remote Automated Weather Station are provided in Table 1.

Data Collection

We collected data in September 1999 to quantify fuels and fire severity differences between treated and untreated stands affected by the Fontainebleau Fire. Data were collected in nine variable radius plots in each of the two stand types (treated and untreated). Plot areas were defined with a Cruiser's Crutch with a metric basal area factor of 2 (Avery and Burkhart 1994). We employed a systematic sampling design in which plot centers were separated by 60 m along three transects also separated by 60 m. A 60 m buffer on either side of the railroad that separates the treated and untreated areas minimized edge effects. Figure 1 depicts a map of the fire perimeter, treatment area, and plot locations.

The trees sampled at each plot were distinguished by species and crown position and measured for the following aerial fuel descriptors: stand density, tree size and height, and height to the base of the pre-fire live crown. The

Table 1—Weather conditions during the Fontainebleau Fire on April 18, 1999 (weather data from an onsite Remote Automated Weather Station).

Time	Wind speed	Wind Direction	Temperature	Relative Humidity	Dead Fuel Moisture Content 1hr [a]	10hr [b]	100hr [c]
hr	*km per hr*	*Azimuth*	*°C*	- - - - - - *percent* - - - - - -			
1400	10.9	315	21.0	27	5.5	6.7	15
1500	9.0	270	22.3	28	5.5	6.7	15
1600	12.1	315	21.3	28	5.6	6.6	15
1700	9.7	315	21.3	29	5.9	5.8	15

[a] Dead fuel moisture content is expressed by standard equilibrium time lag classes: 1hr refers to fuels less than 0.25 inch diameter
[b] 10hr fuels are less than 1 inch in diameter
[c] 100hr fuels are less than 3 inches in diameter

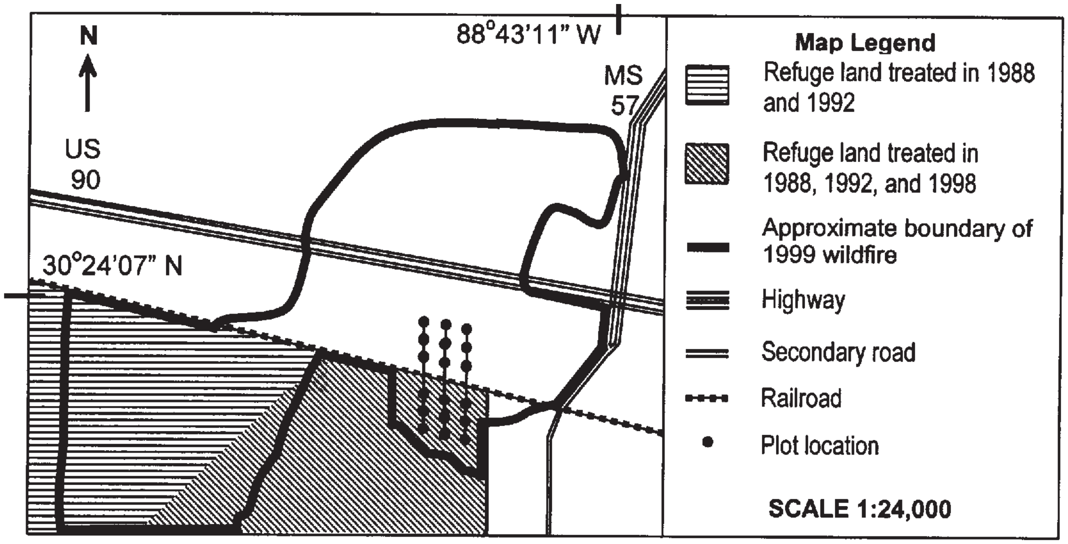

Figure 1—Plot locations in relation to fuel treatments involved in the 1999 Fontainebleau wildfire on and adjacent to the Mississippi Sandhill Crane National Wildlife Refuge. The fire started as a prescribed burn on the Refuge (in the area shaded with horizontal lines), but was declared a wildfire when it spotted across the railroad and onto private property. The wildfire later spotted back across the railroad and into an area the Refuge had previously treated.

base of the pre-fire live crown was judged to be the lowest branch with twigs, though this may have been an overestimate in severely burned plots if lower live branches or twigs were completely consumed; or an underestimate if lower branches with twigs were needleless prior to the fire. We also attempted to quantify the pre-fire density and height of shrub fuels (an important component of Fuel Model 7) by sampling four 1 m^2 circular plots located at 90 degree angles and 17.85 m from each plot center. No attempt was made to quantify pre-fire conditions of other surface fuel components post hoc, since the fine fuels that contribute most to surface fire spread are consumed in most fires (Ottmar and others 1993).

Following the methods used by Pollet and Omi (2002), we evaluated wildfire severity at each plot in terms of stand damage, as well as upward and downward heat pulse components. Stand damage ratings were adapted from Omi and Kalabokidis (1991) while the downward heat pulse was estimated with ground char ratings adapted from Ryan and Noste (1985). Rating criteria are provided in table 2. Stand damage was evaluated for the plot as a whole, while the downward heat pulse was estimated with ground char ratings in four 30 m x 60 m subplots at the same locations as the shrub subplots described above.

Table 2—Criteria used to evaluate fire severity in sampled stands.

Rating	Stand Damage Criteria	Ground Char Criteria
0	All tree crowns unscorched.	No evidence of surface fire.
1	Partial scorch on at least 1 tree, but some trees unscorched.	Litter and twigs charred.
2	Partial scorch on all tree crowns, but few trees completely scorched.	All twigs, leaves, and standing grasses consumed, branches and logs charred.
3	Nearly all tree crowns completely scorched, but few crowns consumed.	Branches and logs mostly consumed.
4	Nearly all tree crowns consumed.	

The height of needle scorch on the coniferous trees sampled at each plot was measured as an indicator of fireline intensity (Van Wagner 1973). Percent canopy scorch was ocularly estimated on all trees, as well. Since height of needle scorch underestimates fireline intensity on trees that are either unscorched or completely scorched (the upper bound of scorch height is limited by tree height, while the lower bound is limited by crown base height), we modified calculations for average scorch height at each plot by excluding measurements from trees that were uninformative or misleading. Specifically, only the following measurements contributed to plot averages for scorch height:

1) Scorch heights of all partially scorched trees.
2) Tree heights of completely scorched trees added sequentially by decreasing height until average scorch height was maximized.
3) Bole char heights of unscorched trees added sequentially by decreasing height until average scorch height was maximized.
4) Crown base heights of unscorched trees added sequentially by increasing height until average scorch height was minimized.

Data Analysis

Standard statistical software (SAS Institute 2001) was used to conduct two-sample one-tail parametric tests for comparisons of continuous variables between treated (n = 9) and untreated (n = 9) sample plots. Specifically, we tested the following null hypotheses:

H_{o1}: Vertical and horizontal fuel profiles do not differ between the area treated with prescribed fires and the untreated area.
- H_{o1a}: Trees are not larger (in diameter and height) in the treated area.
- H_{o1a}: Crown bases are not higher in the treated area.
- H_{o1a}: Shrubs are not shorter in the treated area.
- H_{o1b}: Densities of trees and shrubs are not greater in the untreated area.

H_{o2}: Wildfire severity does not differ between the area treated with prescribed fires and the untreated area.
- H_{o2a}: Scorch height is not greater in the untreated area.
- H_{o2b}: Crown volume scorch on overstory trees is not greater in the untreated area.
- H_{o2c}: Stand damage is not greater in the untreated area.
- H_{o2c}: Ground char depth is not greater in the untreated area.

Non-parametric Wilcoxon tests were used for ordinal categorical data (that is the fire severity ratings). Significance levels for all tests were adjusted by partial Bonferonni correction to account for multiple comparisons (the Bonferonni adjustment was increasingly liberalized as the correlations among the set of compared variables increased (see *ad hoc* adjustments to the Bonferonni procedure in Sankoh and others (1997) or Uitenbroek (2001)).

Results

The forest treated with repeated prescribed fires on the Mississippi Sandhill Crane National Wildlife Refuge was found to have significantly different fuel profiles than the adjacent unmanaged private forest (table 3). The untreated plots had nearly seven times as many trees as the treated plots and these

Table 3—Comparison of stand conditions and fire severity indicators between treated and untreated stands within the Fountainebleau fire (means with standard deviations in parentheses).

Variable	Treated (n = 9)	Untreated (n = 9)
Tree diameter (cm)	20.9[e]	10.7
	(3.4)	(4.7)
Tree height (m)	16.5[c]	10.6
	(2.5)	(4.2)
Height to crown (m)	11.1[c]	7.3
	(2.2)	(2.7)
Tree density (# per ha)	373[b]	2,496
	(224)	(2,092)
Tree basal area (m^2 per ha)	14.2	19.1
	(7.8)	(10.8)
Shrub height (cm)	61.2[c]	164.3
	17.2	(77.9)
Shrub density (# per m^2)	15.9	13.7
	(5.8)	(3.7)
Scorch height (m)	10.0[b]	15.4
	(2.9)	(5.0)
Crown volume scorch (percent)	14[e]	99
	(22)	(1)
Stand damage rating	0.8[e]	3.1
	(0.7)	(0.8)
Ground char rating	1.0[b]	1.2
	(0.0)	(0.2)

Treatment means followed by a superscript indicate a significant difference from the untreated mean in the hypothesized direction as follows:
[a] $p<0.1$.
[b] $p<0.05$.
[c] $p<0.01$.
[d] $p<0.001$.
[e] $p<0.0001$.

were substantially smaller in diameter and height. Trees in the treated plots had twice the girth and were 50 percent taller than those in the untreated plots. Live crown bases were nearly twice as high off the ground in treated plots compared to untreated plots where shrubs were more than twice as tall. However, no significant difference was found in shrub density between the two sampled areas.

The two areas with distinctly different fuel profiles were observed to have experienced distinctly different wildfire severity (fig. 2, table 3). Average height of needle scorch was nearly twice as high in the untreated plots. With very few exceptions crown volume scorch in the untreated plots was 100 percent and significantly greater than in the treated plots. Ground char was light in all the treated plots, but somewhat deeper in the untreated plots.

(a)

(b)

Figure 2—Adjacent treated (a) and untreated (b) stands burned by the Fontainebleau fire.

Discussion

The differences we observed between the treated and untreated areas burned over by the Fontainebleau fire were dramatic. Still, our highly significant results may be conservative, since the 1998 prescribed fire that served as our treatment was reportedly more intense than the subsequent wildfire when it burned in the treatment area. Thus, the scorch heights and crown damage that we observed in the treated area probably resulted from the treatment itself, masking the less severe effects that resulted from the wildfire.

Vertical and horizontal fuel continuity was clearly greater in the private unmanaged forest, as evidenced by taller shrubs, lower tree crowns, and higher tree density. We attribute the lower severity observed on the Refuge primarily to a less hazardous fuel profile that resulted from distinct land management practices, most notably the repeated application of prescribed fire.

However, several caveats associated with this study bear mention. Unlike completely randomized pre-planned experiments, retrospective studies such as this one are inherently prone to selection bias both in the choice of study sites and the location of sample plots. Further, the availability of treatment replicates that might be considered independent samples is beyond the control of the investigators.

When the Fontainebleau fire was selected for investigation, our approach to identifying potential study sites relied on advertising our interest and criteria on relevant electronic list serves and at professional meetings attended by land managers. It soon occurred to us, however, that we might only be contacted in the case of an obviously effective treatment. We have since taken a more rigorous approach to defining the universe of possible study sites in any given year and now contact land managers directly wherever a wildfire exceeds 4,000 ha (10,000 acres).

Wildfires smaller than 4,000 ha are unlikely to encounter a single fuel treatment area, much less multiple treatments. Prior to the recent expansion of fuel treatment initiatives it was rare even for large wildfires to encounter more than one treatment. Unfortunately, any analysis of the effect of a single treatment must be based on pseudo-replicated samples (Hurlbert 1984), resulting in underestimated variance and compromised statistical tests. Such was the case with Fontainebleau, as well as all of Pollet and Omi's (2002) study sites. Few fuel treatment studies have been published based on samples from (approximately) replicated treatments and all but Cram and others (2006) relied on an analysis of remote sensing data that failed to control for the effects of weather and topography (for example, Weatherspoon and Skinner 1995; Martinson and others 2003, Finney and others 2005). However, since sampling Fontainebleau we have been able to restrict our investigations to wildfires that burned over at least three spatially dispersed areas that were similarly treated. We have now completed data collection from eight such study areas.

Once a wildfire is selected for investigation, we follow the procedures established by Pollet and Omi (2002) to minimize potential bias in locating sample plots. Plot locations are selected prior to any field visits and based solely on maps of treatment boundaries, roads, streams, vegetation, topography, and wildfire progression. Comparison plots are situated such that they straddle a treatment boundary, burned on the same day and under similar weather conditions, and have similar slope, aspect, elevation and tree species. We further seek to avoid areas that were a focus of fire control activities, as well as treatment boundaries defined by a significant fuel break, such as a major road or stream. The straddle point along each treatment boundary is then chosen by random number generation, if any choice remains after all criteria are satisfied. The Fontainebleau site met all these criteria with the notable exception of a railroad separating the treated and untreated areas. While this was a substantial fuel break, it failed to stop fire spread; not once but twice. Further, the fire was not even curtailed by a much wider divided highway that included a mown median. We therefore concluded that any reduction in fire severity accomplished by the prescribed burns was undiminished by the presence of the railroad.

A final caveat for the Fontainebleau site is the unknown management history of the privately owned stand that served as our untreated control. While no activity has occurred in this stand since establishment of the Wildlife Refuge in 1975, its condition differed from the treated stand to such a degree that we find it difficult to believe three prescribed fires alone accomplished the difference. Rather, the untreated stand had probably been clearcut sometime in the past with no subsequent management (personal communication from Tony Wilder, Refuge Fire Management Officer). Nonetheless, the Fontainebleau site illustrates the differential consequences of fuels management and lack thereof when a wildfire occurs.

Conclusion

Like all studies of fuel treatment effectiveness, the data from the Fontainebleau fire are limited in many respects. Nonetheless, the results of this study provide a rare addition to a depauperate literature. Fuel treatment activities are expanding rapidly on public lands despite minimal empirical evidence to support their use. At least one beneficial consequence of this should be an increase in the number of wildfires that burn over multiple treatments, providing greater opportunity to achieve a semblance of replication and control in future retrospective studies of fuel treatment effectiveness. Thus fuel treatment activities are perhaps best viewed as experiments that provide potential learning opportunities. Knowledge must be gleaned from both the successes and the failures so that we might eventually define the conditions under which fuel treatments are an effective pre-suppression strategy for the mitigation of extreme wildfire behavior and effects. Every effort to collect empirical information from natural experiments such as that presented by the Fontainebleau fire brings us a step closer to this end.

Acknowledgments

We thank Malia Boyum for field assistance and Tony Wilder for facilitating our field visit and providing fire weather and behavior information. The Joint Fire Science Program funded this research.

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A Fuel Treatment Reduces Potential Fire Severity and Increases Suppression Efficiency in a Sierran Mixed Conifer Forest

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Abstract*—Fuel treatments are being widely implemented on public and private lands across the western U.S. While scientists and managers have an understanding of how fuel treatments can modify potential fire behavior under modeled conditions, there is limited information on how treatments perform under real wildfire conditions in Sierran mixed conifer forests. The Bell Fire started on 9/22/2005 on the Plumas National Forest, CA. This fire burned upslope into a 1-year old, 390-acre mechanical fuel treatment on private land. Prior to impacting the fuel treatment, the main fire ignited spot fires 400 feet into the treated area. Within the treated area, loadings of 1, 10, and 100-hour fuels averaged 5.2 tons per acre. Stand density averaged 73 trees per acre, with a live crown base of 30 feet, and 36% canopy cover. This fuel treatment resulted in: 1) increased penetration of retardant to surface fuels, 2) improved visual contact between fire crews and the IC, 3) safe access to the main fire, and 4) quick suppression of spot fires. This treatment was relatively small and isolated from other fuel treatments but resulted decreased severity, suppression costs, and post fire rehabilitation needs leading to cost savings for local public and private land managers.*

Introduction

Fuel treatments are being widely implemented on public and private lands across the western United States (Stephens 2005). Over 11 million acres of hazardous fuel reduction and landscape restoration activities have been implemented since federal fiscal year 2000 (Healthy Forests Report 2005). The stated goals of these treatments are to: "1) Directly reduce wildfire threats to homes and communities that are adjacent to or within the wildland urban interface (WUI), 2) Treat areas outside of the wildland-urban interface (non-WUI) that are at greatest risk of catastrophic wildland fire. These high priority non-WUI treatments move towards restoring fire to its historical role and 3) Maintain previous treatments to ensure resiliency to catastrophic wildland fire and implement activities that are in line with other long-term management goals" (Healthy Forests Report 2005).

While scientists and managers have an understanding of how fuel treatments can modify potential fire behavior under modeled conditions (Stephens and Moghaddas 2005), there is limited information on how treatments perform under real wildfire conditions in Sierran mixed conifer forests (Fites and Henson 2004). Public land managers are often tasked with designing projects to meet "desired future conditions" for fuel treatments, though there is limited information on what these conditions should be across a broad range of site classes and forest types. While several fires have been documented by fire managers burning or spotting into recently established fuel treatments

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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(Beckman 2001; Hood 1999), relatively few of these events are formally studied to determine the effects of the fuel treatment on fire behavior and severity in Sierran mixed conifer forests.

The purpose of this paper is to document one example of how a fuel treatment influenced fire behavior and enhanced suppression efficiency in a mixed conifer stand within the wildland urban interface. Secondly, this paper quantifies a stand structure which was functioned as an effective fuel treatment under the weather conditions described.

Methods

Study Site

The study area is on the Beckworth Ranger District of the Plumas National Forest, approximately 1 mile south of Highway 89 at Lee Summit. The treatment described was established on private timberlands owned by the Soper-Wheeler Company. The treatment unit is located within the 1.5 mile extended wildland urban interface of Spring Garden, a Community at Risk (Callenberger and Lunder 2006; PCFSC 2005). The parcel is bordered on two sides by untreated National Forest Land (Figure 1, Figure 2). The fuel treatment was established on the north side of a ridge, immediately above the Middle Fork of the Feather River Drainage. The dominant aspect of the treated area is north facing with an average slope of 11 percent. The area within the treatment is classified as a site class II (Dunning 1942). Data available from the timber harvest plan and associated inventory plots were used to establish pre-treatment stand conditions. Post treatment, three $1/10^{th}$ acre fixed radius plot were established along a transect which ran through the area impacted by spot fires. These plots were measured within 2 months of the fire.

Treatment Prescription

The forest type is Sierran Mixed Conifer forest dominated by Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense cedar (*Calocedrus decurrens* [Torr.] Floren.), ponderosa pine (*Pinus ponderosa* Dough. Ex. Laws), sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Gord. & Glend.), and California black oak (*Quercus kelloggii* Newb.) (table 3). Prior to treatment, stand basal area was 258 ft^2 per acre and tree density was 478 trees per acre. Stands were thinned in the summer of 2005 under a selection harvest (CDF 2003) using a leave tree mark. Biomass and sawlog material was removed mechanically using a whole tree harvest system. Sub-merchantable material and tops were chipped at the landing and hauled to a local mill. An average of 2,460 board feet and 8.6 bone dry tons of biomass per acre were removed from the project area (Violett 2005).

General Fire Information

The Bell fire was reported at 12:13 on September 22nd 2005 (Table 1). The fire was accidentally ignited by railroad activity along the tracks immediately downhill and below the project area (Figure 1). Relative humilities and peak wind speeds averaged 18 percent and 10 miles per hour, respectively, during the burning period between 12:00 to 16:00 (Table 2).

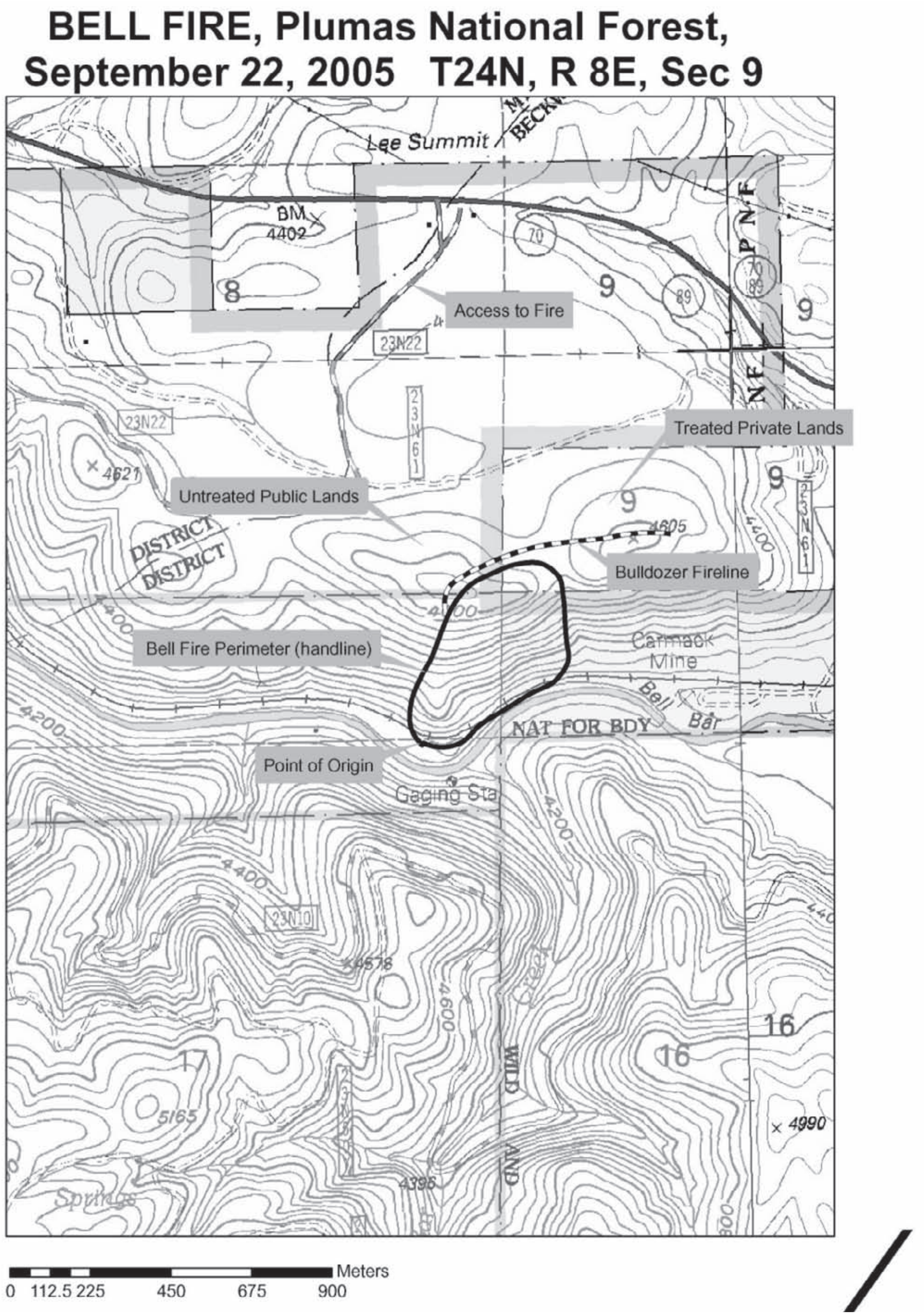

Figure 1—Location of treated area and fire perimeter

Figure 2—Treated stands (foreground) and untreated stands on public land (background). Property line follows edge of thinned area

Table 1—General fire information

Fire Name	Bell Fire
Location	Plumas National Forest, Beckworth Ranger District: T 24N, R 8E, Section 9
Elevation	4,125 ft to 4,605 ft
Burning Index on day of fire	61
Energy Release Component on day of fire	57
Report Date and Time	09/22/2005 at 12:13
Contain Date and Time	09/22/2005 at 19:00
Control Date	09/24/2005 at 18:00
Cause	Ignition from railroad activity
Final Size	35 acres

Table 2—Weather parameters during active burn period on 09/22/2005. Weather taken from Quincy remote access weather station (#40910).

Time	Relative Humidity	Dry Bulb Temperature	10-hour Fuel Moisture	Fuel Temperature	Peak Windspeed	Wind Direction
	Percent	*°F*	*Percent*	*°F*	*mi/hr*	*degrees*
12:00	25	74	8.9	74	6	260
13:00	18	85	8.7	103	6	144
14:00	15	86	8.0	101	14	224
15:00	14	85	7.5	98	13	243
16:00	17	82	7.2	93	17	267
17:00	21	79	7.1	81	12	256
18:00	23	75	7.0	78	11	256
19:00	31	67	7.0	63	7	259

Results

Post Treatment Stand Structure

Mechanical treatments resulted in a relatively open stand with vertical and horizontal separation of ladder and crown fuels (Figure 2). Treatments reduced the percent species composition of white fir (Table 3). Treatments raised the average height to crown base and reduced canopy cover, basal area, and overall stand density (Table 4). Though surface fuels were not treated, residual 1, 10 , and 100 hour fuels combined averaged 5.3 tons per acre (Table 5). Fuel depth average 1.4 inches (Table 5). There was no evidence of brush on the plots at the time of measurement.

Predicted and Actual Fire Behavior

The fire moved quickly up a steep hill from the point of origin to the ridgeline which was also the boundary of the fuel treatment. At the ridgeline, flame lengths from torching trees were observed as high as 30 feet above the tree canopy. Trees on the slope between the ridgeline and the point of origin generally had over 75% scorch. This level of scorch was observed on trees over 20 inches in diameter. From the point the fire impacted the fuel

Table 3—Percent species composition of conifers and hardwoods before and after treatment[a].

Species	Pretreatment	Post Treatment
	- - - - - - - - - *Percent*	- - - - - - - - -
Douglas-fir	21	41
Incense cedar	18	21
Ponderosa pine	19	20
Sugar pine	10	12
White fir	29	6
Black oak	2	na

[a]Note: pre and post treatment data collected within the same stand but from different plots

Table 4—Post treatment vegetation structure

	Live Trees	Basal area per acre	Height to live crown base	Tree Height	Canopy Cover	Quadratic Mean Diameter	Stand Density Index
	Trees per acre	*Ft²/acre*	*- - - - - - -Feet*	*- - - - - - -*	*Percent*	*Inches*	
Post Treatment Average	73.3	103.3	30.1	72.5	36.3	15.6	130.3
Post Treatment Range	40 to 130	73.2 to 154.3	24.9 to 40.2	59.0 to 84.0	25 to 48	11.9 to 18.3	105.5 to 171.1

Table 5—Post treatment fuel characteristics

	Litter & Duff	All 1, 10, and 100 hour fuels	1,000 hour sound	1,000 hour rotten	Fuel Depth	Cover of Brush
	- - - - - - - - - - - - - - -	*Tons per acre*	*- - - - - - - -*	*- - - - - - -*	*Inches*	*Percent*
Average	73	5.3	1.9	0.6	1.4	0
Range	19.5 to 110.5	1.3 to 8.3	0.9 to 2.8	0.0 to 0.9	0.5 to 2	0

treatment and approximately 200 feet into the fuel treatment, the level of scorch decreased. Similar patterns of scorch were observed in the Cone Fire at Blacks Mountain Experimental Forest (Skinner and others in press).

Up to four spot fires were ignited within the fuel treatment area. These fires ignited directly in activity fuels left after the harvest. Predicted flame lengths and mortality for these spot fires are shown in table 6. Observed flame lengths on these spot fires was less than 2 feet and there was little evidence of scorch on trees larger than 10 inches DBH.

The actions taken for suppression of the fire are based on discussions with on-scene personnel (Craggs 2006) and summarized here. Hand crews hiked into the base of the fire along the railroad tracks, anchored their fireline and continued constructing line up the east and west fire flanks. The Incident Commander (IC) and two bulldozer transports could access the main fire from Highway 89, along a dirt road, and directly through the treated area. From this point, the IC could also easily locate established spot fires. Due to relatively low rates of spread and flame lengths, the decision was made to line spot fires using the bulldozer. After lining the spot fires, the bulldozers then cut a line between the approaching fire front, the untreated USFS land, and the treated private property. The dozer line between the main fire and untreated USFS land was completed prior to the main fire reaching the ridge. When the fire reached the main ridge and the fuel treatment, torching stopped though direct scorch still occurred within the first 200 feet of the treatment. Finally a water tender and "pumpkin" were brought forward into the treated area and used in conjunction with engines to extinguish and mop up the spot fires. Mop up continued the next day.

Table 6—Predicted fire behavior and mortality

	Flame Length	Torching Index	Crowning Index	Predicted Mortality Trees 1 to 10 inches	Predicted Mortality Trees 10 to 20 inches	Predicted Mortality Trees 20 to 30 inches
	Feet	*- - - Miles Per Hour- - -*		*- - - - - - - - - - - DBH - - - - - - - - - - - -*		
Predicted	3.2	>40	>40	60	14	5

During the active suppression period, aerial retardant was being delivered to the area between the main fire and both the private treated area and the untreated US Forest Service property. Based on visual observations, substantially more retardant reached surface fuels in the treated area than on the untreated USFS lands. Within untreated areas, retardant was evident on upper foliage of dominant and co-dominant trees where it would not help slow the spread of surface fire.

Discussion

The treatments utilized principles of fuel reduction including thinning from below and use of whole tree harvest (Skinner and Agee 2005). While no further treatment of activity fuels generated by the harvest were completed, residual, post treatment fuel loads and arrangement resulted in observed flame lengths in spot fires was less than 2 feet. These low flame lengths in conjunction with relatively high crown base heights resulted in limited observed scorch in spot fire areas at the time of measurement. Spot fires were easily lined and allowed to burn out while suppression resources were concentrated on the main fire flanks.

In terms of suppression tactics, the treated area established a safe access point which could be use to move equipment and other resources towards the head of the main fire. Had this area not been in place, crews would have likely had to hike in an additional ¼ to ½ mile. This would have resulted in the use of indirect suppression methods, leading to increased suppression intensity than the direct control methods utilized. The relative openness of the stand allowed the Incident Commander (IC) to maintain visual contact with equipment and personnel. In addition, greater penetration and coverage of aerial retardant to surface fuels was observed in the treated areas adjacent to un-treated areas. In untreated areas, retardant primarily ended up in the upper tree crowns were it was less effective at containing and reducing surface fire spread. The overall results of this treatment were decreased suppression intensity and increased suppression effectiveness. This in turn resulted in decreased damage to the stand due to suppression activities and direct scorch. In turn, these factors decreased the relative total cost of suppression and follow up rehabilitation.

Conclusion

It is important to emphasize that fuel treatments are not designed to stop all fires the purpose of this work is not to make this assertion. Fuel treatments are typically designed decrease flame lengths, fire spread, and ideally, reduce landscape level fire severity (Stratton 2004; Finney 2001). Often, they are to be used in conjunction with suppression resources (Agee and others 2000). This is an important point to bring out when communicating the potential effectiveness of fuel treatments with the public. Not all fuel treatments will work all the time in all vegetation types or weather conditions. Breaking up vertical and horizontal continuity of live and dead fuels in this particular case reduced passive crown fire within treated areas. Decreased flame lengths and visual contact in treated areas allowed more direct suppression methods to be employed. It is difficult to say how big the fire would have been without treatments in place or if in indirect methods were used but based on discussions with personnel on-scene, suppression intensity and cost were decreased by these treatments. If the fire had become established in the un-treated areas, suppression intensity, cost, and follow up rehabilitation would have likely been higher.

Fire managers should be able to easily document their direct experiences with fire behavior within established fuel breaks. Fire fighters are often the only ones to witness “real time” fire behavior within fuel treatments- their direct observations and experiences are critical in determining when fuel treatments work and don’t work, and how they can be modified to be more effective in the future. This is imperative considering the limited funds available for establishing fuel treatments in comparison to the number of acres that need treatment. If documented and available for public access, these observations may inform the research community of sites for possible future studies of fire behavior as well as inform and refine current hypothesis used for these studies. This information will help provide the necessary feedback for changing and improving practices through adaptive management.

Acknowledgments

Thanks to Paul Violett and the Soper-Wheeler Company for allowing access to their land and records for this study. Special thanks to Larry Craggs, Fire Management Officer, and Ryan Southwick, Dozer 2 Operator both from the Mount Hough Ranger District on the Plumas National Forest. Their eyewitness experiences on this fire were essential in conveying the story of what happened as seen by the folks who were there as it burned.

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The Use of Silviculture and Prescribed Fire to Manage Stand Structure and Fuel Profiles in a Multi-aged Lodgepole Pine Forest

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Abstract*—This paper presents several components of a multi-disciplinary project designed to evaluate the ecological and biological effects of two innovative silvicultural treatments coupled with prescribed fire in an attempt to both manage fuel profiles and create two-aged stand structures in lodgepole pine. Two shelterwood silvicultural treatments were designed to replicate as well as enhance the existing multi-aged stand structure on the Tenderfoot Creek Experimental Forest in central Montana: the first, with reserve trees evenly distributed; the second, with reserves contained within small (1/10-1/4 acre) groups. Retention of reserve trees was targeted at 50%, without regard to diameter or species. Eight even distribution and eight group-retention treatments were applied on 16 units totaling 649 acres. Half of the units were broadcast burned following harvest using a common burn prescription on all units. Allowable overstory mortality specified in the prescribed fire plan was 50%. Plot-based fuel inventories and fire effects observations were performed at permanent plot locations prior to and following harvest, and after burning. Fuel moisture samples were acquired immediately prior to ignition. Data from four prescribed-burned treatment units were evaluated for this paper: two even-retention units and two grouped retention units. Harvest activities resulted in significant increases in fine-fuel loading (1-, 10-, and 100-hour fuel), which was subsequently reduced by prescribed fire to near pre-harvest levels. Consumption of large woody fuel was similar for both treatment types. The fire-induced mortality of overstory trees was greater in the even distribution than in the grouped distribution. Despite careful execution of a relatively conservative burn plan, mortality in the even treatments exceeded the prescription threshold of 50% by an additional 28%. Additional data collected at the plots include trees per acre, residual tree mortality, residual tree growth, regeneration, windthrow, hydrologic responses, soil impacts, and beetle activity. A comprehensive summary of the treatments will follow subsequent monitoring scheduled to occur five and ten years after burning.*

Introduction

The Tenderfoot Research Project is a multi-disciplinary effort designed to evaluate and quantify the ecological and biological effects of innovative restoration treatments in an attempt to both manage fuelbed profiles and create two-aged stand structures in lodgepole pine. The suite of sixteen fire and silvicultural treatments were implemented on the Tenderfoot Creek Experimental Forest (TCEF) in the Little Belt Mountains of central Montana (fig. 1). Although the USDA Forest Service has established seventy-seven experimental forests and ranges, the TCEF is the only reserve dominated by the lodgepole pine forest type (Adams and others 2004). The research presented here was guided by the Tenderfoot Creek Research Project mission (USDA Forest Service 1997):

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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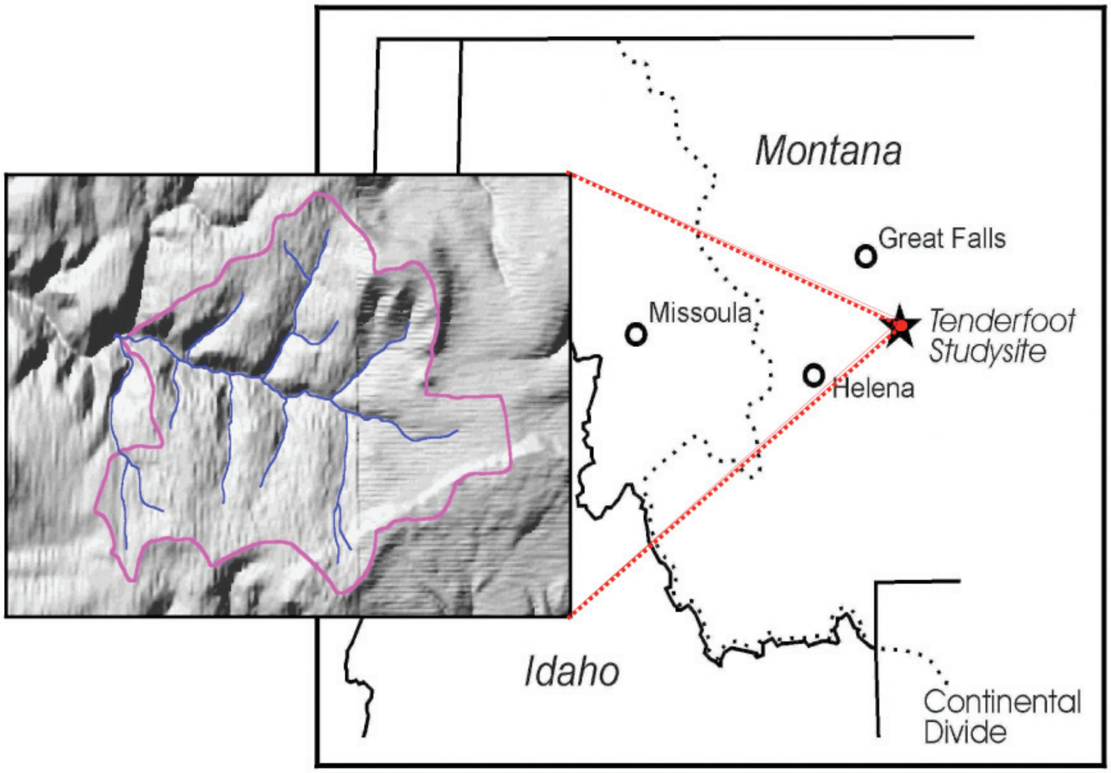

Figure 1—The Tenderfoot Creek Experimental Forest is a 9,125 acre watershed located in Central Montana.

> *"Test an array of management treatments for regenerating and restoring healthy lodgepole pine forests through emulation of natural disturbance processes, but avoiding catastrophic-scale disturbances."*

This paper documents a preliminary exploration of selected results following completion of all phases of treatment activities. It is our intent to follow this paper with a comprehensive compilation of results that synthesize all aspects of the multi-disciplinary efforts.

Background

The subalpine lodgepole pine forest type is estimated to cover about 15 million acres in the western United States and a much larger area (nearly 50 million acres) in western Canada (Lotan and Critchfield 1990). Its latitudinal range extends from Baja (35° latitude) to the Yukon (65° latitude), and longitudinally from the Pacific coast to the Black Hills of South Dakota. In the Rocky Mountains of the Interior West, lodgepole pine is the third most extensive forest type. The adaptations of lodgepole pine to severe, stand replacement fire—in particular its serotinous cones—have long been acknowledged (Lotan and Perry 1983). Less well-known is that lodgepole pine forests also burn in low- to mixed-severity fire, often creating two-aged stands and variable patterns across the landscape (Agee 1993; Arno 1980; Barrett and others 1991). Numerous studies in the interior Northwest have documented the intricate mosaic patterns of historical fires in lodgepole pine forests (Arno and others 1993; Barrett 1993; Barrett and others 1991). Newer studies are looking more closely at the details of these patterns and their implications for management (Hardy and others 2000; Stewart 1996). These studies are being used as a basis for designing and refining silvicultural and prescribed fire treatments in National Forests of the Northern Rocky Mountains.

Historically, clearcutting and broadcast burning of lodgepole pine forests was considered to be economically efficient and conducive to regeneration. These treatments roughly mimic effects of natural, stand-replacement fires. More recently, foresters have recognized that burning irregularly shaped cutting units containing patches of uncut trees, while also creating snags, would far more effectively simulate effects of historical fires. One negative effect from leaving patches or individual uncut trees in lodgepole pine forests is the vulnerability of the species to windthrow. However, recognition of the extent of the mixed-severity fire regime in lodgepole pine, and the recent success and experience gained from other pilot projects have led to continued efforts toward more ecologically-based management of lodgepole pine.

Paired watersheds at TCEF have been monitored for several years and serve as a basis for comparison of water quantity and quality under different cutting and burning treatments. A detailed fire history study and map completed by Barrett (1993) documents a sequence of stand replacement and mixed-severity fires extending back to 1580 (fig. 2A). Stand-replacing burns occurred at intervals of 100 to over 300 years, with low- or mixed-severity burns often occurring within these intervals. Two-aged stands cover about half the area at TCEF, ranging in size from a few acres to about 1,000 acres (fig. 2B). Experimental treatments at TCEF were designed to reflect these historical disturbance patterns. The study design for TCEF integrates observations of on-site treatment response with water yield and water quality data from paired, experimental sub-watersheds that have monitoring flumes.

In this paper we present new research and preliminary results specifically related to fuel management that may lead to more complete knowledge and innovative techniques to manage lodgepole pine forests in the Interior West.

Methods

Timeline for Planning and Execution

The timeline for execution of the study is given in table 1. The Tenderfoot Creek Experimental Forest is administered by the Rocky Mountain Research Station (RMRS) in collaboration with the Lewis and Clark and National Forest. Research is proposed and planned by RMRS and timber sales on the EF are conducted and administered by the National Forest. Implementation of any research on the Experimental forest requires close and continuous cooperation between research and National Forest personnel.

Planning for this extensive study was initiated by Forest Service Research in 1995, and an interdisciplinary planning team was assembled by the Lewis and Clark National Forest to accomplish the Environmental Assessment (EA) process required for the project. The EA was completed in 1998 and a final decision notice was issued in early 1999. Construction of approximately 2 ½ miles of roads was accomplished in 1999, with harvesting completed in 2000. Prescribed burning operations were executed in 2002 and 2003.

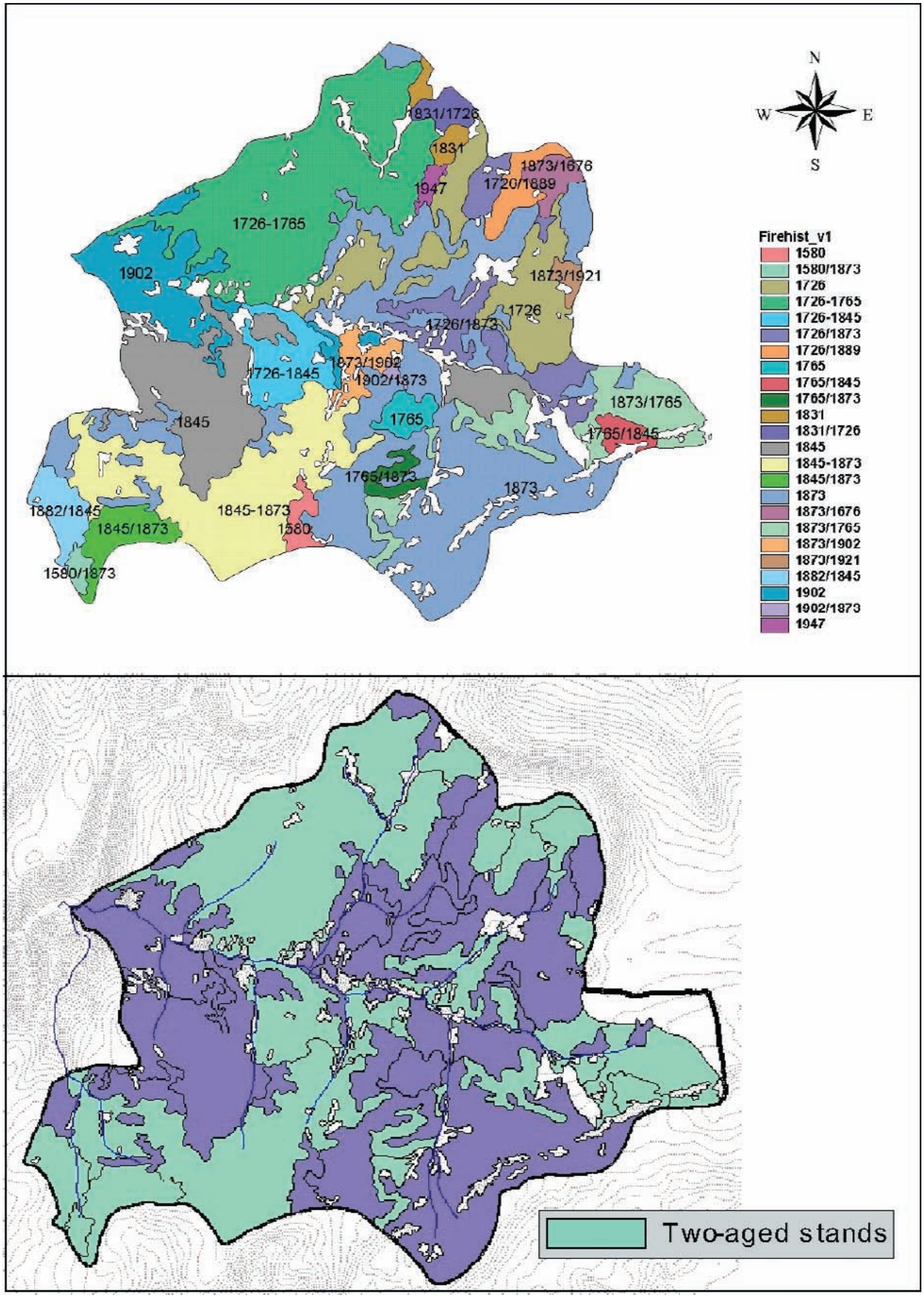

Figure 2—An extensive fire history study done at TCEF in 1986 documented a complex mosaic of fires dating back to 1580 (top), and determined that about half of TCEF is comprised of two-aged stands resulting from low- to mixed-severity fire(s).

Table 1—Timeline of activities, from project proposal to post-burn assessments.

Date(s)	Activity
1995 – 1997	Draft Research Proposal MOU between FS Research and L&C Nat'l Forest
1997 – 1998	Planning with L&C Nat'l Forest Scoping/public comment
Spring 1999	Environmental Assessment
1999 – 2000	Establish treatment units Sale administration Road installation Pre-harvest sampling Harvest activities Prepare burn prescriptions
Autumn 2001	Burn all piles and windrows
Summer 2002	Post-harvest sampling
2002 – 2003	Burn treatments
2003 – 2005	Post-burn sampling and assessments

Treatment Descriptions and Locations

The large-scale set of treatments were implemented on two sub-watersheds within the 9,125-acre Experimental Forest, with two adjacent sub-watersheds left as untreated controls. The two treatment sub-watersheds are Spring Park Creek (north of Tenderfoot Creek) and Sun Creek (south of Tenderfoot Creek) (fig. 3). The silvicultural system used was a two-aged system termed "shelterwood with reserves," with two forms of leave tree retention: one with leave trees evenly distributed, and the other with leave trees retained in unharvested retention groups distributed across the treatment units in a noticeably uneven pattern. The harvest system utilized in all units included felling by excavator-mounted "hot saws" and whole-tree skidding to centralized processing locations where the trees were de-limbed and decked for transport. All unutilized materials were piled and burned on site. About 50 percent of the basal area and stems were removed in both treatment types, with low intensity underburns in one-half of the treatment units. One objective for low intensity underburns was mitigation of surface fire hazard exacerbated by high loadings of harvesting debris (slash). The fuelbed components most relevant to a hazard reduction objective are the fine fuels: 1-hour, 10-hour, and 100-hour timelag fuelbed components. It is these fuel particles that contribute most significantly to surface fire behavior, and a reduction in loading of these fuelbed components was a principle objective in the treatment prescription. The sum of these three fuelbed components is hereafter referred to as "fine-fuel loading."

The treatment labels and descriptions are summarized in table 2, and a satellite (IKONOS®) image of the two Sun Creek treatments is shown in figure 4.

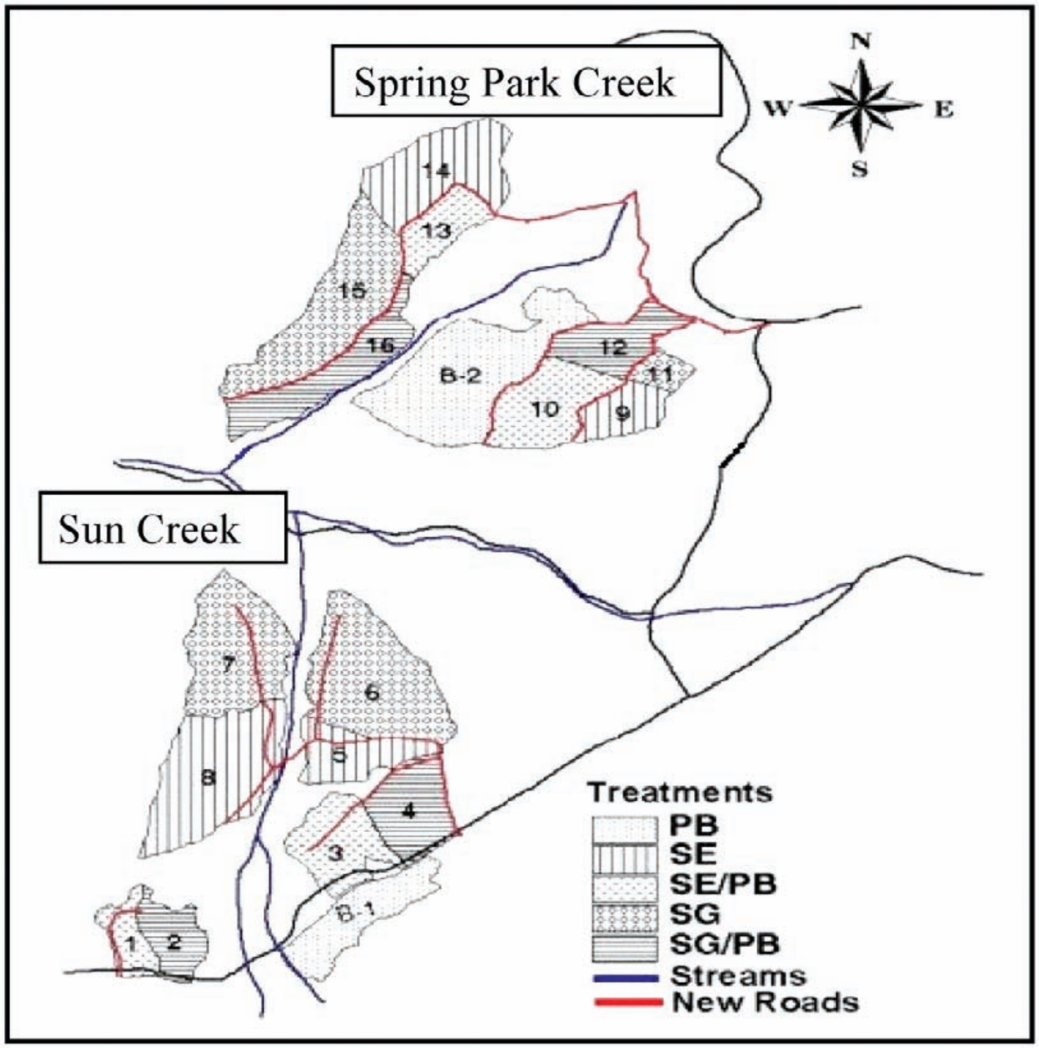

Figure 3—Treatment units were located in two sub-watersheds of Tenderfoot Creek: Spring Park Creek (south aspect, north of Tenderfoot Creek), and Sun Creek (north aspect, south of Tenderfoot Creek).

Table 2—Treatment labels and descriptions.

Treatment label	Distribution of retention trees	Prescribed fire
SE	Evenly distributed	None
SEB	Evenly distributed	Burned (B)
SG	Group-retention	None
SGB	Group-retention	Burned (B)

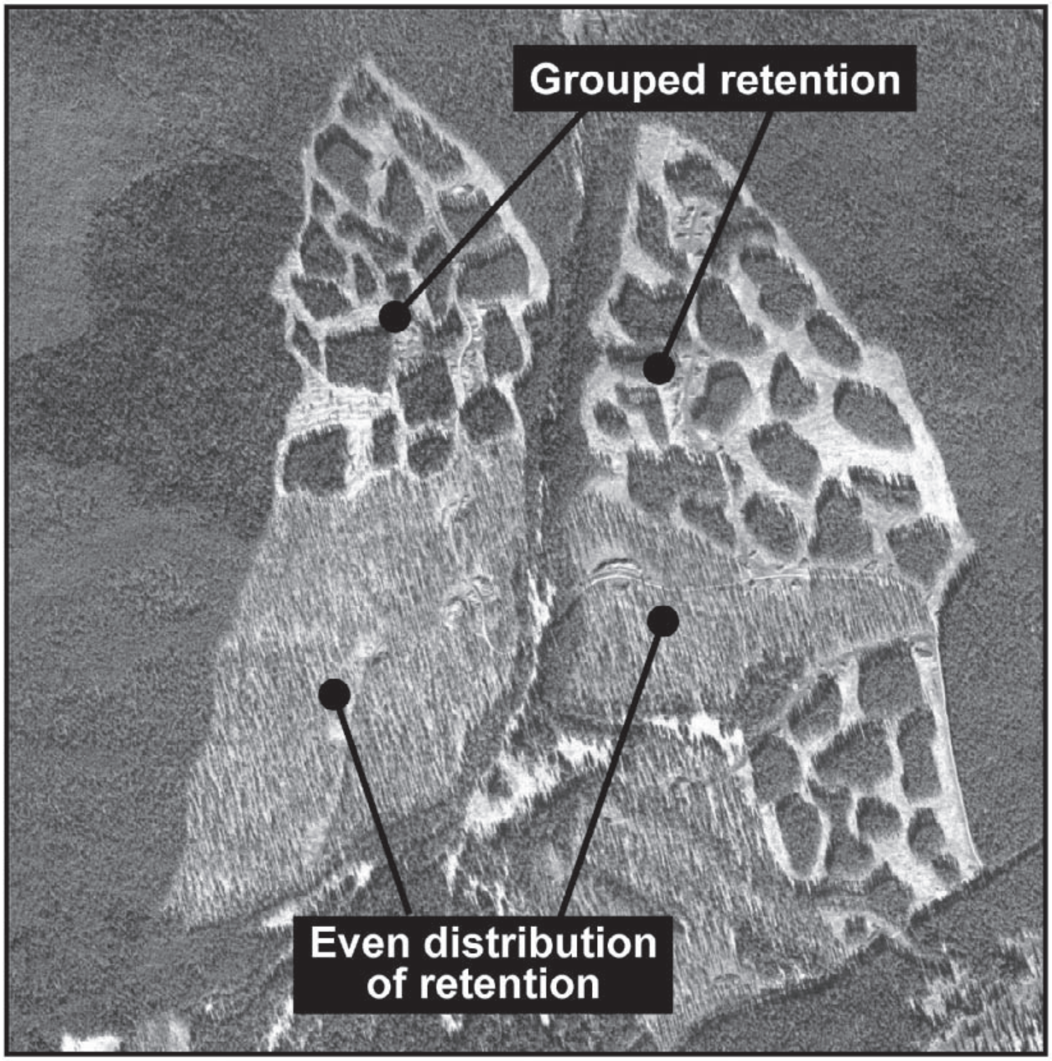

Figure 4—An IKONOS® satellite image showing the two types of "shelterwood with reserves" silvicultural treatments.

Field Sampling

The average size per treatment unit was 43 acres. An average of 32 sampling plots per unit (about one plot per 1.3 acres) were permanently located to facilitate multiple-year sampling at each plot—pre-harvest, post-harvest, and post-burning. In addition to a comprehensive assessment of vegetation and stand characteristics, fuelbed data were collected on one-half of the plots, where two 75' line-intercept fuel transects were installed and permanently located at each plot. Fuel loadings (mass per unit area) of all fuel components along each transect were then estimated per Brown (1974). This allows the generation of summary statistics and analyses that can be calculated at multiple levels—plot, unit, and treatment type (pooled-unit).

The consumption by prescribed burning of large woody fuel was determined by measuring the reduction in diameter of sampled logs using wires installed prior to burning. Following burning, the wires were tightened, and the difference in wire length was used to determine reduction in diameter and associated mass.

Following burning, annual assessments will continue for several years to document windthrow (a problem common to lodgepole pine) and both fire- and insect-caused tree mortality. The burn prescription for both the *Even* and *Grouped* treatment type specified a maximum target overstory tree mortality of fifty percent. Data from three years of post-burn mortality sampling are available for the present analysis.

Analysis

Although the study included treatment units in both Spring Park Creek and Sun Creek sub-watersheds, we did not obtain pre-harvest sample data from the Sun Creek Units. Therefore, fire- and fuels-related data spanning all phases of the study (pre-harvest, post-harvest, and post-burn) are only available for Spring Park Creek.

The fuels analysis in his paper is focused on the four treatment units within Spring Park Creek that included prescribed burning following harvest (SEB and SGB). This selection constraint for the current analysis provides two pairs of treatment units: one pair of *Even* distribution with burning (SEB—units 10 and 13), and one pair of *Grouped* retention with burning (SGB—units 12 and 16). The Spring Park Creek units are illustrated in figure 5.

Prior to pooling the fine-fuel loading data from pairs of units, we evaluated the individual unit statistics to ensure similarity of variances and central tendencies between units within a pooled pair. This analysis was done for each of pre-harvest, post-harvest, and post-burn fine-fuel loading data. The box-and-whisker plots given in figure 6 present median values and interquartile ranges (expressed as tons per acre), and also illustrate the 0.05 *Student's t* statistic. We can conclude from the plots in figure 6 that no significant difference existed in fine-fuel loading between pairs of units in either the *Even* retention pool (fig. 6A) or *Grouped* retention pool (fig. 6B). Therefore, results will be presented with respect to the pooled classes.

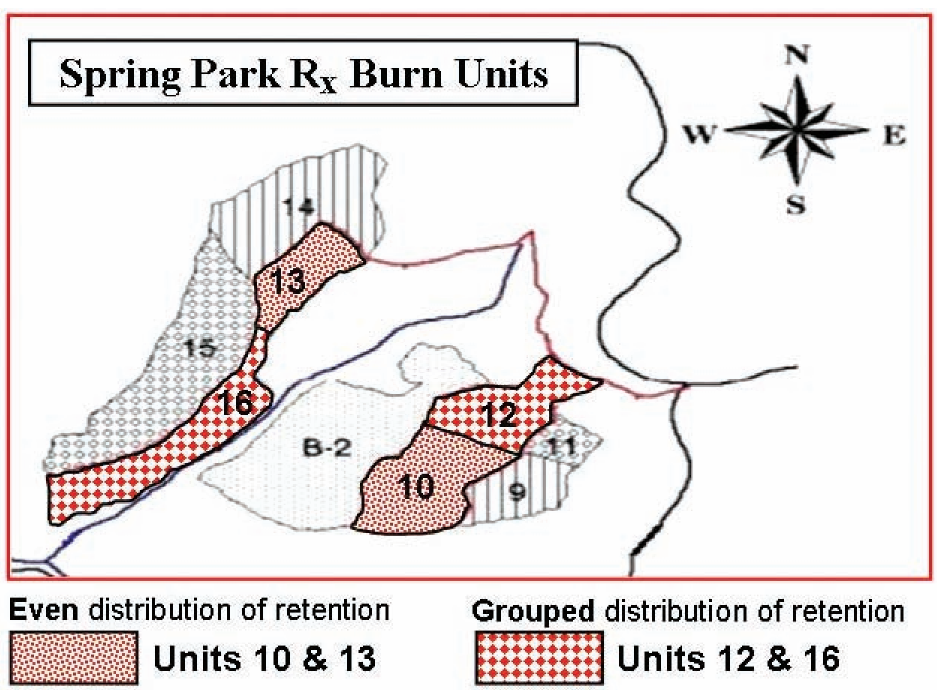

Figure 5—Two pairs of units in Spring Park were selected for analysis: SEB (units 10 & 13), and SGB (units 12 & 16).

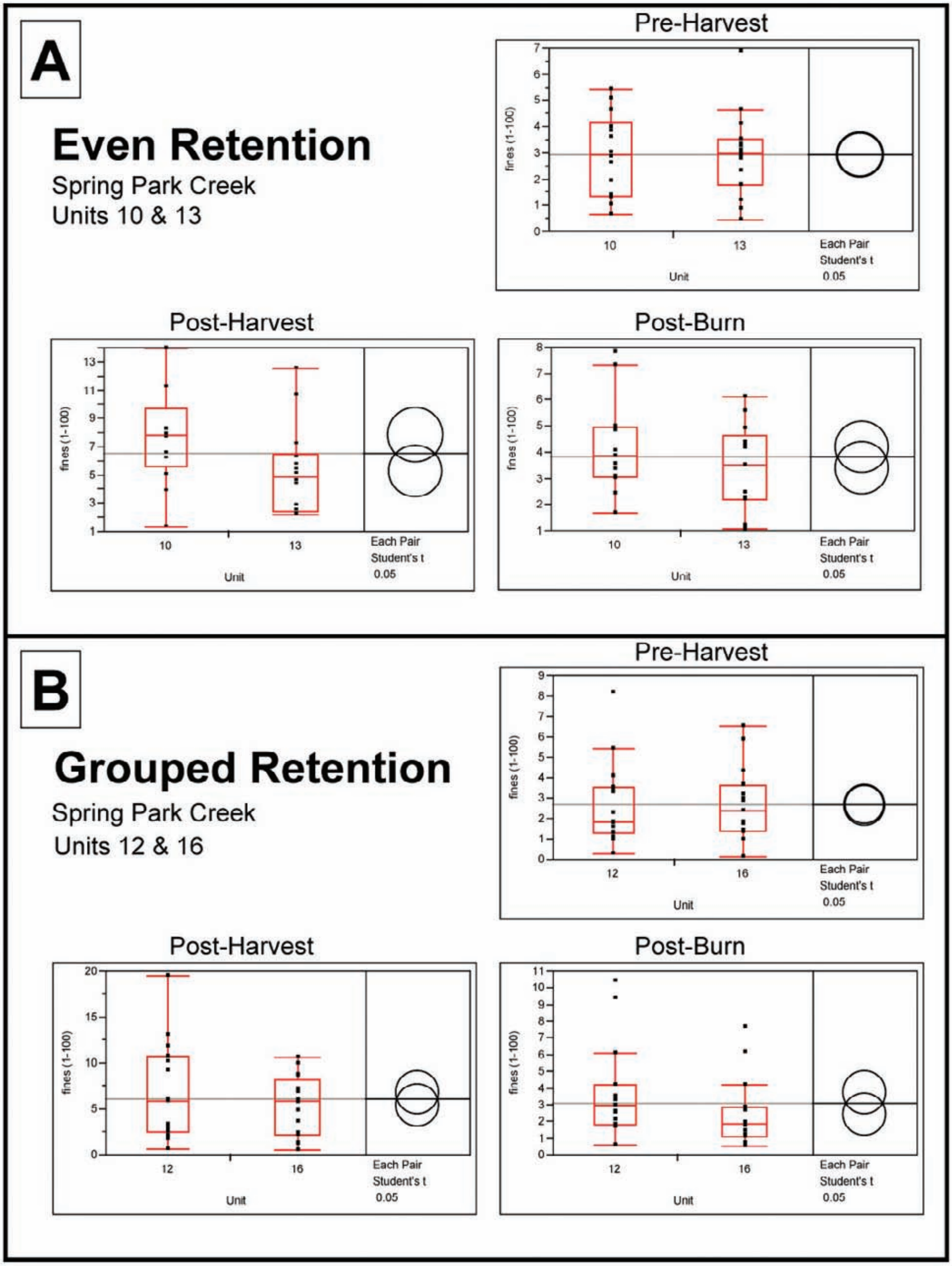

Figure 6—Median values, interquartile ranges, and the 0.05 *Student's t* statistic (expressed as tons per acre) presented as confirmation that fine-fuel loadings in the pooled units are not significantly different for either the Even (6A) or Grouped (6B) treatments.

Results

We present results of preliminary analyses by comparing pre-harvest, post-harvest and post-burn conditions between the two harvest-and-burn treatments on Spring Park Creek. As described above in methods, two treatment units are pooled for each of the two treatment types—SEB and SGB. Results presented here are limited to fine-fuel loading, large-woody fuel loading, and fire-caused overstory tree mortality.

Fine-Fuel Loading—Harvesting activities contributed approximately 3.5 tons per acre of fine fuels in both the *Even* and *Grouped* treatments, as illustrated in figure 7 by the mean values of all plots within the pooled units for each treatment type—this is roughly a one hundred percent increase from pre-harvest conditions (fig. 7). The prescribed burning treatment following harvest reduced the fine-fuel loading to near pre-harvest conditions in both treatment types; reductions were 2.7 tons per acre and 3.0 tons per acre for the *Even* and *Grouped* treatments, respectively. While the post-harvest fine-fuel loadings were significantly higher ($\alpha=0.05$) than either the pre-harvest or post-burn loadings for both treatment types, the differences between pre-harvest and post-burn fine-fuel loadings were not statistically significant ($\alpha=0.05$) for either treatment type. In summary, the harvesting activities resulted in significant increases in fine-fuel loadings, and post-harvest prescribed burning effectively reduced the fine-fuel loadings to pre-harvest levels.

Large Woody Fuel Loading—We compared the consumption (mass reduction measured in tons per acre) of large woody fuel due to prescribed burning between the *Even* and *Group* treatment types. Mean values and 95% confidence intervals representing all plots within the pooled units for each treatment type are presented in figure 8. In both treatment types, less than one ton per acre of large woody fuel was consumed, with no significant difference between the treatment types ($\alpha=0.05$) (fig.8). The percent mass reduction in large woody fuels for the *Even* and *Group* treatment types was

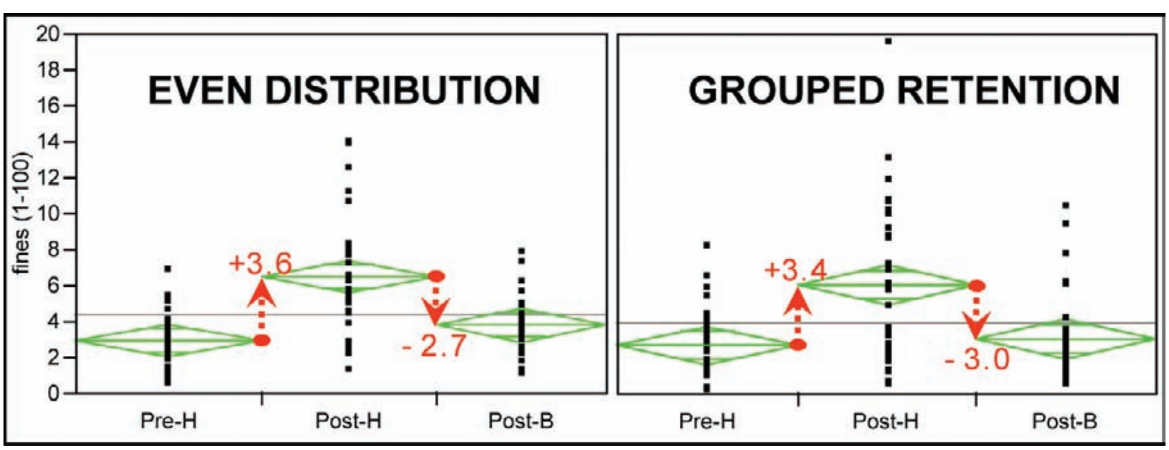

Figure 7—Changes in fine-fuel loading (tons/acre) between pre-harvest, post-harvest, and post-burning for pooled *Even* (left) and *Grouped* (right) distribution units.

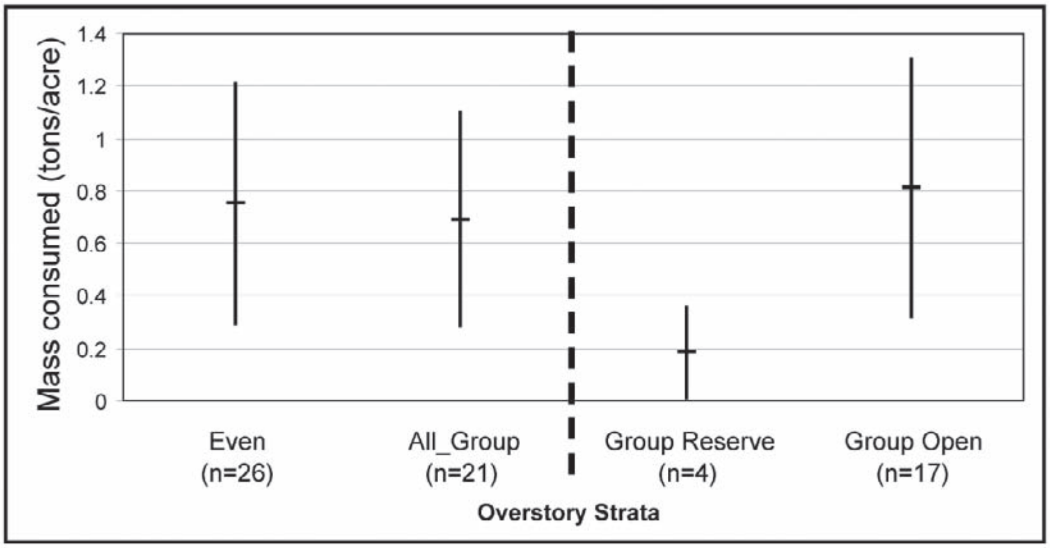

Figure 8—Comparison of means and 95% confidence intervals for consumption of large woody fuel (1000-hour) between Even and Grouped (*All_Group*) distributions. The data labeled "*Group Reserve*" are from plots within the grouped retention areas, and data labeled "*Group Open*" are from plots located in the open (harvested) areas between groups.

14.5% and 12.9%, respectively. Within the grouped treatment types are two distinct distributions of overstory: 1. The un-harvested retention groups; and 2. The completely harvested (effectively, "clearcut") open areas between grouped reserves. These two strata are labeled in figure 8 as "*Group Reserve*" and "*Group Open*," respectively. While the total mass consumption of large woody fuel in the *Group Open* plots was somewhat greater than the average for the overall group treatment (labeled "*All_Group*" in figure 8), consumption within the *Group Reserves* was significantly lower than either the *Group Open* or the *Even* distribution (α=0.05). In terms of percent mass reduction in large woody fuels within the two *Group* treatment strata, there was a 19.5% reduction in mass for the *Group Open* strata and only a 2.7% reduction for the *Group Reserves* strata.

Fire-induced Overstory Tree Mortality—Although most of the results presented here have been confined to the Spring Park treatments, data on fire-induced overstory tree mortality were acquired and analyzed for treatments in both Spring Park Creek and Sun Creek. Mortality data from each of the first three years following burning are presented in figure 9. Within a treatment type (*Even* or *Group*) the three-year trends are similar for both sub-watersheds. However, a general comparison of mortality between the two sub-watersheds indicates higher levels of mortality in the Spring Park units, regardless of treatment type (fig. 9). By the third year following burning, mortality in the *Even* treatments was twenty-three percent and thirty-seven percent higher than for the *Group* treatments in Sun Creek and Spring Park, respectively. The highest mortality, seventy-eight percent, was observed for the *Even* treatment type in Spring Park— twenty-eight percent higher than the maximum prescription target of fifty percent.

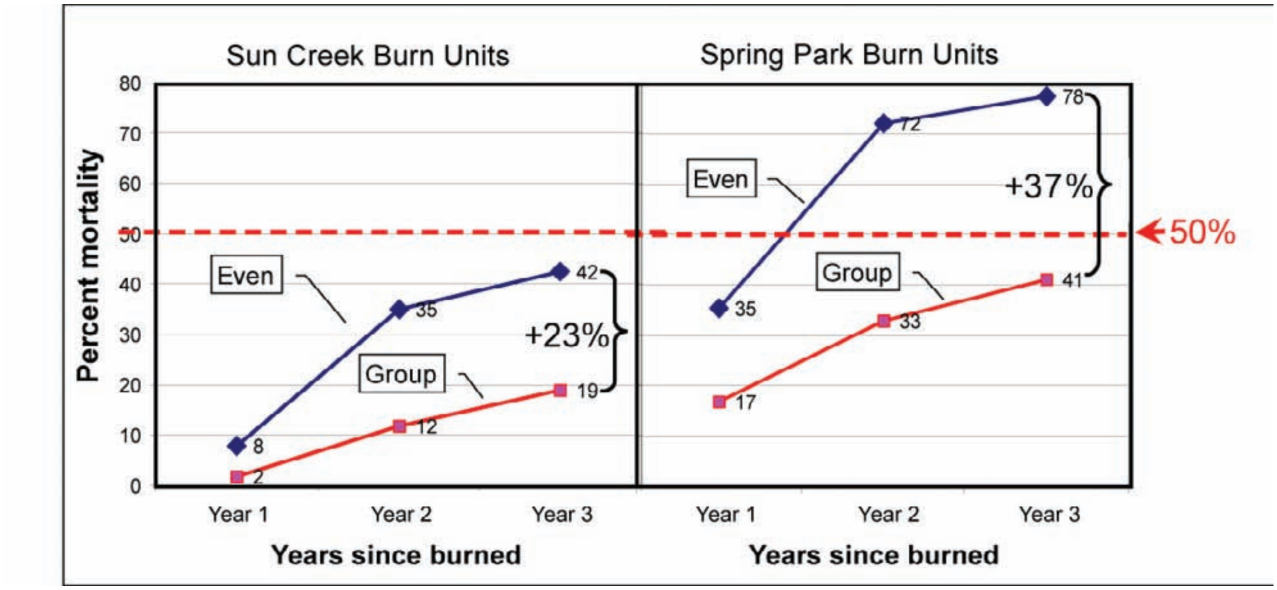

Figure 9—Fire-caused mortality was much higher for the Spring Park units than for Sun Creek; mortality for the even distribution was much higher (23%-37%) than for the grouped distribution; and in the even distribution for Spring Park mortality greatly exceeded the prescribed upper limit of 50%.

Discussion

Specific evidence presented here regarding the consequences related to two of four treatment alternatives is limited to fine-fuel loadings, consumption of large woody fuel, overstory tree mortality, and anecdotal observations. The significant increase in fine-fuel loadings resulting from harvest activities was well mitigated by post-harvest prescribed burning. Although fine-fuel loadings were effectively doubled by harvest activities, the absolute loadings were not particularly high (3.5 tons/acre). In lodgepole pine, however, the vulnerability of the thin-barked species to bole-related mortality is high, relative to most other coniferous species. This makes management of fine-fuel loadings—the principle contributor to surface fire intensity—of paramount importance. Despite very careful execution of a conservative prescribed fire plan, increased levels of fine-fuel loadings caused by the harvesting activities in the *Even* distribution treatment were high enough to cause unacceptable fire-induced mortality. During a typical wildfire season, most fuel and weather conditions would be significantly warmer, drier, and windier than conditions under which the prescribed burning treatments were applied. In such cases, the fine-fuel loadings present following the harvesting activities would lead to dramatic, unacceptable increases in overstory tree mortality. For example, the comparison of mortality between the Sun Creek units and the Spring Park Creek units shown in figure 9 indicates much lower mortality for the Sun Creek units. Despite our desire to burn all units within similar weather and fuel conditions, the relative humidity was considerably higher during the burning operations in Sun Creek, with lower temperatures and wind speeds. Although not considered in the statistical analyses, these conditions provide substantial anecdotal evidence supporting the sensitivity of the lodgepole pine forest type to fire-weather conditions.

In contrast to the prescriptions targeting reductions in fine-fuel loading through prescribed fire treatments, there is neither a fire hazard-related nor ecological advantage to burning of large woody fuel components (there are, in fact, a number of advantages to retaining large woody biomass). When the large woody fuel becomes involved in combustion, there are significant increases in heat flux to the soil and organic surface components, and also production of significantly elevated levels of smoke emissions from combustion of the large woody fuels as well as other biomass associated with the large fuel combustion. There was no significant difference in large woody fuel consumption between the two treatment types, however, so there are no management implications associated with large-woody fuel consumption.

Although there is an on-going field effort to assess and document windthrow in all treatment units, quantitative data are not yet available. However, anecdotal evidence from observations over the short period of time since completion of management activities show significant windthrow in several of the *Even* treatment units. In contrast, windthrow in the Group treatment have been observed to be limited to an occasional tree at the perimeter of the retention groups.

These preliminary results provide a first-look at the relative successes of innovative silvicultural and prescribed fire treatments targeting restoration and maintenance of lodgepole pine forest systems. They are not, however, sufficient enough to support conclusions from which to formulate management direction. The research mission for TCEF directed us to "test an array of management treatments for regenerating and restoring healthy lodgepole pine forests through emulation of natural disturbance processes, but avoiding catastrophic-scale disturbances." Results from further examination of the complete data set from this study will be integrated with results from other Tenderfoot Creek Research Project studies in a comprehensive assessment of the feasibility and consequences of these innovative treatments. More management direction may be provided at that time.

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Effectiveness of Prescribed Fire as a Fuel Treatment in Californian Coniferous Forests

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***Abstract**—Effective fire suppression for the past century has altered forest structure and increased fuel loads. Prescribed fire as a fuels treatment can reduce wildfire size and severity. This study investigates how prescribed fire affects fuel loads, forest structure, potential fire behavior, and modeled tree mortality at 80th, 90th, and 97.5th percentile fire weather conditions on eight National Forests in California. Potential fire behavior and effects were modeled using Fuel Management Analyst. Prescription burning did not significantly change forest structure at most sites. Total fuel loads (litter, duff, 1, 10, 100, and 1000-hour) were reduced by 23 to 78 percent across the sites. This reduction in fuels altered potential fire behavior by reducing rate of spread, flame length, and fireline intensity. Increased torching index values coupled with decreased fuel loads reduced crown fire potential post-treatment in some stands. Predicted tree mortality decreased post-treatment as an effect of reduced potential fire behavior and fuel loads. With the vast forested areas classified at high risk for catastrophic wildland fire in California, it is most efficient to target stands that benefit the most from treatment.*

Introduction

In many coniferous forests, fire suppression has lead to higher tree densities (Biswell 1959), changes in species composition (Weaver 1943), and higher fuel loads (Dodge 1972), which have altered fire regimes (Beaty and Taylor 2001; Stephens and Collins 2004). A recent analysis of fire cause and extent on U.S. Forest Service (USFS) lands from 1940 to 2000 demonstrated that California experienced a significant increase in the total number of fires and had the most area burned relative to other regions in the United States (Stephens 2005). Although the area burned has not significantly increased from 1940 to 2000 in California (Stephens 2005), the wildland fire problem has only worsened as suppression has become more effective (Brown and Arno 1991).

Fuels treatments can be effective at reducing the severity (Pollet and Omi 2002; Agee and Skinner 2005; Finney and others 2005) and size of wildland fires (Stephens 1998; Piñol and others 2005). Reduction of surface fuels, and in some cases crown fuels, can reduce the likelihood of crown fires (van Wagner, 1977). Typically, mechanical methods are used to alter stand structure (i.e., reduce tree density, decrease basal area, increase the height to live crown base, and reduce canopy cover) (Keyes and O'Hara 2002; Pollet and Omi, 2002; Stephens and Moghaddas, 2005a,b). Prescribed fire alone can decrease surface and ladder fuels which reduce potential fire behavior and thus lower the risk of crown fire and spot fire ignition (van Wagtendonk 1996; Stephens 1998).

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The objective of this study is to determine how prescribed fire effects fuel loads, vegetation structure, and potential fire behavior and effects in eight National Forests in California. The null hypothesis investigated is that there will be no significant difference in vegetation structure, fuel load, fire behavior, and predicted tree mortality at each study site when comparing pre- and post-treatment characteristics. Information from this study could be used to assist in the development of forest management plans that use prescribed fire to reduce fire hazards.

Methods

Study Location

Nine project sites are located on eight National Forests: the Klamath (one on the eastern section, KNF E, and one on the western section, KNF W), Lassen (LNF), Los Padres (LPF), Modoc (MDF), Mendocino (MNF), Plumas (PNF), Shasta-Trinity (SHF) and Sierra (SNF) (fig. 1). LPF, MDF, MNF, and SNF are dominated by yellow pine [>80% of basal area is composed of ponderosa pine (*Pinus ponderosa* Laws) or Jeffrey pine (*Pinus jeffreyi* Grev.)] and KNF E, KNF W, PNF, and SHF are in mixed-conifer forests.

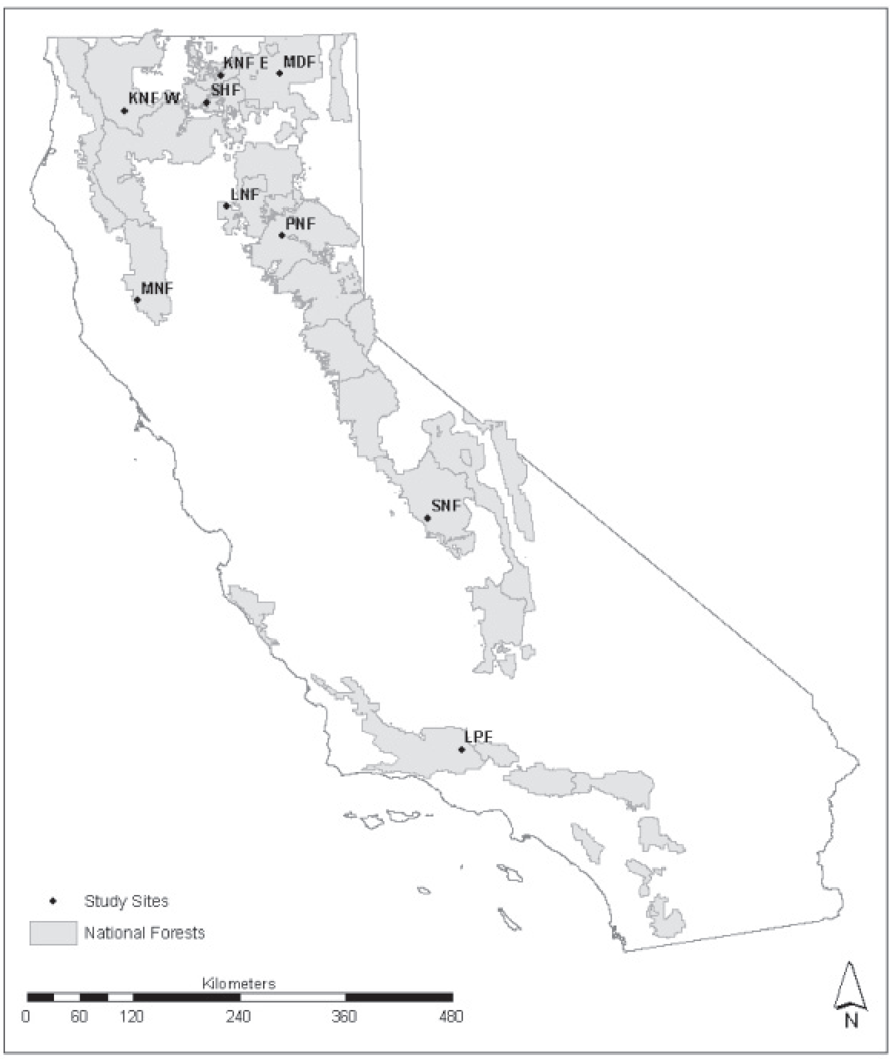

Figure 1—Location of study sites.

Climate in the study sites is Mediterranean with a summer drought period that extends into the fall. The majority of precipitation occurs during winter and spring. Tree species present include ponderosa pine, Jeffrey pine, sugar pine (*Pinus lambertiana* Dougl.), white fir (*Abies concolor* Gord. and Glend.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), incense-cedar (*Calocedrus decurrens* Torr.), western juniper (*Juniperus occidentalis* Hook.), California black oak (*Quercus kelloggii* Newb.), canyon live oak (*Quercus chrysolepis* Liebm.), and bigleaf maple (*Acer macrophyllum* Pursh).

The average elevation of the study sites ranges from approximately 1000 to 1600 m. Average slopes vary from three to 61 percent. Pre-treatment percent-cover of tree canopy, shrubs, and grasses varies between study locations.

Treatments

All of the study sites were treated with prescribed fire. The primary objectives of the prescribed burns were to reduce the potential for catastrophic stand replacing fire events and to reintroduce fire into the ecosystem. Each of the National Forests implemented their own prescribed fires. The prescribed fires occurred either in spring or fall depending on weather, available personnel, and funding, with the majority of prescribed fires taking place in the spring (six out of nine).

Vegetation Measurements

In each of the nine project sites, vegetation was measured using 0.2 ha randomly-placed, permanently-marked circular plots (26 total plots). Tree information was collected in two nested subplots; 0.1-ha for all trees greater than 15 cm diameter at breast height (d.b.h.), and 0.025 ha for trees 2.5 to 15 cm d.b.h. Tree measurements (species, d.b.h., height, height to live crown base (HTLCB), and tree crown position (dominant, codominant, intermediate or suppressed)) are recorded for live trees; for snags species, d.b.h., and total height was recorded. Canopy cover was measured every meter along two perpendicular 50 m transects using a Moosehorn sight tube (Gill and others 2000). Shrub measurements were also taken along the same transects in each of the plots to estimate percent shrub cover. An ocular estimate of percent cover by grasses was made along the shrub transect in a 1 m^2 frame every 10 m.

Ground and Surface Fuel Characteristics

Surface and ground fuels were measured with four transects in each of the plots using the line-intercept method (van Wagner 1968; Brown 1974). For each transect, one-hour (0 to 0.64 cm diameter) and 10-hour (0.64 to 2.54 cm diameter) fuels were sampled from 0 to 1.83 m, 100-hour fuels (2.54 to 7.62 cm diameter) from 0 to 3.66 m, and 1000-hour fuels (diameter >7.62 cm) from 0 to 15.24 m. Species, diameter, and decay status (rotten or sound) were recorded for all 1000-hour fuels. Litter, duff, and fuel bed depth (cm) measurements were taken every 1.52 m totaling 10 per transect. Surface and ground fuel loads were calculated using arithmetically-weighted coefficients specific to the California tree species based on the average basal area fraction of the individual sites (van Wagtendonk and others 1998; Stephens and Moghaddas 2005a).

Fire Modeling

Fire behavior and effects were modeled under upper 80^{th}, 90^{th}, and 97.5^{th} percentile fire weather conditions. Eightieth, 90^{th}, and 97.5^{th} percentile fire weather represent moderate, high, and extreme fire weather, respectively. Percentile weather was computed using Fire Family Plus (Main and others 1990). Forty-three years (1961 to 2004) of weather data from the most representative Remote Automated Weather Station (RAWS) for each site (NFAM 2004) were analyzed to determine percentile weather conditions.

Fuels Management Analyst (FMA) was used to model fire behavior and effects (rate of spread, flame length, fireline intensity, crowning index, torching index, and tree mortality) (Carlton 2005). Fire behavior predictions were made for stand and fuel structures before and after prescribed burning. A surface fuel model was assigned to each sampling plot based on stand structure, shrub cover, grass cover, and fuel loads (Scott and Burgan 2005).

Data Analysis

Paired t-tests were used to determine if significant differences ($p<0.1$) existed in vegetation (trees ha^{-1}, basal area ha^{-1}, tree height, HTLCB, canopy cover, crown bulk density (CBD)) and fuel loads (litter, duff, 1-hr, 10-hr, 100-hr, 1000-hr sound, 1000-hr rotten, total fuel load (1 to 1000-hr, litter and duff), and fuel depth) for each site pre- and post-prescribed fire (Zar 1999). The choice of $p<0.1$ was made due to high natural variation found between plots in each study site. The number of sample plots varied by site location due to the ability of the individual National Forests to burn the proposed units and because some prescribed fires did not burn the entire intended area.

Results

Forest Structure

The inventory plots in the nine study locations included 860 live trees greater than 2.5 cm d.b.h. pre-treatment and 801 post-treatment. No significant differences were found for any of the measured variables (basal area, trees ha^{-1}, d.b.h., tree height, HTLCB, canopy cover, CBD) at KNF W, MDF, SHF or SNF (table 1). At LNF, LPF, MNF and PNF some but not all of the variables were significantly different (table 1). All variables were significantly different at KNF E except HTLCB.

Fuels Characteristics

A total of 104 fuel transects were analyzed over the nine project sites to characterize surface and ground fuels pre- and post-prescribed burning. All locations had a significant difference post-treatment in at least one of the fuels parameters (table 2). All of the locations except PNF experienced a significant reduction in litter loads. Total fuel load was reduced at all sites; however, the difference was only significant at MNF and LPF.

Potential Fire Behavior

Rate of spread (ROS) increased for all sites with increasing percentile weather (table 3). Post-treatment ROS either decreased or experienced no change when compared to pre-treatment. Flame length (FL) increased with

Table 1—Average pre- and post-treatment vegetation structure for all trees greater than 2.5 cm d.b.h. by site location for nine stands in eight Californian National Forests.

Site	Basal area (m^2 ha^{-1})		Trees (ha^{-1})		DBH (cm)		Tree height (m)		HTLCB (m)		Canopy cover (percent)		CBD (kg m^{-3})	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
KNF E	37.0[a]	36.0[a]	706.7[a]	533.3[a]	27.2[a]	29.6[a]	14.4[a]	15.6[a]	4.9	4.6	43.2[a]	35.3[a]	0.094[a]	0.091[a]
KNF W	48.2	42.6	585.0	420.0	33.7	34.5	15.0	17.1	3.4	8.9	76.3	70.6	0.054	0.050
LNF	51.9	48.8	490.0[a]	405.0[a]	34.7	36.2	21.0	21.4	8.9	9.4	96.6	93.1	0.046	0.044
LPF	28.1	27.3	600.0	306.7	27.3	37.1	14.3	13.3	3.6	3.2	24.0[a]	19.8[a]	0.049[a]	0.044[a]
MDF	26.9	24.3	313.3	263.3	33.3	34.1	14.3	15.1	3.8	4.8	29.4	30.2	0.057	0.050
MNF	27.3	27.2	520.0	516.0	27.3	26.6	14.0	14.0	4.2	4.2	69.0[a]	50.7[a]	0.090	0.089
PNF	38.1	35.9	423.3	360.0	33.9	35.3	19.3[a]	21.0[a]	7.8[a]	11.3[a]	64.7	62.1	0.069	0.067
SHF	34.4	33.8	163.3	120.0	52.5	58.6	27.9	31.4	10.4	11.7	30.5	27.6	0.034	0.033
SNF	40.7	40.8	525.0	525.0	36.2	36.2	19.1	19.1	7.1	7.1	51.0	44.2	0.074	0.071

HTLCB= height to live crown base, CBD= crown bulk density, [a]=significantly different pre- versus post-treatment.

Table 2—Average fuel loads (metric t ha^{-1}) pre- and post-treatment by site location.

Site	Duff		Litter		1-hr		10-hr		100-hr		1000-hr sound		1000-hr rotten		1-1000-h plus litter, duff		Fuel depth (cm)	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
KNF E	21.4	2.2	11.1[a]	4.4[a]	1.5	0.9	2.7	1.3	2.8	2.5	3.5	6.5	39.7	0.0	82.7	17.8	28.2[a]	7.7[a]
KNF W	33.2	7.4	18.5[a]	3.0[a]	1.4	0.3	6.1	1.4	5.9	1.3	9.7	6.9	61.4	33.7	136.0	53.9	25.6	12.3
LNF	17.0	9.2	18.9[a]	3.5[a]	2.1	0.6	7.7	3.8	4.5	2.7	7.4	0.8	7.4	29.8	65.1	50.3	14.7	11.5
LPF	22.3[a]	10.0[a]	4.4[a]	1.7[a]	0.6	0.2	1.0	0.8	2.8	4.1	0.0	4.6	13.2	0.0	44.3[a]	21.3[a]	9.7	3.4
MDF	13.6	5.2	5.6[a]	3.8[a]	0.5[a]	0.2[a]	1.2	0.9	1.7[a]	2.8[a]	1.2	0.0	12.0	3.6	35.6	16.5	7.9	3.5
MNF	16.7	14.8	12.9[a]	3.0[a]	0.3	0.4	2.5	1.6	3.6	4.8	2.7	7.3	64.7[a]	12.2[a]	103.5[a]	44.1[a]	67.0[a]	8.3[a]
PNF	22.5	9.0	4.3	10.0	1.3	0.6	2.0	2.1	5.1	3.9	13.8	0.2	25.2	15.3	74.2[a]	41.0[a]	16.2[a]	10.3[a]
SHF	28.9[a]	6.9[a]	5.4[a]	1.9[a]	0.9[a]	0.2[a]	3.4[a]	1.0[a]	7.6	3.1	0.4[a]	9.5[a]	17.6	7.6	64.3	30.2	11.1[a]	7.4[a]
SNF	15.4	8.5	12.1[a]	2.7[a]	0.9	0.5	2.3	0.8	5.3	3.7	1.5	2.5	6.0	2.6	43.6	21.3	51.3	8.1

[a]=significantly different pre- versus post-treatment .

Table 3—Average modeled fire behavior under 80th, 90th, and 97.5th percentile weather by site location.

Site	ROS			FL			FI			TI			CI		
	80th	90th	97.5th	80th	90th	97.5th	80th	90th	97.5th	80th	90th	97.5th	80th	90th	97.5th
Pre	*(m min⁻¹)*			*(m)*			*(kW m⁻¹)*			*(km h⁻¹)*			*(km h⁻¹)*		
KNF E	2.9	7.2	15.7	0.6	0.7	6.6	75.5	153	49286.6	152.8	119.5	109.7	41.5	37.2	33.2
KNF W	2.0	12.6	24.9	0.9	4.3	5.2	213.3	10476.3	16751.5	76.1	26.9	24.0	51.6	47.0	41.3
LNF	1.4	1.8	2.1	0.7	0.8	0.9	160.3	201.8	248.6	595.2	462.7	417.3	60.6	56.0	51.4
LPF	3.6	4.6	12.5	1.4	1.5	2.8	570.8	685.4	2950.5	35.3	26.2	23.2	75.9	67.0	60.6
MDF	1.2	1.6	2.9	0.8	1.0	1.2	185.5	245.9	379.3	135.9	104.5	88.5	73.1	68.4	60.8
MNF	6.4	8.3	16.0	3.2	3.7	7.1	5430.0	8500.2	44942.9	48.3	37.6	34.2	34.1	31.4	28.6
PNF	1.5	1.6	1.8	0.6	0.7	0.7	100.8	111.3	129.9	770.3	612.8	560.1	44.2	38.8	32.5
SHF	0.4	0.5	0.7	0.3	0.4	0.4	25.3	30.2	40.4	1894.2	1491.6	1401.0	80.6	75.1	70.4
SNF	1.8	4.5	5.4	0.9	1.4	1.5	22.9	578.4	685.9	212.2	140.1	117.7	45.6	29.8	24.7
Post															
KNF E	0.7	0.9	15.4	0.4	0.4	6.3	33.9	42.6	46828.1	434.7	347.0	321.2	42.8	38.4	34.2
KNF W	0.5	0.7	0.9	0.3	0.3	0.3	15.6	19.7	24.2	3023.2	2422.0	2218.5	58.0	53.0	46.8
LNF	0.5	0.7	0.8	0.3	0.3	0.3	15.9	19.9	21.9	2167.4	1766.4	1650.3	61.8	57.2	52.7
LPF	0.7	0.7	4.6	0.4	0.4	0.5	31.2	33.9	53.4	299.6	238.2	217.8	84.6	74.8	67.8
MDF	0.4	0.5	0.7	0.2	0.3	0.3	12.1	15.9	24.2	619.0	521.8	466.9	85.6	85.9	71.2
MNF	2.4	2.6	3.9	1.2	1.2	1.5	408.4	451.3	659.7	104.7	83.2	76.2	34.3	31.6	28.8
PNF	1.5	1.7	2.0	0.6	0.7	0.7	94.4	107.2	125.4	981.9	782.0	715.1	51.2	45.1	38.1
SHF	0.4	0.5	0.6	0.2	0.3	0.3	12.1	14.5	19.7	2677.8	2134.9	2012.2	82.9	77.2	72.4
SNF	0.6	0.7	0.7	0.3	0.3	0.3	17.7	21.9	21.9	1299.2	1052.0	968.1	47.2	40.4	38.1

ROS-rate of spread; FL-flame length; FI-fireline intensity; TI-torching index; CI-crowning index.

respect to higher percentile fire weather pre-treatment except at PNF and SHF where no change occurred between the 90th and 97.5th percentiles (table 3). FL was shorter post-treatment as compared to pre-treatment in all locations except PNF where it did not change. Modeled fireline intensity (FI) increased as percentile weather increased both pre- and post-treatment for all site locations except SNF (table 3). FI decreased post-treatment as compared to pre-treatment for all site locations. Torching index (TI) decreased as percentile weather increased pre- and post-treatment (table 3). Crowning index (CI) decreased with increasing percentile weather except at MDF where it only increased between the 80th and 90th percentile. CI increased slightly post-treatment for all locations, following the decreasing trend with respect to increasing severity of fire weather.

Fire type (FT) remained 100 percent surface fire in the LNF, PNF, SHF, and SNF sites pre- and post-treatment for all weather scenarios (table 4). Prescribed fire changed predicted FT in the KNF E, KNF W, LPF, MDF, and MNF sites by either decreasing the likelihood of crown fire or decreasing the severity of crown fire. At 80th and 90th percentile fire weather conditions, all post-treatment sites experienced only surface fire.

Predicted Tree Mortality

Probability of mortality was modeled for four diameter classes (2.5 to 25, 25 to 51, 51 to 76, >76 cm d.b.h.) as well as for all trees at each study site pre- and post-treatment (table 5). For all sites, a higher percentage of trees was predicted to die prior to treatment than after treatment. A higher amount of

Table 4—Modeled fire type under 80th, 90th, and 97.5th percentile weather by site location.

Site	80th	90th	97.5th
Pre			
KNF E	33%PCF,66%SF	33%PCF,66%SF	33%ACFWD, 66%SF
KNF W	33%PCF,66%SF	33%SF, 66%PCF	33%SF,33%PCF,33%ACFPD
LNF	100%SF	100%SF	100%SF
LPF	33%PCF,66%SF	33%PCF,66%SF	33%SF, 66%PCF
MDF	100%SF	100%SF	33%PCF, 66%SF
MNF	40%PCF, 60%SF	40%PCF, 60%SF	20%PCF, 20%ACFPD, 60%SF
PNF	100%SF	100%SF	100%SF
SHF	100%SF	100%SF	100%SF
SNF	100%SF	100%SF	100%SF
Post			
KNF E	100%SF	100%SF	33%ACFWD, 66%SF
KNF W	100%SF	100%SF	100%SF
LNF	100%SF	100%SF	100%SF
LPF	100%SF	100%SF	33%PCF, 66%SF
MDF	100%SF	100%SF	100%SF
MNF	100%SF	100%SF	100%SF
PNF	100%SF	100%SF	100%SF
SHF	100%SF	100%SF	100%SF
SNF	100%SF	100%SF	100%SF

SF=surface fire; PCF=passive crown fire; ACFWD=active crown fire wind driven; ACFPD=active crown fire plume dominated.

mortality was predicted in smaller diameter classes (2.5 to 25 cm and 25 to 51 cm d.b.h.) regardless of location, weather condition, or treatment status. An increase in mortality with respect to increasing predicted fire weather conditions occurred in most study sites prior to prescribed fire; the trend was not the same post-treatment (table 5).

Table 5—Average pre- and post-prescribed burn percent predicted mortality by diameter class and site location for three percentile weather conditions.

	DBH range (cm)	KNF E	KNF W	LNF	LPF	MDF	MNF	PNF	SHF	SNF
Pre										
80th	2.5-25	62.7	90.6	56.1	99.4	86.0	95.4	64.3	65.5	58.7
	25-51	21.9	52.1	24.1	70.5	27.5	79.6	17.5	20.4	17.3
	51-76	6.9	8.0	7.3	6.0	8.4	•	6.4	5.2	4.9
	>76	•	4.6	2.0	2.8	•	•	2.0	3.6	2.0
	All	30.5	38.8	22.4	44.7	40.6	87.5	22.5	23.7	20.7
90th	2.5-25	66.5	98.1	57.8	99.6	92.4	96.9	64.7	65.5	77.5
	25-51	26.7	84.1	25.0	79.6	32.6	85.7	17.5	20.4	28.8
	51-76	8.2	50.0	8.0	8.9	12.1	•	6.4	5.2	5.4
	>76	•	48.3	2.0	3.8	•	•	2.0	3.6	2.0
	All	33.8	70.1	23.2	48.0	45.7	91.3	22.6	23.7	28.4
97.5th	2.5-25	69.5	99.1	59.2	99.6	97.8	99.2	66.0	65.5	83.8
	25-51	46.6	87.9	26.6	89.0	44.0	95.5	17.6	20.4	37.2
	51-76	35.6	64.0	9.3	39.4	20.6	•	6.4	5.2	6.5
	>76	•	58.6	2.0	5.5	•	•	2.0	3.6	2.0
	All	50.6	77.4	24.3	58.4	54.1	97.3	23.0	23.7	32.4
Post										
80th	2.5-25	52.3	58.9	46.0	52.4	53.6	81.7	52.2	40.2	48.0
	25-51	21.1	23.1	23.2	22.5	17.2	58.8	17.8	18.6	13.9
	51-76	6.9	5.6	8.6	7.1	5.0	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	26.8	22.6	19.9	18.3	25.2	70.2	19.6	16.9	17.1
90th	2.5-25	52.3	58.9	46.0	52.4	53.6	85.7	52.2	40.2	48.0
	25-51	21.1	23.1	23.2	22.5	17.2	67.2	17.8	18.6	13.9
	51-76	6.9	5.6	8.6	7.1	5.0	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	26.8	22.6	19.9	18.3	25.2	76.5	19.6	16.9	17.1
97.5th	2.5-25	65.7	58.9	46.0	56.9	53.9	87.6	52.3	40.2	48.0
	25-51	46.7	23.1	23.2	31.0	17.9	78.0	17.8	18.6	13.9
	51-76	35.6	5.6	8.6	16.6	5.2	•	6.3	5.2	4.3
	>76	•	2.9	2.0	2.4	•	•	2.0	3.6	2.0
	All	49.3	22.6	19.9	18.8	25.7	82.8	19.6	16.9	17.1

• = no trees in this diameter class for this location.

Discussion

Topography, weather, and fuels all play a role in the hazard and severity of wildland fire. Altering the fuel load is the most feasible and important factor to decrease hazard and severity of wildland fire. The vertical and horizontal continuity of surface fuels (litter and downed woody debris), ladder fuels (shrubs and small trees), and/or canopy fuels (large trees) must be broken to reduce fire severity. Reduction in surface fuels can reduce FI, increasing HTLCB can reduce the risk of torching, and reduction in crown density can limit tree-to-tree spread of crown fires (Agee 2002; Hessberg and Agee 2003; Agee and Skinner 2005).

Many studies in ponderosa pine and mixed-conifer forests document the effectiveness of prescribed fire in reducing future fire severity (Weaver 1943; Biswell and others 1973; Kauffman and Martin 1989; van Wagtendonk 1996; Stephens 1998; Miller and Urban 2000; Pollet and Omi 2002; Finney and others 2005; Knapp and others 2005; Stephens and Moghaddas 2005a,b). Prescribed fire effectively reduces surface fuel loads as well as kills shrubs and small diameter trees which reduce ladder fuels. Understory burning can also raise the height to live crown base through scorching of lower branches. One unifying goal of the prescribed burns analyzed in this work was to reduce the risk of stand-replacing catastrophic fire.

Stand characteristics did not significantly change in four of the nine site locations after treatment. This is consistent with many of the studies mentioned above. However, KNF E did experience a significant change in basal area, trees ha^{-1}, d.b.h., tree height, canopy cover, and CBD post-prescribed fire. This may be partially due to a tree blowdown event between plot readings (Kit Jacoby, personal communication). In the rest of the sites there were few differences in stand structure pre- and post-treatment. TI and CI moderately increased at all sites post-treatment, which indicates the need for an increase in wind speed to initiate and maintain crown fire. Overall, the modeled outputs document a reduced percentage of crown fires post-treatment; five treatments had a component of passive crown fire pre-treatment and two post-treatment (table 4).

If the primary goal of the prescribed fire treatment is to reduce the potential of stand replacing catastrophic wildfires, then TI and CI might be of particular interest. CI only increased slightly for all sites post-treatment indicating that the prescribed fire treatments did not effect the overstory (CBD or tree canopy cover). Under the 80^{th} percentile fire weather condition, the untreated sites are unlikely to initiate crown fire due to high TI (table 3). For the 90^{th} and 97.5^{th} percentile fire weather conditions, pre-treatment values of TI and CI make the KNF W, LPF, and MNF sites more vulnerable to active crown fire (table 3). The reduction in likelihood of crown fire is due to a combination of changes in stand structures and surface fuel loads. Crown fire is not solely linked to canopy characteristics; surface fuel loads also play a critical role in active crown fire initiation and spread. If surface fireline intensity exceeds the critical level needed to initiate an active crown fire, the canopy is likely to burn as long as high surface fuel loads are present.

Fuel bed depth was significantly reduced at the KNF E, MNF, PNF and SHF sites; however, fuel bed depth was reduced by at least 20 percent at the remaining five sites, but was not statistically significant. Total fuel loads (surface and ground) were reduced significantly at LPF, MNF and PNF. The relatively high consumption of ground and surface fuels is consistent with past studies (Kilgore and Sando 1975; Kauffman and Martin 1989; Stephens and Finney 2002; Knapp and others 2005). Prescribed fire without crown thinning has been shown to greatly reduce fireline intensity relative to no treatment (van Wagtendonk 1996; Stephens 1998). A reduction in surface fuel loads generally results in decreased fire severity, ROS, FL, and FI. Altered stand structures also contributed to the increase of surface fires versus crown fires post-treatment. Smaller diameter trees killed by prescribed fire are initially standing dead fuel. Eventually these trees will fall and contribute to the surface fuel loads (Stephens 1998; Agee 2003), necessitating future prescribed fires to keep hazards low.

Predicted tree mortality was higher pre-treatment than post-treatment for all locations under low, moderate, and extreme fire weather. Probability of tree mortality is primarily based on percent crown scorched which is derived from crown ratio, species tree height, and tree diameter (Reinhardt and others 1997). Predicted tree mortality was greatest in the smallest diameter class (2.5 to 25 cm d.b.h.) and decreased with increasing diameter classes (table 5). Increases in percentile fire weather post-treatment did not increase the likelihood of overall tree mortality at five sites (KNF W, LNF, PNF, SHF, SNF), it only slightly increased tree mortality in two sites (LPF and MDF), and it greatly increased tree mortality in two sites (KNF E and MNF). Predicted mortality almost doubled for all diameters at KNF E between the 90^{th} and 97.5^{th} percentile conditions post-treatment where fire type also changed; however, mortality was still lower relative to pre-treatment conditions (tables 4 and 5).

If reduction of potential stand replacing fires is the primary goal of prescribed fire treatments, selection of treatment locations must consider the existing fire hazards. Four of the nine study sites examined here only experienced modeled surface fire in pre-treatment conditions, including extreme fire weather conditions (table 4). Post-treatment potential fire behavior (ROS, FL, FI) was reduced, but these stands were not at risk of crown fire before treatment. On the other hand, three of the nine sites were at an elevated risk of crown fire (low TI and CI) pre-treatment at 97.5^{th} percentile weather conditions (table 3). For the sites that would experience only surface fire, treatment is not warranted based on the reduction of potential fire behavior and effects. Sites experiencing low TI and CI values may benefit from a mechanical treatment (such as thinning from below) prior to prescribed fire to further reduce the risk of active crown fire.

In addition to the reduced potential for stand replacing catastrophic wildland fires, reintroduction of fire into the ecosystem was a primary goal of these prescribed fire treatments. Seasonality of prescribed fire is important from an ecological and fuels consumption standpoint. Fire history data from the southern Cascades in California document that prehistoric fires occurred mostly during the dormant season (starting as early as August and ending in October) in both pine dominated and mixed conifer forests (Taylor 2000; Beaty and Taylor 2001). In mixed conifer forests of the north-central, south-central, and southern Sierra Nevada, fires occurred most frequently just before dormancy in latewood growth (Stephens and Collins 2004). If reintroducing ecological processes is an important goal of a prescribed burn, it would be best if the burns took place in a time consistent with the fire history records.

Managers must consider many facets when choosing a location for treatment. With the amount of land rated at high hazard in California it would be wise to target stands which would benefit the most from treatment. If reintroduction of fire into the ecosystem is the primary goal and fuel reduction the secondary goal, then choosing treatment locations could include both stands with high and low fire hazards. Unfortunately, there is no one size fits all for fuel treatments in California; managers must consider many factors when implementing a forest restoration plan.

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Changes in Downed Wood and Forest Structure After Prescribed Fire in Ponderosa Pine Forests

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Abstract*—Most prescribed fire plans focus on reducing wildfire hazards with little consideration given to effects on wildlife populations and their habitats. To evaluate effectiveness of prescribed burning in reducing fuels and to assess effects of fuels reduction on wildlife, we began a large-scale study known as the Birds and Burns Network in 2002. In this paper we analyze changes in downed wood and forest structure (trees and snags) measured within one year after prescribed fire treatments that were completed in ponderosa pine (Pinus ponderosa) forests in Arizona and New Mexico (Southwest region), and Idaho and Washington (Northwest region). Apparent reductions in downed wood and trees were observed in both regions. However, statistically significant reductions of downed wood were found primarily in the Northwest ($p < 0.001$), whereas significant reductions of trees were reported only for the Southwest ($p = 0.03$). No significant post-treatment changes were detected in snag densities, although we observed a pattern of non-significant increases in all size classes. Additional fire treatments are likely needed to meet fuels reduction goals. Results of this study are intended to assist managers with developing scientifically sound and legally defensible prescribed fire projects that will reduce fuels and concurrently enhance wildlife habitat.*

Introduction

Fire regimes of lower elevation forests, particularly ponderosa pine (*Pinus ponderosa*) of the Interior Western United States, have been altered since Euro-American settlement (Agee 1993; Schoennagel and others 2004). Alterations in fire regimes and subsequent changes in forest structure and composition stem primarily from fire suppression, logging, and livestock grazing (Allen and others 2002; Schoennagel and others 2004; Veblen 2000). After decades of fire suppression, elevated fuel loads in many ponderosa pine forests have increased the likelihood of unusually large and severe fires (Arno and Brown 1991; Covington and Moore 1994), and the area burned annually has increased (Grissino-Mayer and Swetnam 2000; Keane and others 2002).

In an effort to restore ponderosa pine forest ecosystems, land managers have increasingly relied on prescribed burning (Horton and Mannan 1998; Arno 2000; Machmer 2002; Carey and Schumann 2003). Most prescribed fire plans focus on reducing the intensity of wildfire, with little consideration given to effects on wildlife populations and their habitats. Strategies for fire management should not only reduce fire risk but also maintain habitat for wildlife and other components of biodiversity (Saab and others 2005).

Ponderosa pine trees, snags and downed wood are among the most valuable habitat components for wildlife species in western North American forests (Balda 1975; Bull and others 1997; Hall and others 1997; Szaro and others

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1988). Large-diameter ponderosa pine snags, trees with decay, and downed logs are relatively easy to excavate by woodpeckers and provide roosting, nesting, and foraging habitat for a variety of wildlife (Bull and others 1997; Hall and others 1997; Szaro and others 1988; Scott 1979).

Many cavity-nesting birds depend on fire-disturbed landscapes for breeding, dispersal, and other portions of their life history (Saab and others 2004). Several cavity nesters are designated by state, federal, and provincial governments as species at-risk because they are responsive to fire and timber management activities. Stand-replacement fires in conifer forests are particularly important to breeding and wintering cavity-nesting birds (Blackford 1955; Raphael and White 1984; Saab and Dudley 1998; Kriesel and Stein 1999; Hannon and Drapeau 2005). Little is known, however, about bird population responses to prescribed fire, particularly in the Intermountain region (Bock and Block 2005; Saab and others 2005). In 2002, we began a regional study to evaluate effectiveness of prescribed fire in reducing fuels and to assess the effects of fuels reduction on habitats and populations of birds in ponderosa pine forests throughout the Interior West. Our study is known as the Birds and Burns Network (BBN) (see web page http://www.rmrs.nau.edu/lab/4251/birdsnburns/), with study areas located in seven states encompassing much of the range of ponderosa pine in the United States (Arizona, Colorado, Idaho, Montana, New Mexico, Oregon, and Washington). As of 2005, study areas in Arizona and New Mexico (Southwest region; SW), and Idaho and Washington (Northwest region; NW) have received prescribed fire treatments.

In this paper, our objective was to evaluate the magnitude of change in the quantities of downed wood, dead stems (hereafter termed snags), and live stems (hereafter termed trees) measured within one year after prescribed fire treatments. Based on previous studies (Horton and Mannan 1988; Machmer 2002; McHugh and Kolb 2003; Raymond and Peterson 2005), we hypothesized that downed wood of all sizes, large snags (≥ 9 inch diameter breast height [d.b.h.]), and smaller trees (< 9 inch d.b.h.) would be reduced as a result of prescribed burning, whereas we expected smaller snags (< 9 inch d.b.h.) to increase after fire treatments. Results of this study are intended to help managers develop scientifically sound and legally defensible prescribed fire projects that will reduce fuels and concurrently maintain and enhance wildlife habitat.

Study Area and Methods

Study areas were located in forests dominated by ponderosa pine, where prescribed fire treatments were implemented by the USDA National Forests. On each study area, a single treatment unit ranged in size from 500 to 1000 acres and was paired with an unburned control unit of equivalent area. As of 2005, prescribed fire treatments were completed at seven study units in four states and data from these units were used in the analyses presented in this paper. General objectives of these "low-intensity" fire treatments included fuels reduction, fire threat mitigation, and forest restoration.

Pre-treatment data were collected during the summers of 2002 and 2003. Four units were treated with fire in the SW on USDA National Forests (NF); two units during fall 2003 in Arizona (Apache-Sitgreaves and Coconino NFs), and two units that were initiated in fall 2003 and completed during spring 2004 in New Mexico and Arizona (Gila and Kaibab NFs, respectively). Three units were treated in the NW during spring 2004, one unit in Idaho

(Payette NF) and two units in Washington (Okanogan and Wenatchee NFs). Post-treatment data were collected one growing season after fire treatments during the summers of 2004 or 2005.

Overstory vegetation (trees ≥ 9 inches d.b.h.) on all units in both regions was dominated by ponderosa pine. For trees ≥ 20 inch d.b.h. or larger, ponderosa pine was also the dominant tree species for all locations except for the Gila NF, where alligatorbark juniper (*Juniperus deppeana*) had higher densities.

In Arizona, common understory vegetation included green rabbitbrush (*Chrysothamnus viscidiflorus*) and Fendler rose (*Rosa woodsii*), whereas gambel oak dominated the understory in New Mexico. Arizona fescue (*Festuca arizonica*) and blue gramma (*Bouteloua gracilis*) were the most common grass species throughout the SW. Elevations in the SW region ranged from 6800 feet on the Coconino NF to nearly 8200 feet on the Gila NF.

The understory vegetation in the NW was comprised of various species, including snowberry (*Symphoricarpos albus)*, spirea (*Spirea* spp.), serviceberry (*Amelanchier alnifolia*), and chokecherry (*Prunus* spp.). Bluebunch wheatgrass (*Pseudoroegenaria spicatus*) and Idaho Fescue (*Festuca idahoensis*) were the common grass species. Elevations ranged from 2200 feet in Washington to 6500 feet in Idaho.

Within each unit we established 20 to 40 permanently marked 1-acre random plots to measure fuel and vegetative characteristics. All plots centers were at least 820 feet apart (Dudley and Saab 2003). To determine the effects of prescribed fire on downed wood, snags, and trees, we measured these forest components at each plot before (pre) and after (post) prescribed fire. We considered the difference in pre and post values by plot to be a measure of the treatment effect size.

Measurements were nested within the 1-acre plot configured as two 66 x 326 feet rectangles that crossed in the center (that is, a rectangular cross plot). Tree and snag measurements followed methods outlined by Bate and others (1999). Snags ≥ 9 inches d.b.h. were counted within 33 feet of the centerline in the rectangular cross plot. Trees ≥ 9 inches d.b.h. were counted within 16.5 feet of the centerline in the SW and within 9.8 feet in the NW. Plot widths for trees and snags were based on power analyses of pilot data from each location to maximize efficiency of data collection (Bate and others 1999). For trees and snags < 9 inches, we counted within 6.6 feet of the centerline in the SW and within 3.3 feet in the NW.

In this paper we present preliminary results for both snags and trees in four categories: (1) < 3 inch; (2) ≥ 3 to 9 inch; (3) ≥ 9 inch; and (4) total density of all stems (snags or trees). Snags and trees in the ≥ 9 inch d.b.h. category were of special interest to us because they commonly represent the smallest size class that woodpeckers use for nesting (for example, Saab and others 2004) and the smallest sized trees harvested for timber values (USDA 1996).

We measured the weight (tons per acre) of downed wood following Brown's (1974) protocol. Downed wood is defined as the "… dead twigs, branches, stems, and boles of trees and brush that have fallen and lie on or above the ground" (Brown 1974, page 1). Downed wood pieces less than 1 inch diameter (1- and 10-hour fuels) were sampled along 41 feet of transect in two directions (north and south) from the plot center. Material in the ≥ 1 to 3 inch size class (100-hour fuels) was measured in the same two directions but along twice the length (82 feet). For coarse wood ≥ 3 inches (≥ 1000-hour fuels), we recorded the intersection diameter of each woody piece along 164 feet in each of the four cardinal directions originating from the plot center (total of 656 feet sampled). Downed wood pieces ≥ 3 inch were classified as either sound or rotten and we used the specific gravities provided by Brown (1974) to obtain a weight estimate for each condition class. That is, we used 24.96 lbs/ft^3 and 18.72 lbs/ft^3 for sound and rotten wood, respectively, relative to the density of water (62.4 lbs/ft^3) (Brown and See 1981). Here, we present results for downed wood in four size categories: (1) < 3 inch; (2) ≥ 3 inch; (3) ≥ 9 inch; and (4) total weight of all downed wood. Weights calculated for the ≥ 9 inch category were based on the large-end diameter (LED), whereas weights of other size classes were based on the intersect diameter.

We calculated a response to the prescribed fire as an "effect size" on each plot, which represented the change in fuels attributable to the prescribed fire. The effect size was measured by subtracting pre-fire fuel quantities from post-fire fuel quantities. We then computed least-squares means (PROC MIXED SAS Institute 2003) to test whether the effect size was significantly different from zero for weight of downed wood, snag densities, and tree densities. We accepted $p \leq 0.05$ as the observed probability level for Type I error in hypothesis tests. We used a nested analysis with plots nested within units, and units nested within regions. Results are reported for the mean effect size of stems per acre (± 1 standard error [SE]) and tons per acre (± 1 SE) at the regional level. A likelihood ratio test was computed to compare a model with a pooled estimate of variance across regions to a model with a separate variance estimate for each region. Generally, the model with separate variance estimates had significantly better goodness-of-fit and was used for the least-squares means analysis. Pooled variance results are reported only for trees ≥ 9 inch d.b.h. and for total trees.

Results

Weight of downed wood in all size classes decreased after prescribed fire treatments (Table 1), however most of the statistically significant differences were measured in the NW (Table 2). Downed wood was reduced by 25 to 43 percent in the SW and by 29 to 58 percent in the NW. Total weight of downed wood was reduced by nearly half in the NW region, where most of the downed material was comprised of large logs ≥ 9 inches LED (Table 1). In contrast to the NW, pre-fire weight of downed wood in the SW region was composed almost exclusively of small diameter material < 9 inches LED (Table 1).

Our hypothesis about reductions of small diameter (< 9 inches d.b.h.) trees (seedlings, saplings, and poles) was generally supported by the data; however, trees of all diameter classes in the SW region also decreased significantly after fire treatments (Table 2). Trees were reduced by 19 to 74 percent in the SW and 0 to 39 percent in the NW (Table 1). Stems in the smallest size class (<3 inches) contributed the most to changes in tree densities, whereas large tree (≥ 9 inches) densities changed the least.

We hypothesized that snags of the smaller size classes (< 9 inches d.b.h.) would increase and that large snags (≥ 9 inches d.b.h.) would decrease after fire treatments. Our results indicated no significant post-treatment changes in snag densities (Table 2), although we observed a pattern of non-significant increases in all size classes (Table 1). Increases in snags ranged from 30 to 72 percent in the SW and 29 to 229 percent in the NW. Large snags (≥ 9 inches d.b.h.) contributed to the greatest changes in dead stems in the SW, whereas smaller diameter stems (≥ 3 – 9 inches d.b.h.) contributed most to snag changes in the NW.

Table 1—Means, standard errors (SE), and percent change for downed wood (DW; mean tons per acre), and trees, and snags (mean stems per acre) measured pre- and post-fire treatment by region (Southwest [SW] and Northwest [NW]) in the Birds and Burns Network during 2002-2005. Downed wood was measured at large end diameter (LED) and stems were measured at diameter breast height (d.b.h.).

		SW [n = 134]			NW [n = 60]		
	Size class	Pre-fire mean	Post-fire mean	Percent change	Pre-fire mean	Post-fire mean	Percent change
	(inches)	- - - - - - - - - - - *(SE)* - - - - - - - - - - -			- - - - - - - - - - - *(SE)* - - - - - - - - - -		
DW	< 3	2.0 (0.2)	1.5 (0.1)	–25	1.8 (0.2)	1.3 (0.1)	–27.8
(tons/ac)	≥ 3	2.3 (0.2)	1.3 (0.1)	–43.5	7.6 (0.8)	3.8 (0.5)	–50
	≥ 9	0.7 (0.1)	0.4 (0.1)	–42.9	6.3 (0.8)	2.6 (0.4)	–58.7
	Total	4.3 (0.3)	2.8 (0.2)	–34.9	9.4 (0.9)	5.1 (0.5)	–46
Trees	< 3	256 (26.5)	66.3 (12.6)	–74.1	234 (29.4)	144 (26.6)	–38.5
(stems/ac)	≥ 3 to 9	124 (9.5)	72.6 (8.4)	–41.5	191 (23.6)	133 (17.1)	–30.4
	≥ 9	52.2 (2.5)	42.2 (2.9)	–19.2	45.5 (2.4)	48.1 (2.9)	+.057
	Total	432 (33.2)	181 (18.2)	–58.1	470 (46.8)	324 (36.2)	–31.1
Snags	< 3	28.6 (3.9)	44.6 (5.6)	+55.9	62.2 (10.2)	110 (16.7)	+76.8
(stems/ac)	≥ 3 to 9	15 (2)	19.5 (2.4)	+30	12.7 (2.1)	41.8 (7.9)	+229
	≥ 9	2.5 (0.3)	4.3 (0.7)	+72	2.8 (0.4)	3.6 (0.5)	+28.6
	Total	46 (5.4)	68.4(7.5)	+48.7	77.6 (11.5)	156 (23.5)	+101

Table 2—Results of least–square means analysis to test for statistical differences from zero, or no change in the quantity of downed wood (DW; tons per acre), trees (stems per acre), and snags (stems per acre) measured pre- and post-prescribed fire in western ponderosa pine forests. Mean estimate of the effect size, standard error of the estimate (SE), t-value, *p*-value, and sample size [n] are reported for each size class by region (Southwest [SW] and Northwest [NW]) in the Birds and Burns Network during 2002-2005.

		SW [n =134]				NW [n = 60]			
	Size class	Estimate (effect size)	SE	t-value	*p*-value	Estimate (effect size)	SE	t-value	*p*-value
	(inches)								
DW	< 3	–0.49	0.32	–1.53	0.19	–0.46	0.43	–1.06	0.34
(Δ in tons/ac)	≥ 3	–1.15	0.43	–2.68	0.04	–3.9	0.58	–6.71	0.001
	≥ 9	–0.4	0.18	–2.11	0.09	–3.7	0.54	–6.83	0.001
	Total	–1.66	0.73	–2.28	0.07	–4.3	0.36	–11.97	<0.001
Trees	< 3	–212.6	28.6	–2.7	0.04	–107.1	47.5	–2.26	0.07
(Δ in stems/ac)	≥ 3 to 9	–60.9	29.5	–2.07	0.09	–61.1	35.2	–1.74	0.14
	≥ 9	–13.3	8.06	–1.65	0.16	2.9	9.38	0.31	0.77
	Total	–287.1	99.9	–2.37	0.03	–165.2	117.3	–1.41	0.22
Snags	< 3	19.4	13.7	1.42	0.21	47.9	19.5	2.45	0.06
(Δ in stems/ac)	≥ 3 to 9	5.4	4.2	1.29	0.25	29.2	17.6	1.65	0.16
	≥ 9	1.86	1.06	1.75	0.14	0.79	0.55	1.43	0.21
	Total	26.6	14.8	1.80	0.13	77.9	37.2	2.09	0.09

Discussion

Decreases in downed wood and trees supported our hypotheses regarding changes in these forest components after prescribed fire treatments. While we expected only the smaller size classes of snags (< 9 inch d.b.h.) to increase after prescribed fire, we observed a pattern of non-significant increases in large snag (≥ 9 inch d.b.h.) densities as well. Apparently, prescribed fire treatments were severe enough to kill trees of all size classes, particularly in the SW where this result was statistically significant.

Nearly half of large downed wood (≥ 9 inch LED) was consumed by prescribed fire in both regions. Drought conditions, followed by low wood moistures prior to fire treatments, may have contributed to the large loss of downed wood. When moisture contents are less than 15 percent, fire generally consumes about half of large downed woody materials (Brown and others 1985). Efforts to retain these large structures may require seasonal adjustments for burning times when moisture contents are higher and fire severity effects are lower (Thies and others 2005). Maintenance of large, downed wood is important ecologically because these structures provide foraging habitat, thermal cover, and concealment for many sensitive wildlife taxa (Bull and others 1997; Szaro and others 1988), although logs may have been a limited resource in low-severity fire regimes (Agee 2002).

Overall tree densities in the SW were significantly reduced after fire treatments. Although we observed a pattern of decreased tree densities in the NW, no statistical differences were detected in densities measured before and after prescribed fire. We think, however, that all observed changes in tree densities were important ecologically. For example, in both regions we observed the greatest reduction of tree densities in the smallest size class (< 3 inches d.b.h.), followed by reductions in the medium size class (≥ 3 to < 9 inch), with little change in large (≥ 9 inches d.b.h) tree densities. Small diameter trees function as ladder fuels in dense stands by carrying flames into the crowns of mature trees, where the potential for larger tree mortality increases (Pollet and Omi 2002). Indeed, prescribed fire programs that remove small diameter trees can reduce the likelihood and cost of stand-replacing fires (Arno 1980; Fernandes and Botelho 2003; Pollet and Omi 2002).

We observed relatively little change in densities of large trees ≥ 9 inch d.b.h. This result was not surprising because the thick bark of ponderosa pine is fire-resistant, improving tree survival during low to moderate severity burns (Agee 1993). Historically, large-diameter ponderosa pines were harvested because of their high timber and fuelwood values (Agee 1993). These same trees are also among the most valuable for many wildlife species of conservation concern (Bull and others 1997; Lehmkuhl and others 2003; Saab and others 2004). Retention of large-diameter snags and decayed trees, particularly ponderosa pine, can provide vital nesting and roosting habitat for a variety of wildlife species (Bull and others 1997; Martin and Eadie 1999). For example, the sapwood of ponderosa pine is relatively thick compared to other conifers and exceptionally valuable for the excavation of nesting and roosting tree cavities (Bull and others 1997).

We observed apparent increases in snag densities, including the large diameter size class in both regions. While this pattern was not statistically significant, the result has implications for the creation of wildlife habitat. Maintenance and recruitment of larger diameter snags is particularly important because large snags have greater longevity and provide wildlife habitat for a longer period of time than smaller snags (Raphael and Morrison 1987; Everett and others 1999; Saab and others 2004). Additional tree mortality is expected two to three years after fire, because time allows for crown scorch and consumption to cause further tree death (McHugh and Kolb 2003).

In contrast to our results that suggest increased densities of large snags after fire, Horton and Mannan (1988) reported that large ponderosa pine snags were reduced by about 50 percent within the first year after a moderately-intense prescribed fire. Detrimental effects of prescribed fire on suitable nesting snags were also reported in ponderosa pine forests of Canada, where burning caused heavy scorching of large snags (Machmer 2002). Differences in fire severity among studies likely contributed to the opposing results of snag changes after prescribed fire.

Several authors suggest protecting nest trees by removing combustible materials around their base prior to burning to reduce losses of suitable nest/roost snags (Horton and Mannan 1988; Machmer 2002; Tiedemann and others 2000). Specifically, Horton and Mannan (1988) recommend protecting large (>50 cm [20 inch] d.b.h.) snags and logs with moderate decay. Tiedemann and others (2000) recommended removing combustible material around snags > 30 cm (12 inch) d.b.h. These methods are labor intensive and cost prohibitive for large-scale prescribed fire programs, unless snag protection is required for Threatened and Endangered species. While prescribed fire consumed some wildlife snags, burning also recruited snags (Table 1). Direct effects of prescribed burning on wildlife should also be considered. For example, prescribed fires conducted during spring or early summer may cause direct mortality to nestlings and fledglings (Lyon and others 2000).

Smaller snag (< 9 inch d.b.h.) densities increased 30 to 60 percent in the SW and two to four times that amount in the NW region. While still standing, these dead trees contribute to increased risk of spot fires (Stephens and Moghaddas 2005). With time, these stems create ground fuels and increase the likelihood of higher fire intensities (Reinhardt and Ryan 1998). Such fuel accumulations can limit the effectiveness of prescribed fire programs to a relatively short period of time such as two to four years (Fernades and Botelho 2003). Studies suggest that relatively frequent, natural fires are necessary to maintain ponderosa pine forests in a diverse landscape mosaic more common to historical conditions (Brown and Cook 2006; Fry and Stephens 2006) that existed just prior to European settlement. Similarly, prescribed fires also have the potential to mitigate the likelihood of severe crown fires (Fernandes and Botelho 2003; Finney and others 2005; Pollet and Omi 2002; Raymond and Peterson 2005), which were once rare but regular events in ponderosa pine forests (Shinneman and Baker 1998).

Few of our results were statistically significant at $p \leq 0.05$. Managers willing to take more acceptable risk can interpret our results as being more definitive by using a significance level of $p \leq 0.10$ (Zar 1999). Inherent differences in pre-treatment forest structure existed in our ponderosa pine forests, which possibly influenced fire behavior and resulted in high variability in the effectiveness of fuels reduction. The power to detect statistically significant changes is low without large numbers of replicates. However, long-term prescribed fire programs can still play an important role in reducing fire hazard potential (Fernandes and Botelho 2003), suggesting that our study areas may require multiple fire treatments to reach fuels reduction and restoration goals. In addition, wildland fire can also be used to effectively reduce fuels and to closely mimic past disturbance regimes in ponderosa pine forests (Baker and Ehle 2001).

In this paper we did not evaluate the influence of fire severity on changes in fuels and other vegetation after fire. In the future, we plan to incorporate fire severity data to help with understanding the influences of severity on vegetation mortality, and wildlife populations and their habitat (Saab and Powell 2005). Also, we recommend monitoring vegetation and wildlife populations for several years after prescribed burning because of changes in vegetation and wildlife responses with time since fire (Hannon and Drapeau 2005; McHugh and Kolb 2003; Reinhardt and Ryan 1998; Saab and others 2004). Severity information and monitoring for multiple years after fire will help in developing guidelines for prescribed fire projects that will reduce fuels and concurrently create wildlife habitat.

Acknowledgments

This study was funded by the Joint Fire Sciences Program, National Fire Plan, USDA Rocky Mountain Research Station, USDA Pacific Northwest Research Station, Intermountain Region of the USDA Forest Service, and the USDA Payette National Forest. We thank Craig Bienz and Robin Russell for thoughtful comments on the manuscript. Rudy King provided guidance on statistical analyses. We are grateful to the many field assistants who worked long, hot days to collect the field data.

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Biomass Consumption During Prescribed Fires in Big Sagebrush Ecosystems

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***Abstract**—Big sagebrush* (Artemisia tridentata) *ecosystems typically experience stand replacing fires during which some or all of the ignited biomass is consumed. Biomass consumption is directly related to the energy released during a fire, and is an important factor that determines smoke production and the effects of fire on other resources. Consumption of aboveground biomass (fuel) was evaluated for a series of operational prescribed fires in big sagebrush throughout the interior West. Pre-burn fuel characteristics (composition, amount, and structure), fuel conditions (live and dead fuel moisture content), and environmental conditions (weather and topography) affected fire behavior and subsequent fuel consumption. Total aboveground biomass consumption varied from 1.6 to 22.3 Mg ha^{-1} (18 to 99 %) among the 17 experimental areas. Multiple linear regression and generalized linear modeling techniques were used to develop equations for predicting fuel consumption during these prescribed fires. Pre-burn fuel loading, which is influenced by season of burn, site productivity, time-since-last-fire, and grazing is the most important predictor of fuel consumption. Use of fire in big sagebrush is desirable for several reasons, including wildlife habitat improvement, livestock range improvement, fire hazard abatement, and ecosystem restoration.*

***Keywords**: Artemisia tridentata, big sagebrush, fire effects, fuel consumption*

Introduction

Research to quantify and model fuel consumption during wildland fires has been conducted in managed and unmanaged forest types throughout the United States (e.g., Ottmar 1983; Sandberg and Ottmar 1983; Little and others 1986; Brown and others 1991; Hall 1991; Albini and Reinhardt 1997; Reinhardt and others 1997; Myanishi and Johnson 2002), but is generally lacking or of limited scope in shrub-dominated ecosystems (for example, Sapsis and Kauffman 1991). Much of the existing fire research in shrub types has focused on fire behavior prediction in a limited number of shrub types (for example, Lindenmuth and Davis 1973; Green 1981; Brown 1982). Shrub-dominated ecosystems occur on hundreds of millions of hectares of private, state and federal lands in the United States. Sagebrush (*Artemisia* spp.) occurs on at least 38.5 million hectares in the interior West, making it one of the largest biomes in North America (Shiflet 1994). Sagebrush and other shrub-dominated types may be remotely located or they may occur at the wildland-rural/suburban/urban interface throughout their range. Many shrub-dominated ecosystems are home to sensitive, rare, threatened and endangered species, including numerous species of birds, mammals, mollusks, insects,

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plants, fish, reptiles and amphibians. In terms of sheer land area, proximity to populated areas, and wildlife habitat, research in shrub-dominated types addresses information needs for a diverse array of natural resource managers.

Increasing public awareness of environmental issues necessitates that resource managers fully evaluate regulatory requirements and potential impacts of land management decisions (in other words, no action, prescribed fire use, wildland fire use, grazing, mechanical treatment, chemical treatment, etc.) using the best available information. Where fire is concerned, quantification of fuel consumption is critical for evaluating fire severity (for example, Keely and others 2005), and for effectively modeling fire effects, including smoke emissions, regional haze, nutrient cycling, plant succession, species composition changes, plant/tree mortality, wildlife habitat restoration and maintenance, erosion, soil heating, and carbon cycling. Fuel consumption is the most critical variable for effectively evaluating and managing the consequences of prescribed and wildland fire as related to land management objectives.

Many sagebrush-dominated ecosystems in the western United States have experienced periodic, naturally occurring fire events (Miller and Rose 1999). Resource managers use prescribed fire as a multi-scale treatment for a number of specific purposes, including fuel and fire hazard reduction, wildlife habitat improvement, and ecosystem restoration. In contrast to forested systems where a large proportion of the fuelbed is composed of dead and down organic matter, in sagebrush-dominated ecosystems, the fuelbed is composed almost entirely of living (and standing dead) vegetation. Prior to the application of fire in forests and shrublands it is desirable to gauge the likelihood of treatment success (in other words, desired change in vegetation or fuel structure) by predicting fuel consumption. Change in the vegetation structure (that is, fuel composition, amount and arrangement) is often the most significant measure of treatment success. If resource managers in the sagebrush biome are to develop effective fire plans and prescriptions designed to meet desired objectives for terrestrial and atmospheric resources, research must quantify both fuel characteristics and fuel consumption during wildland fires.

Objective

The primary objective of our research was to develop models to predict biomass consumption in big sagebrush ecosystems using variables that are relatively easily measured or readily obtained. These fuel consumption models have been incorporated into the software CONSUME 3.0 (Prichard and others, in press). Development of consumption models for sagebrush ecosystems and their application in CONSUME 3.0 promotes more effective and informed use of emission production, fire effects, and wildfire/prescribed fire tradeoff models allowing for better wildland fire emissions and fire effects accounting and planning at a variety of scales.

Methods

Data were collected at 17 locations on a series of operational prescribed fires in big sagebrush (*A. tridentata*) ecosystems in southeastern Oregon, northwestern Nevada, northwestern Wyoming, and northern California (table 1). Sampling for fuel consumption occurred on gentle slopes (0 to 15 percent slope) of all

Table 1—Site information for experimental sagebrush burns.

Site Name	# Sites	Latitude	Longitude	Elevation	Slope	State	Admin. Unit[a]
Flook Lake	3	42° 36'	119° 32'	1539-1542 m	0 %	OR	USFWS1
Stonehouse	1	42° 56'	118° 26'	1937 m	15 %	OR	BLM1
V-Lake	5	42° 28'	118° 44'	2018-2056 m	0-15 %	OR	Private
Gold Digger Pass	2	41° 46'	121° 34'	1331-1346 m	0-5 %	CA	NPS
Escarpment	2	41° 52'	119° 40'	1672-1693 m	0-5 %	NV	USFWS2
Sagehen	1	41° 56'	119° 15'	1717 m	0 %	NV	USFWS2
Heart Mountain	3	44° 42'	109° 09'	1764-1823 m	0-15 %	WY	BLM2

[a]USFWS1 = U.S. Fish and Wildlife Service, Hart Mountain National Antelope Refuge; USFWS2 = U.S. Fish and Wildlife Service, Sheldon National Wildlife Refuge; BLM1= Bureau of Land Management, Burns, OR; BLM2 = Bureau of Land Management, Cody, WY; Private = Roaring Springs Ranch; NPS = Lava Beds National Monument.

aspects at elevations ranging from 1,331 to 2,056 m. Sites were selected to represent a broad range of coverage and biomass of standing big sagebrush of all three recognized subspecies: Wyoming big sagebrush (*A. t.* ssp. *wyomingensis*), mountain big sagebrush (*A. t.* ssp. *vaseyana*), and basin big sagebrush (*A. t.* ssp. *tridentata*). Big sagebrush subspecies occur on sites that follow a gradient of increasing precipitation; Wyoming big sagebrush occupies the driest sites (20 to 32 cm annual precipitation), mountain big sagebrush occupies the wettest sites (31 to 149 cm annual precipitation) and basin big sagebrush is found on intermediate sites (Francis 2004). Experimental areas were embedded within larger operational units, and were burned under a variety of environmental and fuel moisture conditions during the fall of 2001 (September 23 to October 25) and spring of 2002 (March 21; table 2).

Data Collection

Fuel Characterization and Consumption—A regular grid of 2 × 2 m plots (or 1.5 × 1.5 m, if vegetation was particularly large or dense) was used to determine fuel loading and composition in a relatively uniform stand or patch of big sagebrush. A total of 36 plots were numbered sequentially; nine plots each were located every 7.6 m along four 76.2-m long transects that

Table 2—Weather and fuel moisture information for experimental sagebrush burns.

		Weather			Fuel moisture		
Site name	Subspp.[a]	Temp.	RH	Windspeed	Grass	Live sage foliage	Dead sage 10hr[b]
		°C	percent	$km\ hr^{-1}$	percent		
Flook Lake	W	17.2-17.8	17-34	12.1-12.9	9.8-10.2	59.9-61.8	9.2
Stonehouse	M	7.2	40	6.4	29.9	78.7	8.4
V-Lake	M	21.1-23.9	22-28	3.2-12.1	19.9-38.7	60.6-74.9	2.8-6.2
Gold Digger Pass	M	16.7	25-26	7.2	13.7	71.9	7.7
Escarpment	W-B	17.8	35	6.4	10.6	68.9	6.8
Sagehen	B	17.2	23	16.1	14.5	77.1	10.8
Heart Mountain	M-W	16.1-20.6	24-28	4.0-12.1	30.3	73.6	5.7

[a]W = Wyoming (*A. wyomingensis*); M = Mountain (*A. vaseyana*); B = Basin (*A. tridentata*).
[b]10hr fuel particles are 0.64 – 2.54 cm in diameter.

were spaced 10 to 20 m apart (no plots were placed at transect endpoints). Odd- or even-numbered plots were randomly selected to be destructively sampled before the fire; remaining plots were destructively sampled after the fire. Fuels were characterized by clipping at ground level or collecting, drying and weighing all standing biomass or surface fuels rooted or located inside the plot frame. Biomass was separated into the following categories in the field: grasses, forbs, live sagebrush, dead sagebrush, shrubs other than sagebrush (hereafter referred to as 'other shrubs'), dead and down woody fuels by size class (1hr, 10hr, 100hr, and 1000hr[1]), and litter. Dead branches and twigs on living sagebrush plants were removed and included in the dead sagebrush category. Grasses, forbs, other shrubs, dead and down woody fuels, and litter were collected, returned to the laboratory, dried for a minimum of 48 hours at 100 °C, and weighed to determine ovendry fuel loading by category on an area basis. Sagebrush was harvested, separated into live and dead biomass, and weighed in the field. One or two complete branches from each field sample were collected in heavy-gauge plastic bags with airtight seals. These subsamples were weighed shortly after collection, returned to the laboratory, dried for a minimum of 48 hours at 100 °C, and weighed to determine live and dead sagebrush moisture content per plot. The following formula was used to adjust sagebrush field weight to ovendry weight:

$$\frac{\text{moisture subsample dry weight}}{\text{moisture subsample wet weight}} \times \text{undried field weight} = \text{ovendry weight} \qquad (1)$$

Pre-fire coverage by category (grass, forbs, sagebrush, other shrubs, litter) was measured using the line intercept method (Canfield 1941) along the full length of all four 76.2-m long layout transects. Grass, forb, sagebrush, and other shrub heights were measured at points every 7.6 m along the full length of all four transects. As most fires were patchy, coverage of the area burned during the fire was measured along parallel transects that were offset 3 m from the original layout to avoid sampling in areas that had been destructively sampled before the fire.

Fuel consumption was calculated by subtracting average post-burn biomass from average pre-burn biomass for sagebrush, and by multiplying average pre-burn biomass by the percentage of the area burned for the other fuel categories. Based on post-fire field observations, we assumed that all non-sagebrush biomass was consumed in areas that were burned.

Day of Burn Fuel Moisture and Weather—Five to 10 grab samples of grass, sagebrush foliage, and standing dead sagebrush in 1hr, 10hr, and 100hr size classes were collected in the interplot area prior to the burning of each experimental area. A single set of fuel moisture samples was collected to represent multiple sites if they were relatively close to one another, and being burned at or around the same time. Samples of approximately 50 to 400 g each were collected in heavy gauge, plastic bags with airtight seals, weighed immediately after collection, returned to the laboratory, ovendried for a minimum of 48 hours at 100 °C, and weighed to determine fuel moisture content on a dry weight basis. Weather conditions during the burning period were measured every 15 to 30 minutes using a sling psychrometer (temperature and relative humidity) and an electronic pocket weather meter (temperature, relative humidity, windspeed 2 m aboveground). Weather conditions were

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[1] 1hr, 10hr, 100hr, and 1000hr timelag fuels are defined as woody material ≤0.64 cm, 0.64-2.54 cm, 2.55-7.62 cm, and >7.62 cm in diameter, respectively.

also measured with a portable weather station (temperature, relative humidity, windspeed 2 m aboveground) logging 15-minute average values at several of the experimental locations. Temperature and relative humidity measurements taken using the sling psychrometer and windspeed measurements taken using the pocket weather meter were used preferentially, as these are the tools available to practitioners on the fireline.

Ignition—Sites were ignited during the course of daily prescribed burning operations. Most experimental sites were ignited by hand with drip torches, although a few areas were aerially ignited using incendiary plastic spheres containing chemicals that undergo a rapid exothermic reaction when mixed (ethylene glycol and potassium permanganate). Experimental areas typically burned in a heading or flanking fire.

Data Analysis

Model Development—Pre-burn coverage and height data, and coverage and height data from the Natural Fuels Photo Series (Ottmar and others 2000) were combined to develop a model to estimate sagebrush loading. Models to predict consumption of biomass were constructed from the suite of fuel characteristics and environmental variables measured before and during the fires. A simple correlation matrix of all variables measured as part of this study identified those that were most promising for constructing the predictive models. Forward and backward stepwise multiple linear regression (Neter and others 1990) was used to identify preliminary models; expert opinion was used to select the final models. Criteria for model selection included parsimony as well as the presence of reasonable physical explanations for a given variable's inclusion in the full model. A generalized linear model (GLM; McCullagh and Nelder 1989) of the binomial family was also developed for predicting the proportion of biomass consumed using the same variables included in the multiple linear regression model. The binomial GLM predicts proportional shrub consumption between [0,1] and therefore avoids predictions of fuel consumption that are either less than zero or greater than the pre-fire fuel amount. The GLM was created in S-plus (Insightful 2002) and programmed into the CONSUME 3.0 software (Prichard and others, in press). Both models' predictive capabilities were compared to independent data sets reported by Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

Results

Tables 3, 4, and 5 summarize pre-fire fuel loading, pre- and post-fire coverage, and fuel consumption, respectively. Total aboveground pre-fire biomass ranged from 5.3 to 22.6 Mg ha^{-1}; sites dominated by mountain big sagebrush tended to have the most aboveground biomass. Pre-fire sagebrush loading ranged from 4.4 to 20.2 Mg ha^{-1} with site coverage of 14 to 67 percent. All, live and dead sagebrush represented from 46 to 92, 25 to 64, and 20 to 56 percent of the total site biomass, respectively; total sagebrush biomass was >80 percent of total biomass for 16 out of 17 sites. Mean sagebrush height ranged from 0.3 to 0.9 m, although many plants were taller than the mean height. Pre-fire herbaceous vegetation and other shrub loading (and coverage) ranged from 0.1 to 0.6 Mg ha^{-1} (5 to 38 percent) and zero to 3.7 Mg ha^{-1} (0 to 19 percent), respectively. Surface fuel loading ranged from 0.3 to 2.7 Mg ha^{-1}.

Table 3—Pre-fire fuel loading for experimental sagebrush burns.

Site name	Loading: Herbaceous vegetation	Live sagebrush	Dead sagebrush	Other shrubs	All vegetation	Surface fuels[a]	All fuels
	Megagrams hectare^{-1}						
Flook Lake 1	0.290	5.521	5.623	0.002	11.435	0.866	12.300
Flook Lake 2	0.109	7.141	5.763	0.000	13.013	1.523	14.536
Flook Lake 3	0.106	6.087	4.214	0.063	10.471	0.714	11.185
Stonehouse	0.614	4.621	1.995	0.580	7.810	2.211	10.021
V-Lake A	0.156	11.113	5.177	0.440	16.885	1.975	18.860
V-Lake 1	0.273	7.919	3.514	0.236	11.942	1.974	13.916
V-Lake 2	0.206	9.207	3.787	0.229	13.430	1.052	14.481
V-Lake 3	0.158	3.239	1.162	0.043	4.602	0.672	5.274
V-Lake 4	0.224	11.062	3.635	0.312	15.233	1.122	16.356
Gold Digger 1	0.543	4.522	3.796	0.191	9.052	0.339	9.391
Gold Digger 2	0.570	6.348	3.396	0.000	10.314	0.511	10.825
Escarpment 1	0.310	3.094	2.652	3.723	9.780	2.709	12.488
Escarpment 2	0.251	7.619	6.626	0.031	14.527	1.562	16.088
Sagehen	0.078	6.081	10.919	0.035	17.112	2.231	19.343
Heart Mtn HM	0.393	12.709	7.492	0.000	20.594	1.994	22.588
Heart Mtn OT	0.411	4.520	2.937	0.409	8.277	0.992	9.269
Heart Mtn SC	0.361	5.531	3.193	0.003	9.088	0.968	10.056

[a]Includes litter and all dead and down woody fuels.

Table 4—Pre- and post-fire coverage for experimental sagebrush burns.

	Pre-fire coverage				Post-fire coverage	
Site name	Herbaceous vegetation	sagebrush	Other shrubs	All vegetation	Area burned	Unburned sagebrush
	percentage					
Flook Lake 1	10.8	35.9	0.2	46.8	32.7	21.5
Flook Lake 2	20.1	38.1	0.0	58.1	38.6	22.6
Flook Lake 3	4.6	29.0	0.2	33.8	36.9	24.6
Stonehouse	20.0	35.7	6.9	62.5	39.8	29.0
V-Lake A	20.0	49.8	6.1	75.8	50.6	21.9
V-Lake 1	12.3	43.9	9.3	65.4	74.6	13.8
V-Lake 2	14.8	43.2	3.7	61.7	53.8	21.3
V-Lake 3	15.1	34.5	1.5	51.2	23.9	20.0
V-Lake 4	23.0	59.5	3.1	85.6	96.9	1.6
Gold Digger 1	22.9	24.5	5.6	53.0	36.4	19.5
Gold Digger 2	23.7	30.3	2.6	56.6	60.4	10.7
Escarpment 1	13.7	13.5	19.1	46.3	75.9	4.3
Escarpment 2	22.0	35.1	0.5	57.6	78.2	7.2
Sagehen	5.0	43.3	5.9	54.2	14.5	33.1
Heart Mtn HM	37.6	66.5	0.3	98.3	98.4	0.6
Heart Mtn OT	34.3	29.7	2.7	66.7	94.8	0.5
Heart Mtn SC	31.5	42.0	0.1	73.6	99.8	0.3

Table 5—Fuel consumed during experimental sagebrush burns.

	Consumption					
Site name	**Herbaceous vegetation**	**Sagebrush**	**Other shrubs**	**All vegetation**	**Surface fuels[a]**	**All fuels**
	Megagrams hectare^{-1} (percentage of pre-fire loading)					
Flook Lake 1	0.097 (33.6)	3.132 (28.1)	0.001 (33.6)	3.230 (28.2)	0.291 (33.6)	3.521 (28.6)
Flook Lake 2	0.042 (38.6)	4.020 (31.2)	—	4.062 (31.2)	0.588 (38.6)	4.650 (32.0)
Flook Lake 3	0.040 (38.0)	4.999 (48.5)	0.024 (38.0)	5.064 (48.4)	0.271 (38.0)	5.335 (47.7)
Stonehouse	0.246 (40.0)	1.992 (30.1)	0.232 (40.0)	2.469 (31.6)	0.885 (40.0)	3.354 (33.5)
V-Lake A	0.082 (53.0)	9.750 (59.9)	0.233 (53.0)	10.065 (59.6)	1.046 (53.0)	11.112 (58.9)
V-Lake 1	0.205 (75.3)	7.571 (66.2)	0.177 (75.3)	7.954 (66.6)	1.486 (75.3)	9.440 (67.8)
V-Lake 2	0.129 (62.4)	9.457 (72.8)	0.143 (62.4)	9.728 (72.4)	0.656 (62.4)	10.384 (71.7)
V-Lake 3	0.050 (31.6)	1.322 (30.0)	0.013 (31.6)	1.385 (30.1)	0.212 (31.6)	1.597 (30.3)
V-Lake 4	0.218 (97.2)	13.648 (92.9)	0.304 (97.2)	14.170 (93.0)	1.091 (97.2)	15.260 (93.3)
Gold Digger 1	0.201 (37.0)	4.660 (56.0)	0.070 (37.0)	4.931 (54.5)	0.125 (37.0)	5.057 (53.8)
Gold Digger 2	0.346 (60.7)	5.655 (58.0)	—	6.001 (58.2)	0.310 (60.7)	6.311 (58.3)
Escarpment 1	0.242 (78.1)	3.116 (54.2)	2.906 (78.1)	6.264 (64.1)	2.114 (78.1)	8.379 (67.1)
Escarpment 2	0.197 (78.6)	12.662 (88.9)	0.024 (78.6)	12.884 (88.7)	1.227 (78.6)	14.111 (87.7)
Sagehen	0.016 (20.5)	2.737 (16.1)	0.007 (20.5)	2.761 (16.1)	0.763 (34.2)	3.524 (18.2)
Heart Mtn HM	0.390 (99.2)	19.916 (98.6)	0.000 (99.2)	20.306 (98.6)	1.978 (99.2)	22.284 (98.7)
Heart Mtn OT	0.411 (100.0)	7.341 (98.4)	0.409 (100.0)	8.161 (98.6)	0.992 (100.0)	9.153 (98.8)
Heart Mtn SC	0.361 (100.0)	8.525 (97.7)	0.003 (100.0)	8.889 (97.8)	0.968 (100.0)	9.857 (98.0)

[a]Includes litter and all dead and down woody fuels.

Total aboveground biomass consumption varied from 1.6 to 22.3 Mg ha^{-1} (18 to 99 percent) among the 17 experimental areas, with 15 to 100 percent of the experimental area burned. Most fires were patchy, although in excess of 90 percent of the area burned for four of the 17 sites. Post-fire coverage of unburned live sagebrush ranged from <1 to 33 percent. Fire spread was most limited in the single spring burn (Sagehen) despite temperature, relative humidity, and windspeed conditions similar to the fall burns (all others). Five out of seven of the study sites where fire burned less than 40 percent of the experimental area had dead 10hr sagebrush fuel moisture values in excess of eight percent. Fuel consumption was highest at sites where dead 10hr fuel moisture was 6.1 percent and less.

Multiple linear regression and generalized linear models are reported in table 6. Percentage of area burned and pre-burn sagebrush loading were strong predictors of sagebrush consumption (fig. 1a). Similarly, percentage of area burned and pre-burn loading of non sagebrush fuels were predictors of non sagebrush consumption (fig. 1b). Pre-burn coverage of herbaceous vegetation, slope, windspeed, 10hr fuel moisture were chosen as variables to predict percentage of area blackened (fig. 2).

Because of our relatively small sample size (n=17), we chose to retain all data points in the model building data set. However, using the generalized linear and multiple linear regression models, predicted total fuel consumption averaged within ±3.1 and ±1.9 percent, respectively, of observed values for four fall prescribed fires, and within ±11.9 and ±12.6 percent, respectively, of observed values for four spring fires measured by Kauffman and Cummings (1989) and Sapsis and Kauffman (1991).

Table 6—Regression equations for sagebrush loading, sagebrush and non sagebrush consumption, and area burned. The generalized linear model (GLM) gives the proportion of the area burned or biomass consumed and follows the form: Y = EXP(y)/(1+EXP(y)); multiply Y_{AB} by 100 to get AB, Y_{C_s} by L_s to get C_s, and YC_n by L_n to get C_n.

Equations	a	b_1	b_2	b_3	R^2
Multiple Linear Regression					
$L_s = a + b_1(P_s) + b_2(H_s)$	–1.364	0.292	1.365		0.85
$AB = a + b_1(P_h) + b_2(FM) + b_3(W \times S)$	30.582	1.951	–4.369	1.737	0.69
$C_s = a + b_1(L_s) + b_2(AB)$	–7.171	0.681	0.111		0.87
$C_n = a + b_1(L_n) + b_2(AB)$	–1.056	0.706	0.016		0.96
Generalized Linear Model					
$y_{AB} = a + b_1(P_h) + b_2(FM) + b_3(W \times S)$	–1.734	0.114	–0.209	0.110	0.75[a]
$y_{C_s} = a + b_1(L_s) + b_2(AB)$	–2.657	0.043	0.047		0.82[a]
$y_{C_n} = a + b_1(L_n) + b_2(AB)$	–2.206	–0.050	0.052		0.89[a]

[a](null deviance - residual deviance) ÷ null deviance; (analogous to R^2 for GLM)
Symbols:
L_s = pre-burn loading of sagebrush, Mg ha^{-1};
L_n = pre-burn loading of non sagebrush biomass, Mg ha^{-1};
P_s = pre-burn coverage of sagebrush;
H_s = pre-burn height of sagebrush, meters;
AB = area burned, percentage of total area;
P_h = pre-burn coverage of herbaceous vegetation, percentage;
FM = day of burn 10hr fuel moisture, percentage by dry weight;
W = day of burn windspeed, km hr^{-1};
S = slope category, <5%=1, 5-15%=2, 16-25%=3, 26-35%=4, >35%=5;
C_s = consumption of sagebrush, Mg ha^{-1};
C_n = consumption of non sagebrush, Mg ha^{-1}.

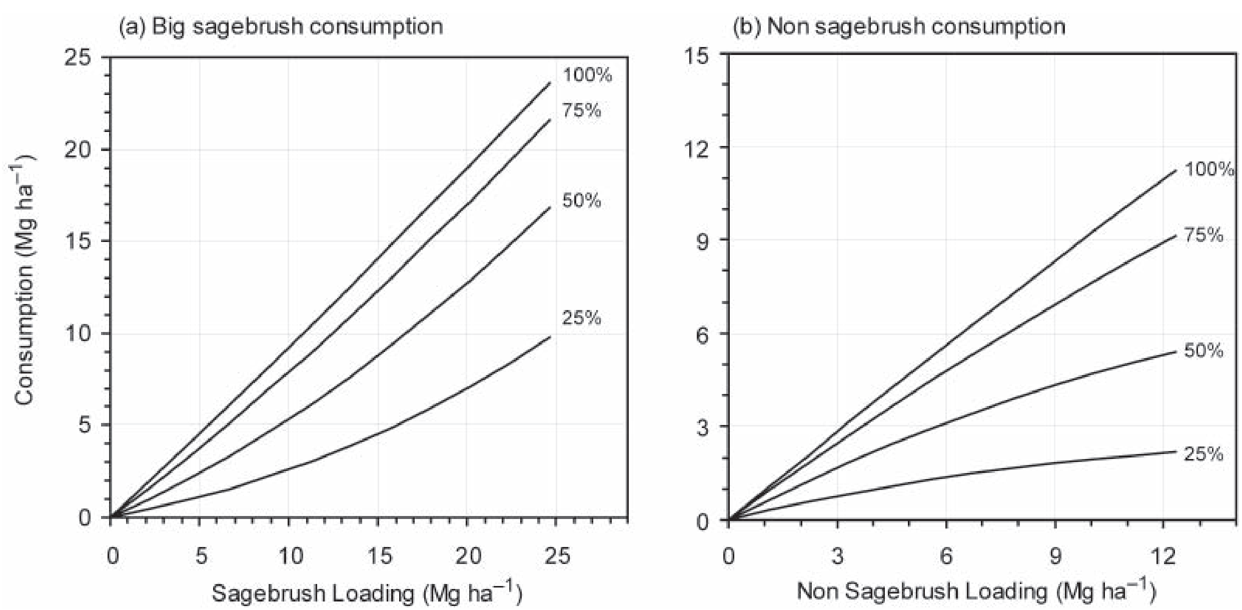

Figure 1—Generalized linear models showing (a) sagebrush and (b) non sagebrush consumption as a function of loading at 25, 50, 75, and 100 percent of area burned (lines).

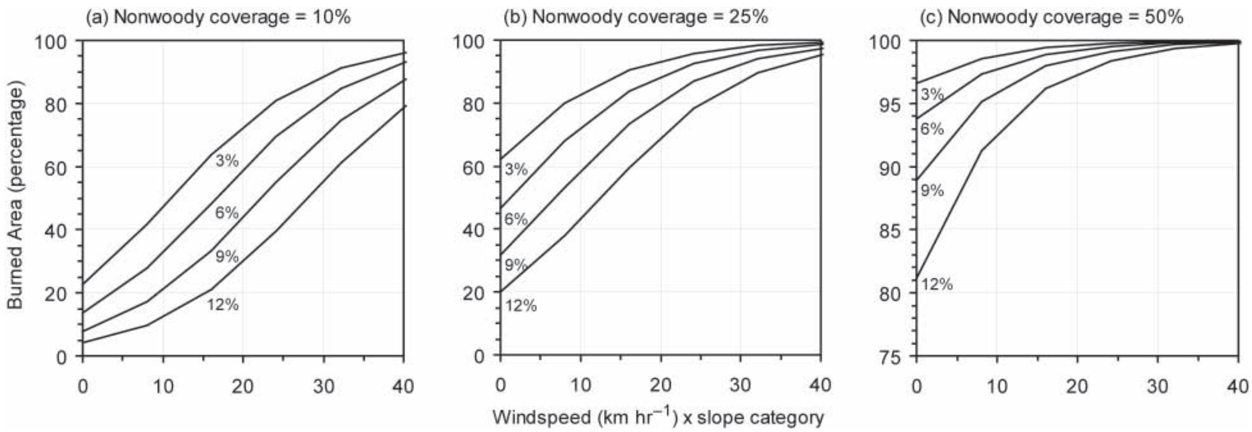

Figure 2—Generalized linear model showing area burned as a function of windspeed × slope category at 3, 6, 9, and 12 percent 10hr fuel moisture content (lines) where herbaceous vegetation coverage is (a) 10 percent, (b) 25 percent, and (c) 50 percent.

Discussion

Two conditions contribute to fuel consumption (and post-fire fuel loading); partially consumed fuel particles, and fuel left in unburned patches. Fuel loading and coverage, fuel moisture, weather (windspeed), and site characteristics (slope) are incorporated in the predictive equations reported here. These equations encapsulate all of the consumption that occurs because of partial burning of fuels and patchy burning of an area. Sites where fire spread was patchier and fire carried through less of the plot area typically experienced lower overall fuel consumption, although a high proportion of the fuels in the burned areas may have consumed.

The final models are relatively simple and incorporate predictor variables for which users are likely to have, or can readily acquire the necessary data. Pre-burn biomass is a key variable for predicting fuel consumption. Biomass can be estimated from locally available inventory data, from fuels assessments using photo guides (for example, Ottmar and others 1998, 2000) or calculated using the equation for estimating sagebrush biomass (L_s) from sagebrush coverage (P_s) and height (H_s; table 6). While managers and planners typically do not have biomass data at their disposal, they often have coverage and height data, or can easily acquire it from a variety of sources. Percentage of area burned is the other key variable for predicting fuel consumption. We include an equation to predict this value (AB), again, based on data that fire managers and planners are likely to have at their disposal and routinely include in prescribed fire burn plans and prescriptions, including windspeed (W), slope (S), and 10hr fuel moisture (FM; table 6).

Users of CONSUME 3.0 can easily predict how environmental, site, and fuel conditions will affect potential percentage of area burned and fuel consumption. This is a tool that can be used for developing burning prescriptions that meet specific management objectives. For example, if one objective of a prescribed fire project is to create a mosaic of burned and unburned vegetation in a specific area for wildlife habitat improvement, users can modify windspeed and fuel moisture inputs until the model yields the desired amount or range of percentage of area burned, thereby defining the prescription parameters. Similarly, a desired percentage of area burned can then be used as an input along with information about site biomass, to predict potential fuel consumption and smoke emissions or other fire effects.

Energy (heat) is required to drive off fuel moisture, to heat fuel particles to pyrolysis and combustion temperatures, and to sustain flaming combustion. Dead 10hr fuel moisture content is an indicator of how readily combustion occurs, how effectively fire spreads from particle to particle and from dead to live fuels, and subsequently how much fuel consumes. Increasing amounts of fuel become available to burn as live and dead fuel moisture decline, however, once fuel moisture has fallen below a critical value, weather and fuel loading appear to become the elements affecting fuel consumption. Where sufficient amounts of fuel are available to burn, prevailing weather conditions (windspeed in our model) appear critical for determining fire spread and fuel consumption. The effects of windspeed can be exacerbated or mitigated to some degree by slope. The multiplier for slope incorporated in the windspeed × slope variable in the equation for predicting area burned is comparable to values suggested by Brown (1982). Poor fuel consumption conditions (elevated fuel moisture, elevated relative humidity, low windspeeds, lack of carrier fuels, etc.) may be mitigated to some degree by an aggressive burning operation. If enough fire can be introduced to the site at once, fire spread can be facilitated, and fuel consumption increased. Use of heli-torches, terra-torches and large numbers of hand igniters can be effective for mass ignition.

Individual plant height, plant to plant spacing, interplant "understory" vegetation amount, overall biomass, and live fuel:dead fuel ratios all may have an effect on how well fire spreads, how much heat and energy are generated, how long flaming and smoldering combustion persist, and therefore how much fuel consumes. Other weather variables, such as temperature, solar insolation (or shading), and relative humidity; and other fuel characteristics, such as live fuel moisture, likely are also important, although they were not useful as predictors of fire spread and fuel consumption given their limited range in our data set. A larger data set with a greater range of values may help identify if or how they are correlated with fuel consumption.

The predictive models reported here are empirical. They represent correlations among variables, and not cause and effect relationships. However, variables were included in the various models only if there was a reasonable physical explanation. For example, cover of herbaceous vegetation was included in the model to predict how much of an area was likely to burn, as the grasses and forbs growing between and under individual sage plants provide a vector for fire to spread from plant to plant. Similarly, windspeed was included as if influences convective heat transfer and flame contact among adjacent shrubs and other fuel particles.

Fuel characterization, fuel moisture, site characterization and onsite weather sampling during the burning experiments allowed us to develop models for predicting fuel consumption that will be useful to fire managers and planners. The ability to predict fuel consumption under varying environmental conditions will facilitate prescription development, burn planning and burn scheduling. The tools available in CONSUME 3.0 will allow resource managers to better assess landscapes for opportunities and hazards, and to develop science-based treatment and mitigation strategies to most effectively manage fuel consumption, fire effects and smoke production.

Acknowledgments

This research was supported by the Joint Fire Science Program and the National Fire Plan. Roger Ottmar, David L. Peterson, and Donald McKenzie reviewed the manuscript.

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The Lick Creek Demonstration — Forest Renewal Through Partial Harvest and Fire

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Abstract*—The Lick Creek Demonstration Site on the Pomeroy Ranger District, Umatilla National Forest, is a Joint Fire Science Program sponsored project to create a demonstration of the effects of fuels management on forest health. The project was initiated in 2001 and involved the integration of two levels of partial harvest with prescribed fire, a burn only treatment and an untreated control treatment. Biomass utilization was incorporated into the burn preparation following harvest. Objectives of the treatments were to improve stand composition and structure, reduce fuel levels, and enhance wildlife habitat. Units were harvested in 2001. Prescribed fire as applied in 2004. Monitoring of fuels and stand attributes was implemented in 2005. Harvest reduced overstory canopy coverage as much as 70%. Understory tree layers remained intact through the harvest but were significantly affected by the prescribed burn. Herbage production increased in areas of moderate fire intensity but showed little response in areas of high fire intensity. Less than 1% mortality was evident in 2005 among leave trees in the treatment units but tree conditions indicate future higher mortality. Fuels reduction was the most uniform in the commercial yarding treatments but was highly varied in the burn only treatments. Contractor revenue profits from the harvest and biomass fuel were modest and dependent on the provision of service contracts by the USFS Pomeroy Ranger District in addition to the release of the products to the contractors for independent sale.*

Introduction

In 2000, the Joint Fire Science Program (JFSP) requested grant proposals for development of fuels management demonstration sites throughout the United States. The sites were to provide the public and research interests opportunity to observe the effects of fuels management involving prescribed fire on wildland ecosystems. The Pomeroy Ranger District of the Umatilla National Forest in southeastern Washington, in conjunction with Washington State University, received a grant from the JSFP to initiate the development of the Lick Creek Demonstration Site in the northern Blue Mountains of southeastern Washington. The project period was originally set for a three-year period from FY 2001 through FY 2003. The last of the project components was completed in 2005.

The overall goal of the Lick Creek project was to develop a demonstration of the application and effects of selective, partial harvest on mid-succession forest stands in combination with prescribed fire to enhance forest condition, amenities, and reduce wildfire hazard. Frequent and timely monitoring of the demonstration site would provide documentation to substantiate, clarify, and

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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explain anticipated ecological relationships and treatment effects throughout the demonstration site. The demonstration was to provide opportunity for general public examination and for the Pomeroy Ranger District to begin a long-term monitoring study of a fuels management strategy applied throughout the District.

Efforts to achieve public understanding and support of forest practices to rectify forest health issues is a priority in the Pomeroy Ranger District because of the sensitivity of the forest landscapes and the multiple interests in the public lands of the District. Successful implementation of any forest practice in the District is predicated on public support. The Lick Creek Demonstration is intended to show how forest practices can enhance forest landscapes for tree growth, wildlife habitat, and reduction of wildfire hazard.

The purpose of this proceedings paper is to provide a synopsis of the character and development of the demonstration site.

Objectives

The specific objectives of the project were (1) to implement four levels of viewable silvicultural and fuels management stand treatment on the Lick Creek site in a replicated manner, (2) prepare documentation of the treatments and treatment effects for public review, (3) initiate a long-term monitoring study of the site to document treatment effects to include response of leave trees, and (4) to assess the economic viability of small diameter timber harvest as a means of accomplishing silvicultural and fuels management objectives. The treatments would represent prescription strategies currently employed by District staff to address management of stand structure, species composition, and fuel conditions in mid-successional forest stands.

Site Location and Pretreatment Vegetation Character

The Lick Creek Demonstration Site lies within the Blue Mountains Physiographic Province of southeastern Washington (Fig. 1). The site is located in the eastern portion of the Pomeroy Ranger District of the Umatilla National Forest and centered at longitude 117.4833°, latitude 46.2333°. The general terrain of the area is a deeply dissected plateau to the south and east of the Snake River Canyon that traverses through southeastern Washington. The specific site terrain is a steep, dissected canyon slope between 4100-5100 ft elevation with aspects spanning northwest to northeast. Slopes average 50 to 60% across the entire site. The area is within the rain shadow cast by the central Blue Mountains ridge, thus is within a dry subhumid climate. Total annual precipitation is ±35 inches with effective moisture varying according to topographic and soil conditions.

The vegetation of the site is a mosaic of forest stands interspersed with grassland sites on side-ridges and shallow soils (Fig. 2). Generally, two distinct zones of vegetation are distinguishable across the site. An upper canyon wall zone of the Douglas-fir/snowberry (*Pseudotsuga menziesii/Symphoricarpos albus*) and Douglas-fir/ninebark (*Pseudotsuga menziesii/Physocarpus malvaceus*) plant associations covers from ¼ to ⅓ of the site slope surface (Johnson and Clausnitzer 1992). The width of this zone is dependent on

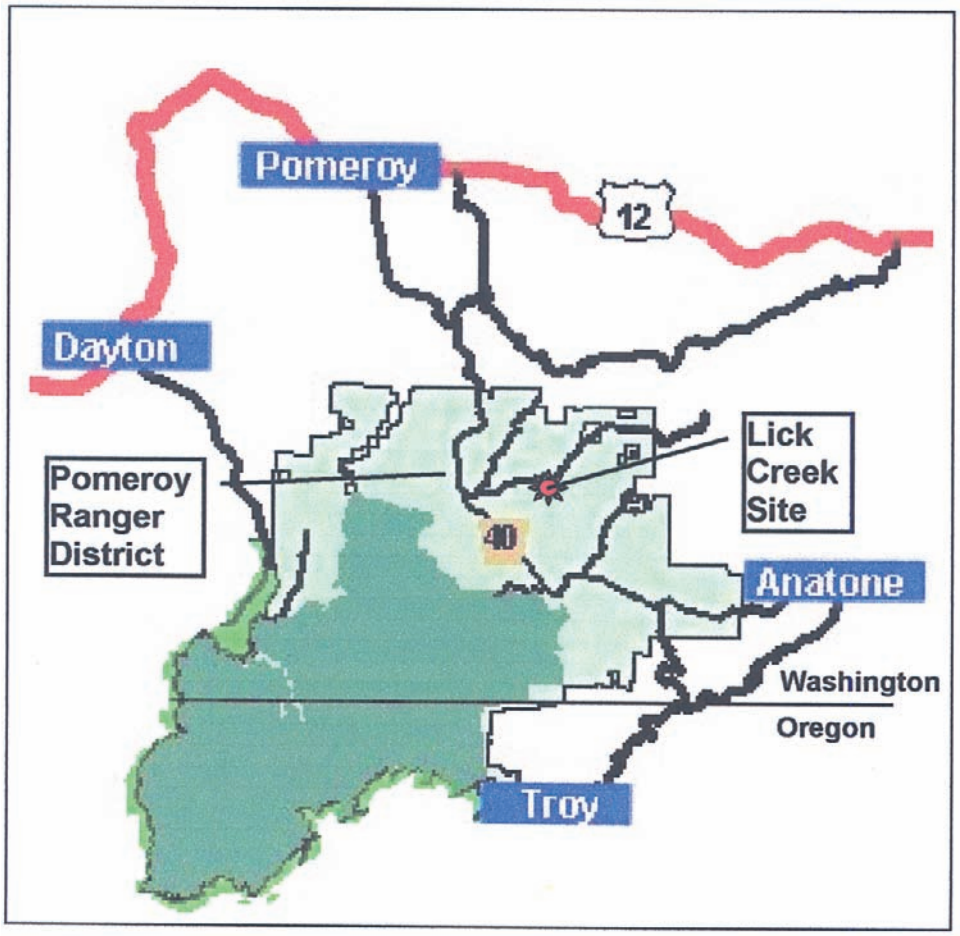

Figure 1—Location of the Lick Creek Demonstration Site in the Pomeroy Ranger District, Umatilla National Forest, southeastern Washington.

Figure 2—Pre-harvest photograph of the Lick Creek Demonstration Site looking east along the face of the site in 2000.

slope surface configuration with the narrowest portions associated with concave surfaces and the broadest portions associated with convex surfaces. The lower ⅔ to ¾ of the canyon wall is dominated by the grand fir/twinflower (*Abies grandis/ Linnaea borealis*) plant association. Ponderosa pine (*Pinus ponderosa*) and western larch (*Larix occidentalis*) are the seral conifer tree species throughout the site.

The existing vegetation over the site prior to treatment generally reflected a mid-successional state (Fig. 3). Most of the area supported a sparse component of 100+ year-old trees of ponderosa pine, western larch, and Douglas-fir that formed an upper overstory layer with canopy cover ranging from 5-15%. Tree heights were 90 ft with average d.b.h. ranging from 20 to 32 inches. The majority of the leave trees in the harvest treatments were in this particular cohort. The bulk of the forest canopy was a deep mid-story tree layer composed predominantly of Douglas-fir (67%) and grand fir (24%) with sparse ponderosa pine (6%) and western larch (3%). Average height of trees within this layer ranged from 45 to 50 ft and averaged 9 to 11 inches d.b.h. Most of the merchantable timber came from this mid-story layer. A distinct third cohart of smaller trees with 3 to 6 inches d.b.h. occurred in the lower portion of the layer between 20 and 40 ft. These smaller trees composed 53% of the total tree density of the layer, and in combination with an understory layer of junvenile trees less than 3 inches d.b.h. and under 10 ft in height, formed the greatest barrier to light penetration to the ground surface.

Figure 3—Example of pre-harvest stand conditions in the Lick Creek Demonstration Site.

History of the Site

The Problem

The Lick Creek site was selectively harvested through several entries during the 1960's and early 1970's for large diameter sawlogs by means of a skyline system. No additional harvest or fuels treatment have occurred on the site since that time. There is no evidence of wildfire in the immediate drainage area of the site in the past 100+ years so the site represents a fire exclusion location. Stand development since the 1960's progressed to mid-successional stages of overstocked, nearly closed stands of small diameter, shade-tolerant Douglas-fir and grand fir. Competition from these shade-tolerant species reduced the abundance of shade-intolerant ponderosa pine and western larch. In addition, surface and ladder fuels were accumulating to the point of creating a severe surface and crown wildfire hazard (Fujishin 1998).

The drainage lies directly above a major Rocky Mountain elk winter range in the Asotin Creek watershed adjacent to the Snake River and is a significant part of a spring elk calving area and summer range for elk herds that utilize the Asotin Creek winter range. Stand closure of forests within the Lick Creek drainage was reducing the diversity and abundance of the understory and detrimentally affecting the quality of elk and wildlife habitat (Lorentz 1997).

The Solution

The prescription for stand management on the Lick Creek site revolved around the principal objectives of opening stands, shifting the balance of species composition to favor ponderosa pine and western larch, and reducing fuel loading (Bott 1998). Selective harvest and thinning from below combined with prescribed fire was prescribed to accomplish the objectives The efficacy of these practices was considered to be well established (Agee 1996, Applegate and others 1997, Graham and others 1999, Williams and others 1993). Multiple entries over time with prescribed fire after harvest was thought necessary in order to ultimately achieve the objectives of the prescription (Martin 1998). The treatment effects of the combined practices were also expected to enhance wildlife habitat in general, and more specifically, the elk habitat of the site that is a central concern to several local public interest groups. Untreated wildlife leave units were integrated into the treatment design to serve a wildlife cover and travel corridors. Non-hazardous snags where left standing and a buffer zone was designated along the bottom of the Lick Creek drainage to protect watershed values and provide additional undisturbed wildlife cover.

Two primary concerns were identified in the development of the Lick Creek Demonstration prescription and are reflected as inclusions in the project objectives. These were (1) the effects of fire on leave trees and (2) the economic viability of small diameter timber harvest.

The mortality of large leave trees from prescribed fire across the Lick Creek site was a major concern (Martin 1998). Several recent studies have confirmed that mortality of trees from a prescribed fire increases as the depth of the duff layer around the base of the tree and the diameter of tree bole increases (Ryan and Frandsen 1995, Hille and Stephens 2005, Stephens and Finney 2002, Thies and others 2006). Documentation of the leave tree post-burn responses was designated as a priority element in the monitoring of the demonstration site.

The majority of the merchantable sawlog trees on the Lick Creek site grade as small diameter timber (5-9 inches d.b.h.), raising questions about the profitability of such a harvest to logging contractors and their interest in undertaking this kind of harvest option. Selective harvest and thinning of small diameter stands is being increasingly considered in the Interior Northwest as a means of reducing wildfire hazard, redistributing tree growth, and re-directing stand development (Wagner and others 1997, Baumgartner and others 2002). But questions remain about the financial viability of such harvest from the standpoint of product marketability and revenue and harvest costs (Johnson 1997, Wagner and others 1997). Harvest costs are affected by tree size and utilization with harvest costs inversely proportional to tree size—small-diameter trees result in small piece sizes with low volumes and are more costly to handle (Stokes and Klepac 1997). Johnson (1997) stated that an economical harvest of small trees is difficult to attain for two reasons—the cost per unit of volume to move the material increases dramatically as diameter of the volume decreases, and the value of the unit volume decreases as piece size decreases. Harvest costs increase with reduced road accessibility and conditions, less steeper and more complex terrain, smaller trees and higher density stands, limited opportunity to use less expensive mechanical yarding, and greater hauling distance. Ultimately, the availability of stable markets for multiple wood products from the harvest will dictate net profit from the harvest (Johnson 1997, Stokes and Klepec 1997). Documentation and evaluation of harvest and fuels treatment costs and product revenues to assess economic viability of the silvicultural and fuels management strategy was included as a primary objective of the project.

Methods

Treatment Design and Installation

The site was divided into three treatment units with wildlife habitat units left between some of the treatment units within the site boundaries (Fig. 4). A 150 ft buffer zone was maintained of at the bottom of the slope between the treatment units and Lick Creek. Each unit was divided into four subunits to replicate the treatment. The following four treatments were installed in each unit—two levels of harvest, a control, and a burn only treatment (Table 1). The replication subunits range in size from 6 to 17 acres, the size being dictated by uniformity of pre-harvest conditions and the facilitation of harvest and prescribed burning operations.

Treatment Schedule

Treatment planning, the timber cruise, and pre-logging stand inventory were conducted in 2000 and 2001. Harvest of the site was completed during the winter of 2001-2002. Preburn inventory was conducted in 2002-2003. Slash piles were removed from the site by means of chipping and selected pile burns in the fall of 2003. The prescribed burn of the treatment units was conducted in September and October 2004. The first year of post-burn monitoring was completed in the summer and fall of 2005.

Figure 4—Aerial view of treatments at mid-elevation within the Lick Creek Demonstration Site showing fuels yarding (a, c) on a wildlife leave unit (b) above Lick Creek (d). Permanent monitoring plots are distributed near the center of each unit from top to bottom.

Table 1—Replicate (3) treatments implemented on the Lick Creek Demonstration Site, Blue Mountains, Pomeroy Ranger District, Umatilla National Forest.

Treatment	Description
Control	No harvest, no prescribed burn - stand left in original state.
Prescribed burn only	No harvest, prescribed burn of stand in its original state.
Commercial yarding - prescribed burn	All trees unmarked as leave trees that were 6 inches d.b.h. or greater that had a minimum 8 foot long piece to a 3 inch top were cut and removed to the landings, whole tree yarding was not required but generally done to improve efficiency of operation; post-harvest prescribed burn was applied. Objective of treatment was to leave a greater quanity of fuel in place on the units.
Fuels yarding - prescribed burn	All trees unmarked as leave trees that were 3 inches d.b.h. or greater that had a minimum 8 foot long piece to a 3 inch top were cut and removed to the landings; whole tree yarding was required; down material meeting the cutting specifications for commercial yarding (6+ inches d.b.h.) were cut and yarded; post-harvest prescribed burn was applied. Objective of treatment was to minimize fuel accumulations on the units.

Harvest

A total of 85 acres of the site were harvested in a 40-day period, commencing in mid December 2001. Winter logging in the Blue Mountains is at risk of being stopped at any time because of severe storm conditions and snow accumulation. Fortunately, severe weather conditions never developed until after the harvest had been completed in late January, 2002, allowing harvest to proceed with minimal snow cover.

Yarding was conducted for 74% of the harvest area with gravity feed skyline system utilizing a skyline yarder and a motorized support carriage. Ground-based yarding with a tracked skidder was conducted over the remaining 26% of the harvest area. Whole tree yarding was required as part of the treatment prescription to minimize fuel loading on the site.

A stationary, pull-through, motorized, radio-controlled delimber was used to process the whole trees that were yarded to the landing. After delimbing, the trees were sorted according to merchantable (sawlog) or unmerchantable (tonwood, fiber wood), cut to specified lengths, and piled into decks for loading. One-hundred loads were hauled from the site—51 sawlog loads, 33 tonwood loads, and 16 fiber loads.

The total yield of the harvest averaged 27.14 tons per acre for the 85-acre harvest area of the Lick Creek Site. Yield was portioned as follows - sawlog (1171 t, ~ 194 gross mbf), tonwood (761 t), fiber wood (374 t).

Chipping for Biomass Fuel

Whole tree removal from the harvest site meant that large slash piles accumulated at the landings at the top of each unit. These piles were large, ranging from 1.41 tons/acre to 4.67 tons/acre and were considered a hazard to the conduct of the prescribed burn because of their location and potential to initiate escape fire. Removal of the piles proceeded in the late fall of 2003 through a service contract to a local contractor to chip the slash for sale as biomass fuel. Because of limited road access, the chipper was stationed at a site that provided access to haul trucks. Slash from the piles was transported by trucks to the chipper for processing. Slippage of some slash piles down the steep slopes of the site made some of the slash inaccessible to loaders. This material was pile burned after the slash chipping had been completed. A total of 33 piles yielded 482.44 dry t of chipped wood for sale as biomass fuel.

Prescribed Burn

The burn was conducted from in a 5-day period from September 30-October 4, 2004. The burn prescription targeted reduction of fuels and understory fire-intolerant and shade-tolerant tree species on the site as the principal objectives. The principal Ignition pattern was strip head-fire over most of the site with backing fire used through heavy fuel accumulations and down very steep slopes. Flame-lengths were to be kept under 4 ft to limit fire intensity. Seven burn units are designated, combining treatment units to facilitate control and consistency in the character of the burn. Ignitions started at highest points of the site and progressed down-slope and to lower elevations within the site over the burn period. Surface fuels were typically a mosaic of grass and woody fuel patches, intermixed with live shrub and tree materials. The small live tree component was especially significant in the higher elevation units. The live shrub component was most significant in the lower elevation and environmentally warmer units. Woody fuel loading varies across the Lick Creek site according to treatment. The highest woody fuel loadings were in the commercial yarding units harvest with fuelbeds in the Fire Behaviror Fuel Model 10 and 11 categories depending on the mix of herbaceous and live fuels and amount of overstory.

At the beginning of the burn period, temperatures (55-62 ° F) and relative humidity (38-44%) were near the lower limit of the burn prescription providing an advantage in keeping fire intensity low while still accomplishing the prescription objectives. Backing fires were ineffective under these conditions, so strip head-fire ignition was the principal means of ignition. Temperatures climbed into the low 70's and humidity dropped into the high 20's by the end of the 5-day burn period and back-firing became the principal means of fire spread. Winds occurred in the typical fall convective wind pattern and were not a factor at anytime during the burn period.

Initial estimates indicate that an average reduction of 80% was achieved in the woody fuel and ground fuel loading over the Lick Creek site.

Monitoring System

Five permanent plots are distributed within each treatment unit near the center from the top to the bottom of the unit (Fig. 4). The plots were inventoried pre- and post-burn. Pre-harvest plots were sampled in the same locality as the permanent plots but do not represent the exact location of the permanent plots. The plot is circular with a diameter of 50 m. The center of the plot is the photo point from which a radial sequence of photos is taken of the entire perimeter of the plot. Two 25-m transects from the plot center along the contour of the slope are used to collect point and microplot data for the following overstory and understory attributes: fuel loading, species composition and canopy coverage, tree density by diameter class and species, stand canopy stratification, height, and composition, and soil surface coverage and composition. A series of digital photos are taken of 1-m^2 microplots along each transect. The data is being entered and summarized in FIREMON (2006).

Summary of Preliminary Findings

Stand structure was significantly altered by harvest with reductions of overstory canopy coverage by as much as 70% in some treatments. The majority of the dominant mid-story canopy layer was eliminated by the harvest. However, a substantial amount of the understory tree layer of short and less than 3 inches d.b.h. remained intact after harvest. The prescribed burn damaged the majority of the understory layer but the full extent of the mortality was not fully expressed in the 2005 inventory. Herbage production increased dramatically in areas of moderate fire intensity but did not show a similar response in areas of high fire intensity. Less than 1% mortality was evident in 2005 in the leave tree populations across all of the harvest treatment units. A low degree of mortality is evident in the overstory of the burn only treatments but the condition of many of the trees suggest that greater levels of mortality are to be expected in coming years. Fuels reduction varied greatly among treatment replications with the most uniformity reduction in the commercial yarding treatments and the greatest variation in the burn only treatments. Contractor revenue profits from the harvest and biomass fuel were modest and dependent on the provision of service contracts by the USFS Pomeroy Ranger District in addition to the release of the products to the contractors for independent sale.

Project Sponsors

Funding to initiate the development of the Lick Creek Demonstration Site was provided by the Joint Fire Science Program, USFS Umatilla National Forest, Washington State University, Rocky Mountain Elk Foundation, Blue Mountain Elk Initiative, and Guy Bennett Lumber Company.

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Response of Fuelbed Characteristics to Restoration Treatments in Piñon-Juniper-Encroached Shrublands on the Shivwits Plateau, Arizona

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***Abstract**—The recent encroachment of piñon (Pinus edulis) and juniper trees (Juniperus osteosperma) into historically shrub- and grass-dominated landscapes has caused major changes in ecosystem structure and function, including dramatic changes in fuel structure and fire regimes. Such encroachment is currently occurring on thousands of acres on the Shivwits Plateau in northwestern Arizona and land managers are seeking effective techniques to restore these areas to pre-invasion conditions and reduce the threat of high severity crown fires. A study was established on the Shivwits Plateau to test the effectiveness of three thinning techniques for reducing the density of recently established piñon and juniper trees and to assess changes to the fuelbed structure. The thinning treatments were: (1) cut and leave; (2) cut, buck and scatter; and (3) herbicide. The line-point intercept method was used to characterize changes in the fuelbed structure. Belt transects were used to quantify tree density. Responses of the shrubs and suffrutescent plants (herein collectively referred to as 'shrubs') are reported. Generally, there was more live shrub cover in the treatment units versus the control units. In addition, the mechanical treatments added woody fuels to the initially sparse sites. These two structural changes are expected to help to carry surface fire through the treated areas.*

Introduction

Tausch and others (1981) found evidence of expansion both in tree densities and geographical distribution of piñon-juniper (*Pinus* spp.- *Juniperus* spp.) woodlands over the last 175 years. The type conversion from shrubland to woodland leads to a decrease in understory plants such as shrubs, suffrutescent plants, bunchgrasses, and herbaceous species as the overstory canopy closes. This woodland expansion is a major concern for land managers due to the resulting loss of wildlife habitat associated with sagebrush steppe, decreased species diversity, loss of soil seedbanks, decreased aquifer recharge, increased soil erosion, and increased intensity of wildfires (Koniak and Everett 1982, Wilcox and Breshears 1994, Davenport and others 1998, West 1999, Miller and others 2000).

The range expansion of piñon and juniper is associated with increased fire return intervals due in large part to fire suppression and the reduction of surface fuels caused by the introduction of livestock grazing by European settlers (Miller and Rose 1999). In an attempt to return stands to pre settlement

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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conditions dominated by sagebrush steppe and shorter fire return intervals and to improve livestock forage and wildlife habitat, land managers have attempted to reintroduce fire and manipulate fuel conditions using mechanical, chemical, and seeding treatments.

Where woodlands are dense, shading inhibits herbaceous development, limiting the surface fuels necessary to support a low intensity surface fire. In this situation, fire does not propagate easily except under extreme fire weather conditions which typically results in undesirable intense overstory crown fires (Miller and others 2000). Where woodlands are more open and surface fuels still exist, managers can create low to moderate intensity surface fires with sporadic torching of larger trees, but even in these conditions fire can be difficult to propagate. For these reasons, sites have often been prepared before burning, typically by chaining landscapes to uproot trees and provide opportunities for early successional forbs, grasses, and shrubs to re-establish. However, chaining results in removal of both pre and post settlement trees and creates significant soil disturbance, which is not compatible with the management goals of many land management agencies, especially the National Park Service. As a result, mechanical thinning or chemical treatment of post settlement trees is becoming more common since such treatments create uneven-aged woodland stands which better represent historic conditions, provide better wildlife habitat, and do not create significant soil disturbance. Minimizing soil disturbance is especially important in areas where cultural resources may otherwise be at risk. By reducing overstory canopy cover, understory plants will have a chance to grow, increase cover, and create fine fuels that will support a lower intensity surface fire through the area.

To this end, this study on the Shivwits Plateau in northwestern Arizona was established to compare the effectiveness of two types of mechanical and one type of chemical thinning treatments as well as their costs for:

1. reducing densities of post-settlement piñon (*Pinus edulis*) and juniper (*Juniperus osteosperma*) trees;
2. increasing cover and seedbank density of native annual plants and perennial grasses;
3. increasing plant species diversity;
4. minimizing cover and seedbank density of invasive alien plants; and
5. creating a fuelbed that promotes the re-establishment of historic low to moderate intensity surface fires.

This report examines the first and fifth objectives.

Materials and Methods

Study Site

The study site (~405 ha/1,000 ac) is located within a single watershed on the northern rim of the Grand Canyon on the western Colorado plateau. The administrative boundaries of the project are within the National Park Service (NPS) portion of the Grand Canyon–Parashant National Monument, an area jointly managed with the Bureau of Land Management (BLM), Arizona Strip Field Office. The site is at 1,890 m (6,200 ft), with slopes from two to 15 percent. Mean annual precipitation is 33 to 43 cm (13 to 17 inches), bimodally distributed in summer monsoons from late June to early September, and winter frontal systems from November through March. Mean annual soil temperature is 9 to 13 °C (49 to 56 °F), and the frost-free period is 135 to 150 days.

European settlement of the area occurred in the mid 1800s and included extensive cattle grazing until the late 1980s when grazing was terminated on the site. Historic evidence of prolific cattle grazing remains in the study region including corrals, drift fences and earthen water tanks. Some of this region was chained in the late 1950s to early 1960s by a local rancher in an effort to improve range forage conditions. The area was "withdrawn land" by the Bureau of Reclamation in the 1930s and was transferred to the National Park Service in 1964.

Fire suppression has likely occurred concomitantly with European settlement. Organized fire fighting responsibilities have been shared by the BLM and NPS since the 1950s. A Prescribed Natural Fire Plan was implemented for the area in 1998 and fires are currently being managed as "wildland fire use" which is synonymous with allowing lightning-ignited fires to burn under certain management approved conditions.

Lightning storms commonly occur in the area throughout the monsoon season. There is evidence that moderately-sized fires burned historically in the area [up to 40 ha (100 ac)], but in the last 25 years smaller fires less than one hectare and single tree fires were more common. In an attempt to reintroduce low- to moderate-intensity surface fires, the NPS has implemented over 2,400 ha (6,000 ac) of prescribed fires in the area since the program started in 1994. Prescribed burn objectives were only met on approximately 600 ha (1,500 ac), which included the majority of the formerly chained areas. Most of the untreated/unchained areas did not carry fire with the use of a helitorch except under extreme fire weather conditions. Monitoring has shown that plant diversity has generally increased in burned areas; however, native grasses have only increased in small isolated areas, possibly due to a depleted soil seedbank. In order to help meet resource objectives, assessment of alternative treatments besides simply attempting to reintroduce fire appears to be necessary.

Current land management goals at this site are to preserve, restore, and maintain naturally functioning ecosystems and cultural resources. Other goals are to maximize native plant and animal diversity within the natural range of variation. Primary management concerns are related to soil erosion potential, and it is believed that current site conditions will not adequately sustain soil resources in the event of a high severity crown fire. The site is ideal to conduct restoration activities since cattle grazing has been excluded; no elk exist in the area; and deer, small mammals, and insects are the only remaining grazers. The lack of excessive grazing pressure should facilitate the re-establishment of native grasses, forbs, shrubs, and suffrutescent plants. The NPS Lake Mead Exotic Plant Management Team is available to control invasive plants in the event that they begin to appear in the study area.

Study Design

Thirty-two, 8.1 ha (20 ac) units were laid out and each unit was randomly assigned to be left untreated (control) or to have one of three thinning treatments applied. The treatments consisted of two types of mechanical and one chemical thinning treatment. The goal of all thinning treatments was an 80 percent reduction of post settlement trees. Land managers estimated that this level of tree reduction would open the stands enough to provide favorable establishment and growing conditions for perennial grasses and other vegetation, provide fuels to support a low to moderate intensity surface fire, and provide enough ground cover to reduce the potential for soil erosion. Post settlement trees were defined as those ranging in age from 1 to 175 years old (Class 1 to 3 trees; Bradshaw and Reveal 1943). None of the oldest trees (Class 4) were to be cut or sprayed. This classification of piñon and juniper trees was based on general guidelines such as diameter at stump height or breast height, tree height, and growth form.

The mechanical thinning options consisted of either a cut-leave or a cut-buck-scatter scenario. Trees were not marked prior to cutting, but rather the thinning crews were briefed on what factors constitute a post settlement tree and were given the direction to cut four post settlement trees and leave the fifth post settlement tree they encountered uncut. In this manner, an 80 percent reduction in tree density of each species should occur. In the cut-leave treatment, trees were cut with either loping shears or chainsaws and left where they fell. The cutting methods were the same in the cut-buck-scatter treatment, but the larger trees were then limbed to manageable lengths and the material scattered across the site, avoiding placing slash under the drip-lines of uncut trees. Approximately 20 percent of the mechanical thinning was accomplished by a National Park Service fire crew with the remainder completed by contract crews.

The herbicide thinning treatment used 15 percent Tordon 22K (DOW) that was batch mixed at 11.4 liters (three gallons) increments directly into SP-3 backpack sprayers at a rate of 709.8 milliliters (24 fluid ounces) of chemical to 3.78 liters (1 gallon) of water with 29.6 milliliters (one fluid ounce) of Blaze-on blue dye and one milliliter (0.03 fluid ounce) of kinetic nonionic surfactant. Since this method is a spot treatment, the rate applied per unit area is dependent upon the target tree density. For this treatment, the average application was 1.84 liters per hectare (25.15 ounces per acre) of Tordon 22K. The spray mixture was applied as a solid stream to the base of the tree at the soil interface (Williamson and Parker 1996). A 4.6 m (15 ft) buffer was left around each pre settlement tree encountered due to concerns for chemical drift in the soil. Other trees, regardless of their classification that fell in this zone, were not treated. It was estimated that these trees would constitute the 20 percent residual leave tree target; therefore, every post-settlement tree located outside the buffer zones was treated with herbicide. Herbicide application was performed by the Exotic Plant Management Team from Lake Mead Recreation Area.

No cutting or herbicide application was implemented in the control units. All treatments were completed prior to the start of our sampling.

Sampling

In each treatment unit, three plots were randomly located. At each plot, we laid out a 50 m (164 ft) line transect, which ran down the center of a 6x50 m (20x164 ft) belt transect. Vegetation data was collected along the 50 m line transect using the line-point intercept method (Lutes and others 2006) and tree data was collected within the belt transect. Plots were established in 2004 after completion of the thinning treatments and measured in late August/early September of 2004 and 2005.

Trees—Since cutting took place before plot establishment, we could not note the features such as tree height, growth form, or diameter at breast height or stump height of cut trees that Bradshaw and Reveal (1943) used for their classification system and that the thinning crew used when making the decision of which trees to cut. We used data from Miller and others (1981) to develop relationships between diameter at stump height, diameter at breast height, and groundline diameter (g.l.d.) and we assigned each of the trees/stumps in our data set a Class based solely on g.l.d. (table 1). Trees that were treated with herbicide were either labeled as dead or "sick." If, by appearance, they were unhealthy and expected to die in the near future they were deemed sick.

All trees/stumps located within the 6x50 m belt transect that had a g.l.d. of 7.6 cm (3 inches) or greater were recorded along with the species. This left the smallest Class 1 trees unmeasured, leading to the assumption that the Class 1 trees measured and those that were thinned were representative of smaller trees as well. Although other tree attributes were measured, density and percent reduction will be the only tree data presented in this paper.

Surface fuels—Along the 50 m (164 ft) line transect that bisected the belt transect, we sampled fuel groups by category (fine slash, coarse slash, fine woody debris, coarse woody debris, grass, live shrubs, dead shrubs, trees by species, forbs, and bare soil) using the line-point intercept sampling methods. The height of the tallest interception by fuel group was recorded at 0.5 m (1.6 ft) intervals. Since we did not sample prior to treatment establishment, the distinction between 'slash' and 'debris' was made in an attempt to determine woody fuel presence prior to and following treatment application. True shrubs such as scrub oak (*Quercus turbinella*), cliffrose (*Purshia mexicana*) and sagebrush (*Artemisia tridentate*) as well as suffrutescent plants such as broom snakeweed (*Gutierrezia sarothrae*) are combined in our 'live shrub' and 'dead shrub' categories. The fuel that will contribute to fire spread in this system is made up of plants such as shrubs and grasses as much as it is woody fuels; therefore, much of our focus was spent on assessing continuity of plant growth. Live shrub cover is the only surface fuel component that will be presented in this paper.

Data Analysis

For the line-point intercept method of cover determination, percent cover is calculated by summing the number of hits per line and dividing by 100. In our situation, we had 100 points per line, so it was a matter of simply summing the number of hits. For example, if forbs were encountered at 13 of the 100 points along a line, this computes to a 13 percent cover for forbs.

Table 1—Groundline diameter classes used to distinguish tree class for juniper and piñon trees. Breakpoint diameters based on Bradshaw and Reveal (1943) and Miller and others (1981).

	Diameter at groundline			
	Juniper		Piñon	
	- - cm - -	*- - in - -*	*- - cm - -*	*- - in - -*
Class 1	<10.2	<4	<8.9	<3.5
Class 2	10.2-24.1	4-9.5	8.9-21.8	3.5-8.6
Class 3	24.2-35.8	9.6-14.1	21.9-31.8	8.7-12.5
Class 4	>35.8	>14.1	>31.8	>12.5

We used general linear mixed models (GLMM) to examine differences in live shrub cover and pre treatment tree density between treatments (SAS Institute v.9.1, Littell and others 1996). All mixed models used a completely randomized design with subsampling and the Tukey-Kramer method to detect treatment differences.

Results

Live Tree Density

Prior to treatment, there were no statistical differences in density of either juniper ($F_{3,26}$ = 0.28; p = 0.84) or piñon ($F_{3,26}$ = 0.65; p = 0.59) between treatment types. Across all treatment units, there was an average of 508 juniper trees per hectare (t.p.h.) [206 trees per acre (t.p.a.)] and an average of 134 piñon t.p.h. (54 t.p.a.).

The cut-leave treatment reduced post settlement juniper trees by 83 percent and piñon by 77 percent. Of the pre settlement trees identified by our definition, 11 percent of the juniper and no piñon trees were cut (table 2).

Ninety-two percent of the post settlement juniper trees were cut in the cut-buck-scatter treatment, with 100 percent Class 1 juniper trees cut and 99 percent of Class 2 trees cut. Seven percent of the pre settlement juniper trees were also cut. Of the post settlement piñon trees identified, 64 percent were cut. None of the pre settlement piñon trees were cut (table 2).

Of the herbicide-treated juniper trees, 50 percent of the post settlement trees were dead three years after application with another18 percent designated as sick. Providing these trees die as a result of the treatment, the juniper trees will be reduced by 68 percent. Thirty-two percent of the pre settlement juniper trees were killed and another 11 percent were sick. Seventy percent of the post settlement piñon trees were dead in 2005 and seven percent were sick. Combined, this will result in a 77 percent reduction in post settlement piñon trees. There was only one pre settlement piñon tree identified and it was killed (table 2).

Table 2—Percent reductions of trees by treatment, species, and tree class. For the herbicide treatment, percent reductions based on dead as well as dead plus sick are included.

Treatment	Species	Class 1		Class 2		Class 3		Total Post Settlement		Class 4 (Pre Settlement)	
		Percent reduction									
Cut-Leave	juniper	93		86		69		83		11	
	piñon	82		84		25		77		0	
Cut-Buck-Scatter	juniper	100		99		69		92		7	
	piñon	89		65		18		64		0	
		dead	dead + sick	dead	dead + sick	dead	dead + sick	dead	dead + sick	dead	dead + sick
		Percent reduction									
Herbicide	juniper	53	73	49	64	49	75	50	68	32	43
	piñon	95	95	69	77	27	45	70	77	100	na

Live Shrub Cover

There were no significant differences in live shrub cover in 2004 ($F_{3,26} = 0.19$; $p > 0.9$) (fig. 1). Cover in the areas treated with herbicide was highest with 5.5 percent cover. The cut-leave treatment had the lowest cover with 3.8 percent. Intermediate between the herbicide and cut-leave treatments were the cut-buck-scatter and control treatments, with 4.3 and 5.1 percent cover, respectively.

Cover increased in all treatments in 2005. Control units had 15 percent cover, cut-buck-scatter units had 27 percent cover, cut-leave units had 38 percent cover, and herbicide units had 36 percent cover. There were statistical differences in live shrub cover between treatments ($F_{3,26} = 12.29$; $p < 0.0001$). Live shrub cover in the control units was significantly lower than the thinned treatments ($p < 0.05$); however, there were no differences between the thinned treatments (fig. 1).

Discussion

Live Tree Density

By only providing general growth form guidelines to the cutting crew, it most likely cost less per unit area to execute the treatments, but it also left more ambiguity and room for failure in meeting the treatment objective of 80 percent reduction in post settlement tree density. Depending on land management goals, the range of reduction in post settlement tree density that we captured

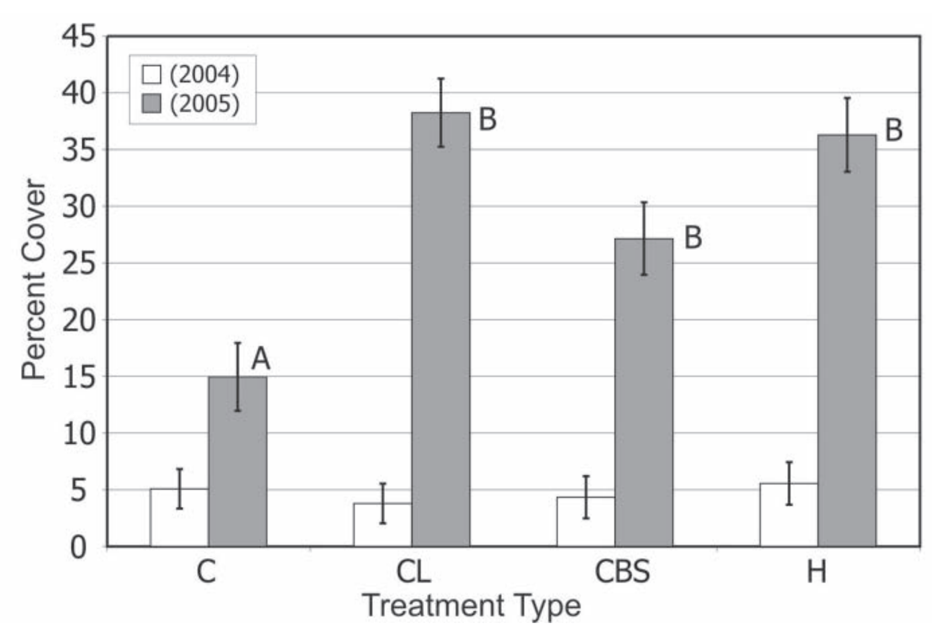

Figure 1—Percent live shrub cover for 2004 and 2005 by treatment type as measured using the line-point intercept method. There were no significant differences between types in 2004 ($F_{3,26} = 0.19$; $p = 0.9033$). Uppercase letters (A, B) represent significant differences between types in 2005 ($F_{3,26} = 12.29$; $p < 0.0001$). C = control; CL = cut-leave; CBS = cut-buck-scatter; and H = herbicide. Error bars represent one standard error about the mean.

(64 to 92 percent) may be acceptable. In addition, if pre settlement tree retention is only of low to moderate priority, then this method of determination for thinning is probably appropriate. If the goal of an 80 percent reduction in post settlement trees is an important target and retaining pre settlement trees is a high priority, it may well be worth the cost of better assessing tree ages by coring the largest trees and marking trees to be thinned or retained. Another option may be to thin trees based on a target tree density, rather than a percent reduction of a portion of current density based on tree diameter.

Based on our methods of assessment, it appears that the cut-leave thinning treatment produced results closest to the objective of 80 percent tree reduction (table 2). This may well be due to the relatively simple nature of this method. A cut tree provides an immediate measure by which to assess efficacy and, by not taking time to buck and scatter the larger trees, a more consistent flow can be kept by the thinning crew. Cutting was heavier in the smaller trees (Classes 1 and 2) in both of the cutting treatments, which may be an indication of the level of uncertainty in using general growth form as a cutting guideline.

The intricacies of the herbicide application, with care taken for soil drift, may have led to the low reductions in post settlement trees that we documented. Another consideration may be that crews were constrained by maximum allowable herbicide application per unit area.

Live Shrub Cover

Live shrubs responded favorably to the thinning treatments. In 2004, live shrub cover was second highest in the control units at 5.1 percent. In 2005, following a strong monsoon season, the cover of live shrubs in the control units nearly tripled to 15 percent. This threefold increase, however, was the lowest in 2005 and was dwarfed by the response seen in the treatment units. The cut-leave units underwent the greatest increase in live shrub cover with a tenfold increase, but were not distinguishable from the other thinned treatments. Live shrub cover in the cut-buck-scatter and herbicide units increased by roughly six times (fig. 1). Observationally, most of the increase in shrub cover came from broom snakeweed (Gutierrezia sarothrae); a suffrutescent plant which is an increaser on disturbed sites (U.S. Department of Agriculture, Forest Service 1937) and can help minimize soil erosion (Campbell and Bomberger 1934).

In summary, regardless of the accuracy of the thinning treatments relative to the goal of 80 percent post settlement tree reduction, thinning is apparently facilitating the creation of a fuelbed which should help to carry a surface fire through the area. The thinning treatments have opened the sites up, allowing an increase in live shrub cover as well as adding woody structure that should help to support a desirable surface fire and provide nurse sites for future plant germination and establishment. Dependant on funding, the next phase of this study will be to burn half of the units to determine the impacts of the thinning treatments on fire behavior and consequent fire effects.

Acknowledgments

We would like to thank the Joint Fire Sciences for funding this study (#03-3-3-58) and Duncan Lutes (SEM; Missoula, MT) for helping to develop our methods. In addition, Duncan Lutes and Mick Harrington of the Missoula Fire Lab greatly improved this paper with their reviews. Logistics support from Shirley Kodele, NPS and Tim Duck, BLM in St. George, UT has been invaluable.

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Effect of a Spaced Thinning in Mature Lodgepole Pine on Within-Stand Microclimate and Fine Fuel Moisture Content

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Abstract—*Thinning mature forest stands to wide spacing is prescribed to reduce crown bulk density and likelihood of severe crown fire behaviour. However, it may adversely affect surface fuel load, moisture content and within-stand wind, which influence surface fire behaviour and crowning potential. Comparison of a mature lodgepole pine (Pinus contorta Dougl. var. latifolia Engelm.) stand in southeastern British Columbia to an adjacent stand with half the basal area removed by thinning to 4 m inter-tree spacing found a decrease in canopy interception of rainfall and increases in solar radiation, windspeed, and near-surface air temperature during peak fire danger hours over 13 fire seasons. Moisture content of needle litter and fuel moisture sticks was measured in both stands in 2005. Between-treatment differences in moisture content of sticks and litter were greatest after rain, but decreased quickly as fuels dried, to very small at moderate fire danger. Prediction of moisture content of lodgepole pine needle litter using the Canadian Fire Weather Index System also improved as fuels dried and worked well for both stands at moderate fire danger. There was only one day at higher fire danger during the study. Further studies should examine physical models of fuel moisture and microclimate under a wider range of stand densities, fuel types and climatic conditions.*

Introduction

Thinning mature forest stands to a wide inter-tree spacing is sometimes prescribed to reduce crown bulk density and lower the likelihood of severe crown fire behaviour (Hirsch and Pengelly 1999). However, thinning may also affect surface fuel loading, fine fuel moisture content and within-stand winds, which in turn affect surface fire behaviour and crowning potential (Rothermel 1983; Scott 1998; Scott and Reinhardt 2001). Rates of wetting or drying, and consequently moisture content, of fine surface fuels are influenced by microclimatic factors that are expected to change when a stand is thinned. These factors include canopy interception of rainfall and solar radiation, and near surface air temperature, relative humidity and within-stand windspeed (Rothermel 1983; Forestry Canada 1992).

The purpose of this paper is to compare and contrast a natural mature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stand to an adjacent stand which was thinned to uniform 4 m spacing in February 1993, with respect to:

- within-stand microclimate parameters that are likely to affect moisture content of fine surface fuels;

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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- measured moisture content of fine surface fuels; and,
- difference between actual moisture content of lodgepole pine needle litter and values predicted by the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987).

Study Area

This study was conducted at one of three sites where, since 1992, researchers from the Canadian Forest Service and Forest Engineering Research Institute of Canada and operations staff from the British Columbia Ministry of Forests and Range have studied the efficacy of commercial thinning to uniform wide spacing for reaching several stand-level management objectives in natural 70 to 100 year old lodgepole pine.

The site is located south of Cranbrook in south-eastern British Columbia at 49° 25′ N, 115° 36′ W, on level terrain in a broad valley at 1350 m elevation. The overstorey consists of a single cohort lodgepole pine stand that originated after wildfire in 1912, with a few scattered western larch (*Larix occidentalis* Nutt.) trees of about the same age.

In 1992, one of three adjacent 15 to 20 ha treatment units (fig. 1) was commercially thinned by Galloway Lumber Co. Ltd. to a uniform inter-tree spacing of approximately 4 m, a second was clearcut and the third was left untreated (Mitchell 1994). Stand characteristics are shown in table 1 and the fuel complexes are described in table 2. Sparse understorey vegetation is typical of the lodgepole pine/Oregon grape-pinegrass site series of the dry cool Montane Spruce biogeoclimatic subzone (Braumandl and Curran 1992). Various studies at this site have examined the harvest operations and effects on stand and tree growth, wildlife habitat, and forest health (for example, Mitchell 1994; Allen and White 1997; Safranyik and others 1999; Safranyik and others 2004; Whitehead and others 2004; Whitehead and Russo 2005). This paper examines and discusses selected microclimatic parameters that may affect fuel moisture from the project's 13-year database at the Cranbrook site (1993-2005) and fine fuel moisture content measured in the thinned and unthinned stands during the 2005 fire season.

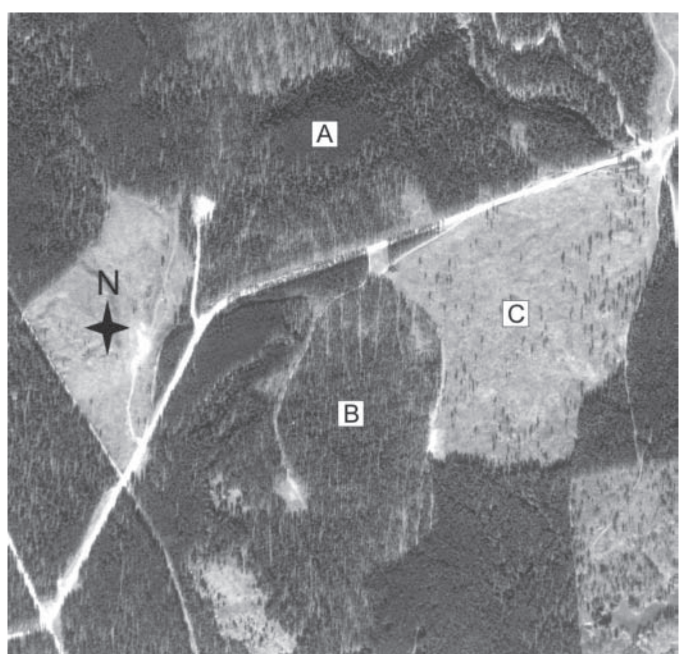

Figure 1—Aerial overview of site with weather station locations represented by letters A (unthinned control), B (thinned to 4 m spacing), and C (clearcut).

Table 1—Distribution of all trees >7.5 cm d.b.h., by 5 cm diameter classes in the unthinned control and thinned stands at the Cranbrook study site.

		Midpoint of diameter class (cm)						
Stand	**Species**	**10**	**15**	**20**	**25**	**30**	**35**	**40**
		trees/ha						
Control	W. Larch	8	0	0	0	0	0	0
	L. Pine	208	700	633	125	17	0	0
Thinned	W. Larch	11	5	5	5	5	5	11
	L. Pine	0	11	155	192	53	5	0

Source: Whitehead, R.J.; Brown, B.N.; Nemec, A.F.L.; Stearns-Smith, S.C. (Submitted 2006). Stand and tree-level growth response to spaced commercial thinning and fertilization treatments in mature lodgepole pine stands in southeastern British Columbia. Natural Resources Canada, Canadian Forest Service, Information Report BC-X---.

Table 2—Description of the fuel complexes (July 2005)[a], in the unthinned control and thinned stands at the Cranbrook study site.

Fuel Complex	**Control**	**Thinned**
Overstory Conifers (7.5+ cm d.b.h.)		
Basal area (m^2/ha)	40.0	21.7
Density (live trees/ha)	1692	464
Mean height (m)	20.6	21.8
Mean diameter at breast height (cm)	19.4	23.9
Mean live crown base height (m)	14.0	12.8
Mean dead crown base height (m)	5.0	2.4
Maximum live crown width (m)	2.6	3.6
Canopy bulk density[b] - foliage (kg/m^3)	0.204	0.053
Understory Fuels		
Understory conifer biomass (kg/m^2)	0.00	0.03
Shrub biomass (kg/m^2)	0.02	0.33
Herbaceous biomass (kg/m^2)	0.03	0.06
Litter biomass (kg/m^2)	0.18	0.18
Litter bulk density (kg/m^3)	19.0	17.1
Litter depth (cm)	0.94	1.06
Duff bulk density (kg/m^3)	113.5	104.9
Duff depth (cm)	2.71	3.22
Dead woody fuels 0.1 to 3 cm in diameter (kg/m^2)	0.15	0.15
Dead woody fuels 3.1 to 7 cm in diameter (kg/m^2)	0.26	0.15
Dead woody fuels 7.1+ cm in diameter (kg/m^2)	0.81	1.95

[a]Source: Russo, G.L.; Whitehead, R.J. Natural Resources Canada, Canadian Forest Service, unpublished data.
[b]Based on foliar weight calculated using equations from Standish and others (1985).

Methods

Microclimate

Weather stations with dataloggers (Campbell Scientific CR-10) were installed in the centre of each treatment unit (at least 125 m from the outside edge) in 1992 (fig. 1). Air temperature and relative humidity (Campbell Scientific HMP 45C) and full spectrum solar radiation (LiCor LI200SZ pyranometer) sensors were mounted on a tower at 1.3 m height and windspeed monitors (RM Young Wind Monitors) at 3 m height. Three air temperature sensors (Campbell Scientific 107B) were also located nearby at 5 cm above the forest floor. Solar radiation and air temperature sensors at 5 cm height were sampled every five minutes, while air temperature at 1.3 m height, relative humidity and windspeed were sampled every minute. Hourly data summaries and statistics were recorded from May 1 through September 15 from 1993 to 2005. Daily precipitation was measured by a Sierra Misco tipping bucket rain gauge in the clearcut treatment unit only until 2003, when gauges were also added in the thinned and unthinned stands. Each rain gauge was mounted at 1.3 m above ground-level and 3 m to 5 m from the sensor tower.

Weather station and sensor maintenance was carried out as per Spittlehouse (1989). Initial screening of raw data followed procedures described by Meek and Hatfield (1994) which included between-sensor comparisons where sensors were replicated on site (e.g. temperature) and nearby Environment Canada station normals, where sensors were not replicated (relative humidity, windspeed, precipitation and solar radiation). Manual filtering and graphical screening were used to account for sensor drift, and records with missing data for any treatment were deleted from the database before analysis.

Moisture Content of Fine Surface Fuels

Fuel Moisture Sticks—Five sets of 10-hour fuel moisture sticks (4-stick arrays of ponderosa pine dowels weighing 100 g), mounted on wire brackets at 20 cm above the forest floor were positioned 2-m apart on an east-west transect (fig. 2) near the weather station in the thinned and control stands. Each array was weighed on site at 16:00 Mountain Standard Time (MST) on 70 days between June 21 and September 25, 2005, and oven dried at the end of the season to determine how much weight was lost due to weathering effects over the season. Moisture content was calculated on each sampling day using equation 1:

$$\text{Moisture Content (\%)} = 100 \times \left(\frac{\text{wet weight - dry weight}}{\text{dry weight}} \right) \qquad (1)$$

with dry weights adjusted for weathering, using equation 2:

$$\text{Adjusted Dry Weight (g)} = 100 - \left(\frac{100 - \text{a}}{\text{b}} \right) \times \text{c} \qquad (2)$$

where *a* is dry weight at end of season (grams), *b* is total number of days exposed, and *c* is number of days exposed before wet weight was measured.

Needle Litter—Ten 1-m^2 quadrats, spaced 1 m apart on a transect perpendicular to the moisture stick transect, were established in each stand for collection of lodgepole pine needle litter (fig. 3). Cured lodgepole pine needles were collected from the forest floor nearby and distributed in a thin

Figure 2—Five sets of fuel moisture sticks set up in the thinned stand (left) and in the control stand (right).

Figure 3—Plots for sampling lodgepole pine needle litter in the thinned stand before adding needles (left) and in the control stand after adding needles (right).

even layer (<1.5 cm thick) amongst the quadrats on May 18, 2005 to ensure ample litter for sampling throughout the season. Five samples (approximately 50 g each) of needle litter were collected at 16:00 MST, from alternating odd and even quadrats each sampling day, at 16:00 MST on 70 days between June 21 and September 25, 2005. Each sample was placed in a numbered tin and weighed on site to the nearest 0.1g, then oven dried for at least 24 hours at 100°C and re-weighed. Moisture content of needle litter was calculated using equation 1.

Predicted Moisture Content of Needle Litter—In Canada, the codes and indices that make up the Fire Weather Index System are calculated from weather station outputs. On June 24, 2005, the B.C. Ministry of Forests and Range Southeast Fire Centre installed a standard Fire Weather Station (Forest Technology Systems) in the clearcut opening to determine daily fire weather indices, including the Fine Fuel Moisture Code (FFMC) and Fire Danger Class (B.C. Ministry of Forests 1983). FFMC is a numerical index of the moisture content of litter and other cured fine fuels (Van Wagner 1987). We used FFMC to predict moisture content of lodgepole pine needle litter using equation 3 (Van Wagner 1987):

$$\text{Predicted Moisture Content (\%)} = \frac{147.2 \times (101 - \text{FFMC})}{59.5 + \text{FFMC}} \quad (3)$$

Data Analyses

Microclimate—Mean hourly within-stand windspeed, air temperature, total solar radiation, and relative humidity (RH) during peak fire danger hours (12:00 to 16:00 MST) in the control and thinned stand over thirteen fire seasons (1993 to 2005) were compared graphically. Precipitation data over three fire seasons (2003 to 2005) were consolidated into 54 "rain events" (periods of 1 or more days when precipitation was recorded at one or more stations and separated from other events by at least one day without rain), For each rain event, canopy interception of rainfall in the thinned and unthinned stands was calculated using equation 4 and between-treatment differences were tested with a Wilcoxon signed-ranks test ($\alpha = 0.05$).

$$\text{Interception (\%)} = 100 \times \left(\frac{\text{Rainfall in clearcut (mm)} - \text{Rainfall in stand (mm)}}{\text{Rainfall in Clearcut (mm)}} \right) \quad (4)$$

Fine Fuel Moisture Content—The variance was not constant across the range of moisture content data for fuel moisture sticks and lodgepole pine leaf litter. We grouped the data by Fire Danger Class for graphical comparisons and it was clear that this problem was associated with rainfall, which occurred primarily when the Fire Danger Class was Very Low (26 days). During periods when Fire Danger Class was Low (31 days) or Moderate (12 days) variance in the data was small and consistent. We therefore restricted statistical analyses of between-treatment differences to days with Low or Moderate ratings and used two-tailed paired sample t-tests to investigate between treatment differences in moisture content of fuel moisture sticks ($\alpha = 0.05$) and differences in moisture content of lodgepole pine leaf litter between treatments, and between each treatment and values predicted from FFMC with $\alpha = 0.02$ to approximate an experiment-wise error of 0.05 (Kirk 1968). All statistical analyses were conducted using Analyse-it® for Microsoft Excel.

Results and Discussion

During 54 rain events over three fire seasons, rainfall in the clearcut opening ranged from 0.1 mm in a single day to 99 mm over an 11 day period, and mean canopy interception was significantly lower ($p<0.0001$) in the thinned stand (51.1 percent; SE = ±2.9254) than in the unthinned stand (65.3 percent; SE = ±2.9596 percent).

Mean hourly within-stand windspeed, air temperature, relative humidity and solar radiation in the thinned stand during peak fire hours (12:00 to 16:00 MST) are plotted against the corresponding hourly means in the untreated control stand in figures 4 to 7, respectively. Windspeed and air temperature were consistently higher in the thinned stand. Although total solar radiation was most often higher in the thinned stand, between-treatment differences were not as consistent as for windspeed and air temperature. This may have been due to effects of shading from one or more trees at a particular sun angle and location relative to the sensors in different treatments. Most between-treatment differences were intuitive, with the exception of relative humidity, where no difference was detectable within sensor error (±3 percent) when measured at 1.3 m above the forest floor. However, there was also no between-treatment difference in mean air temperatures measured at 1.3 m height, although they were consistently higher in the thinned stand when measured much closer to the surface fuels of interest (at 5 cm height). We did not measure RH at 5 cm and cannot discount the possibility that it may also differ nearer the forest floor.

Daily mean moisture contents of fuel moisture sticks in the thinned stand are plotted against corresponding daily means in the untreated control stand in figure 8, and within Fire Danger Classes in figure 9. Moisture content was generally lower in the thinned stand than in the unthinned stand, but the magnitude of that difference decreases when moisture content is below

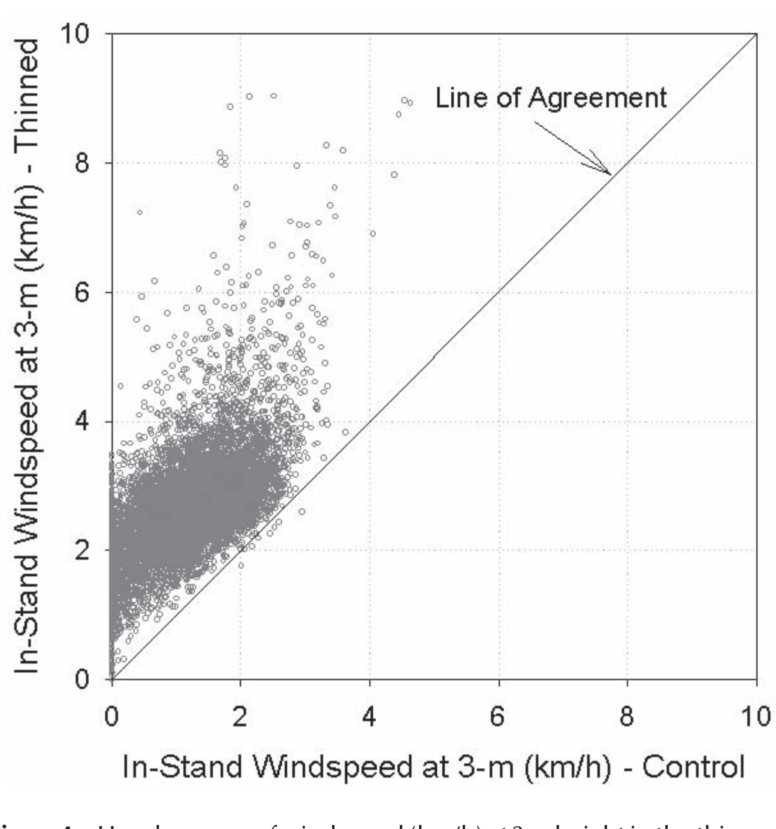

Figure 4—Hourly means of windspeed (km/h) at 3 m height in the thinned stand, measured between 12:00 MST and16:00 MST, vs. corresponding means in the control stand (n=7380 hours).

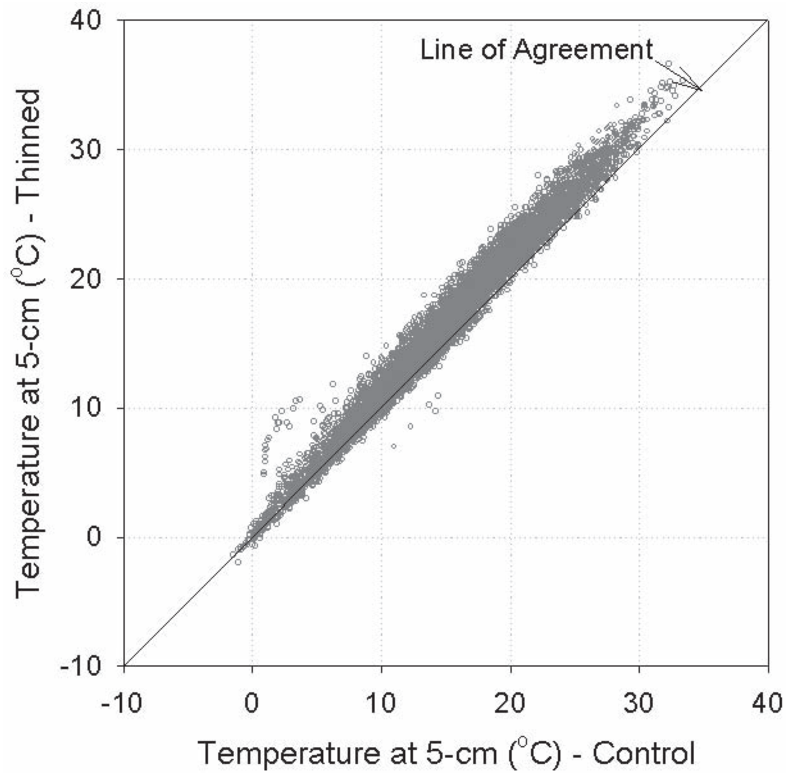

Figure 5—Hourly means of air temperature (°C) at 5 cm height above ground in the thinned stand, measured between 12:00 MST and16:00 MST, vs. corresponding means in the control stand (n=7760 hours).

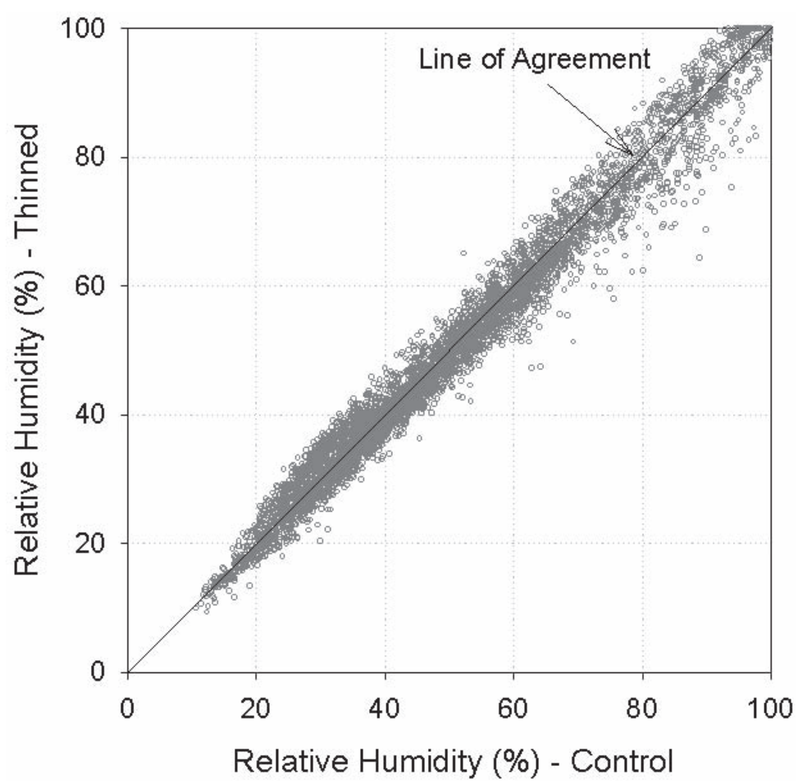

Figure 6—Hourly means of relative humidity (percent) at 1.3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding means in the control stand (n=5809 hours).

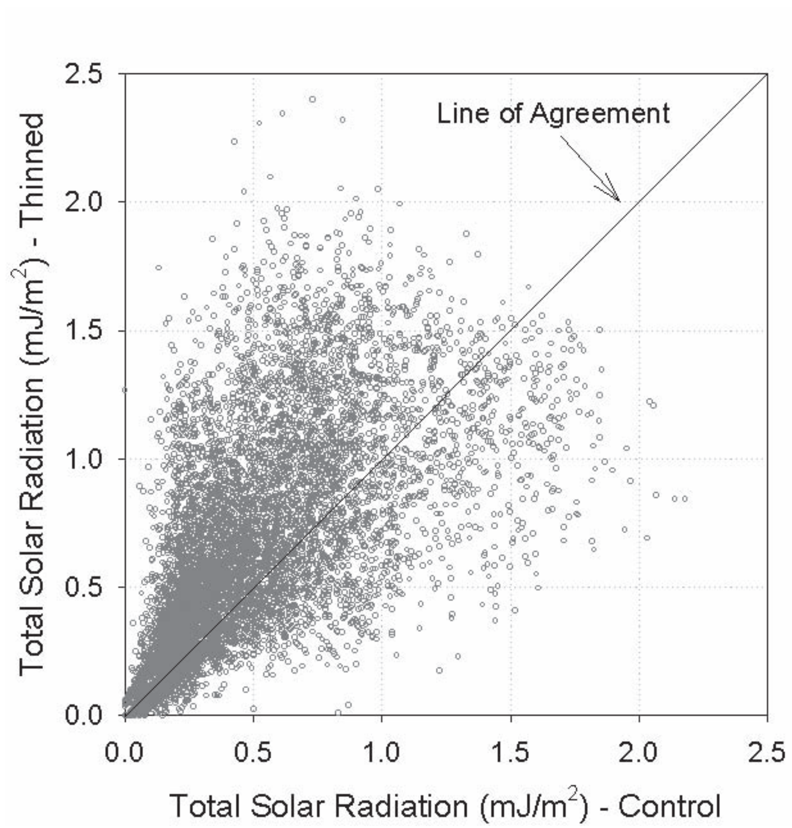

Figure 7—Total hourly solar radiation (mJ/m^2) at 1.3 m height in the thinned stand, measured between 12:00 MST and 16:00 MST, vs. corresponding total hourly solar radiation in the control stand (n=8503 hours).

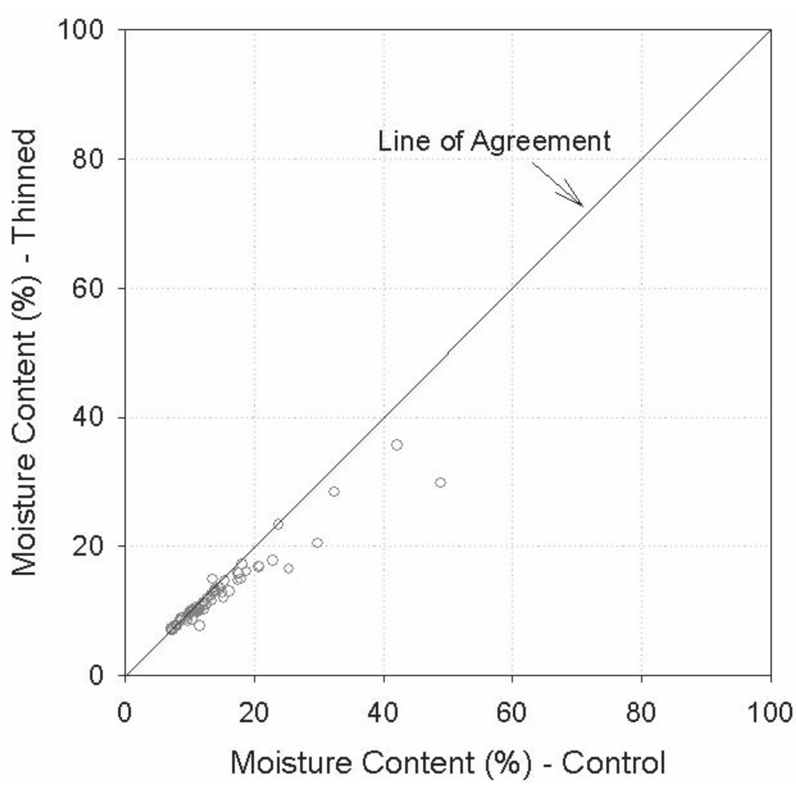

Figure 8—Daily mean moisture content (percent) of fuel moisture sticks at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005.

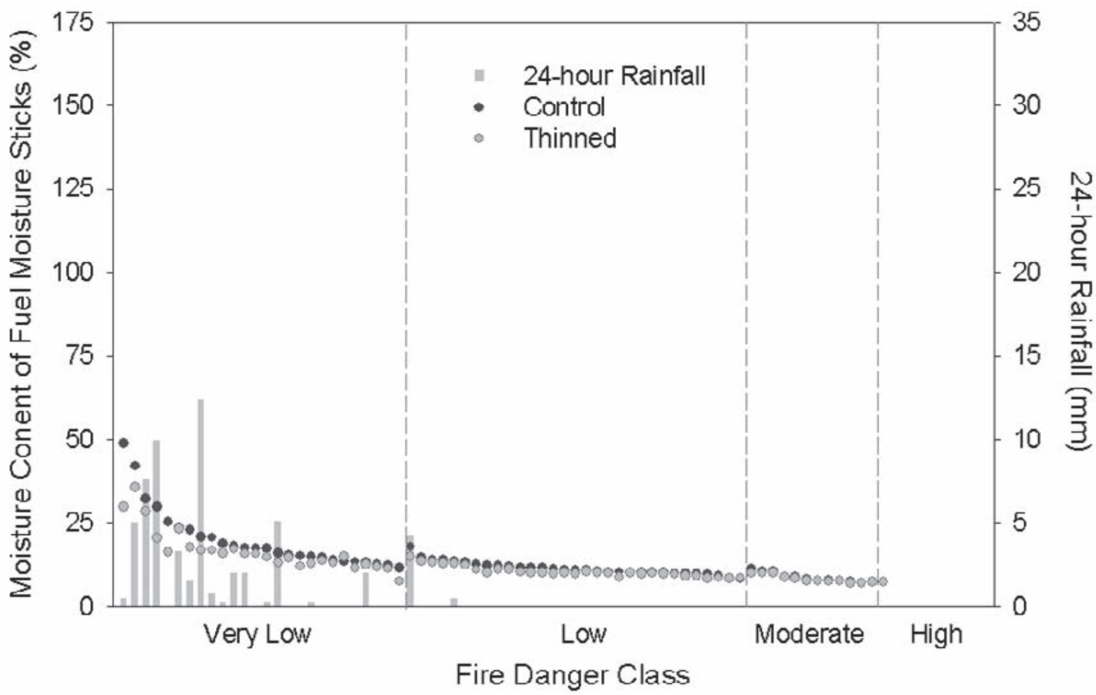

Figure 9—Mean moisture content (percent) of fuel moisture sticks in the thinned and unthinned stands, plotted from wettest to driest control value within different Fire Danger Classes, with corresponding 24-hour rainfall (mm) shown as bars.

about 20 percent and as Fire Danger Class increases (fig. 9; table 3). Variance and between-treatment differences in daily mean moisture contents of needle litter samples were larger than for fuel moisture sticks, but tended to follow the same general trends (fig. 10 and fig. 11; table 3). Pook and Gill (1993) compared an untreated radiata pine (*Pinus radiata* D. Don) stand with one that had been thinned and pruned. They also found that, although litter moisture content was generally higher in the unthinned stand, between-treatment differences decreased with declining moisture content and increasing concern for fire danger.

Table 3—Descriptive statistics (mean, standard deviation and standard error of the mean) for needle litter and fuel moisture stick moisture content at different fire danger classes.

Danger Class		$\overline{X}$	SD	SE	$\overline{X}$	SD	SE
		- - - - - *litter*- - - - - -			- - - - - *sticks*- - - - -		
Low (n=31)	Control	17.2	7.23	1.30	11.4	1.99	0.36
	Thinned	13.2	3.19	0.57	10.5	1.61	0.29
	Predicted	15.7	6.91	1.24	—	—	—
Moderate (n=12)	Control	10.2	2.91	0.84	8.6	1.40	0.40
	Thinned	8.9	2.19	0.63	8.3	1.18	0.34
	Predicted	9.3	1.96	0.57	—	—	—

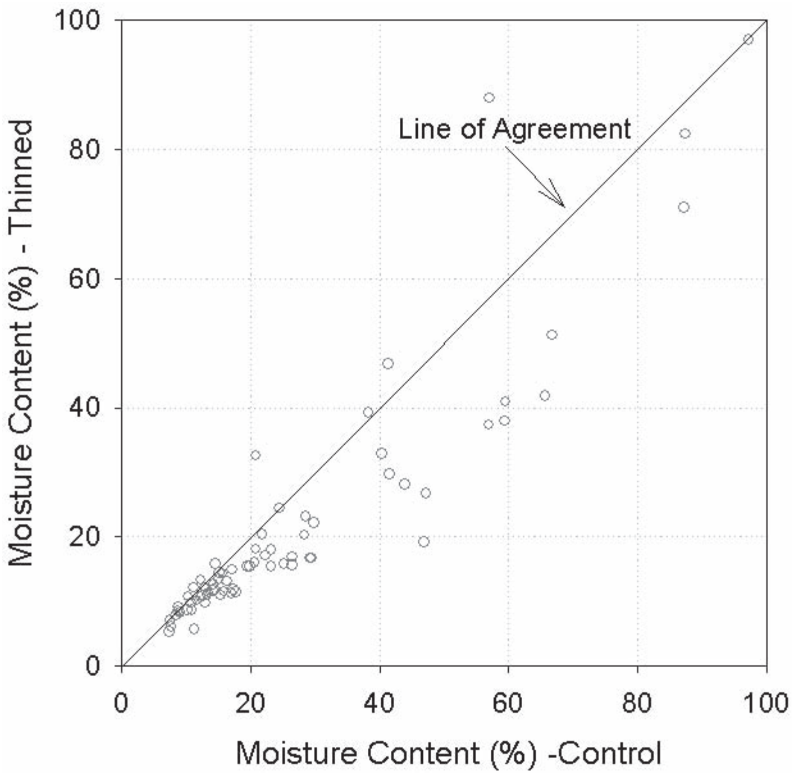

Figure 10—Daily mean moisture content (percent) of lodgepole pine needle litter at 16:00 MST in thinned and unthinned stands on 70 days between June 21 and September 25, 2005.

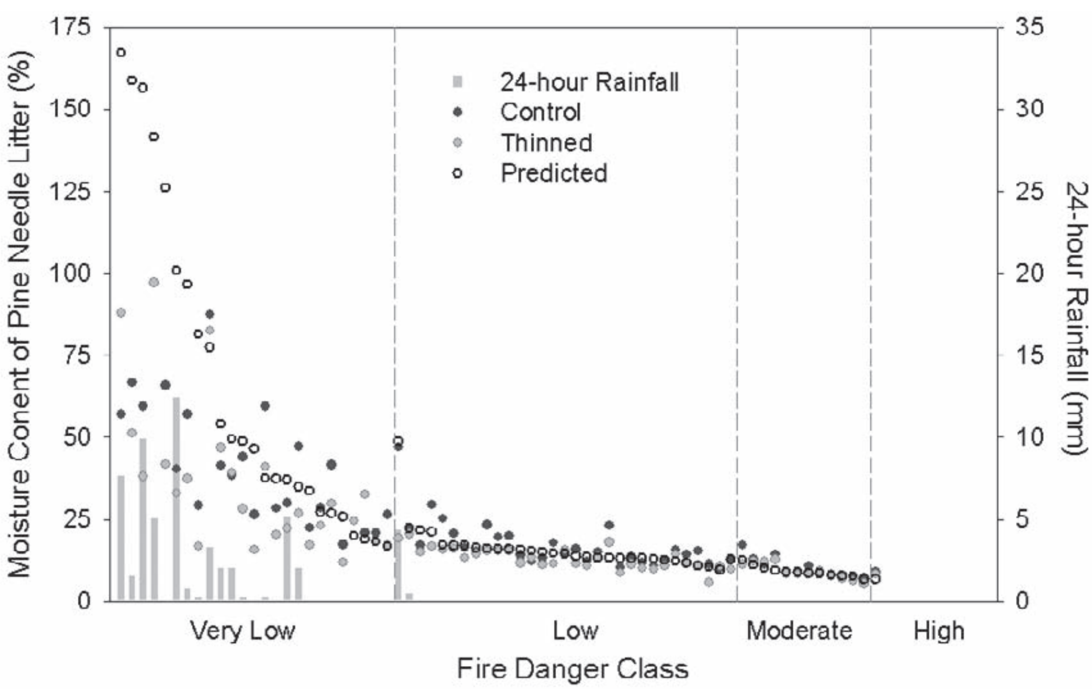

Figure 11—Predicted and actual mean moisture content (percent) of lodgepole pine needle litter in the thinned and unthinned stands, plotted from wettest to driest predicted value within different Fire Danger Classes, with corresponding 24-hour rainfall (mm) shown as bars.

Tanskanen and others (2005) found that canopy characteristics of a mixed Norway spruce (*Picea abies* (L.) Karst) and Scotch pine (*Pinus sylvestris* L.) stand in southern Finland, including canopy depth and leaf area index, correlated strongly with ignition success in surface needle litter. They suggested that differences in surface fuel wetting and drying due to canopy influence on precipitation and wind conditions near the forest floor might have been responsible. Canopy characteristics were quite different in the two lodgepole pine stands we studied (tables 1 and 2), and although we observed a consistent difference in canopy interception of precipitation, windspeed and temperature, the between-treatment differences in moisture content we observed were very small except when fuels were too wet to ignite easily. We found statistically significant between-treatment differences in mean moisture content of both needle litter and fuel moisture sticks when Fire Danger Class was Low, and also for sticks when Danger Class was Moderate (table 4). Although statistically significant, it is unlikely that such small differences in fine surface fuel moisture (for example, 0.3 percent difference in stick moisture content at Moderate fire Danger Class) would have any practical effect on ignition probability or crowning potential. However, there was only one sampling day with a higher fire danger during this study and similar measurements at High and Extreme Fire Danger Classes are recommended to confirm these findings during periods of most concern to fire managers.

Moisture content of fine surface fuels is one important factor used in the Canadian Forest Fire Behaviour Prediction System to model ignition potential (Lawson and others 1994), surface fire intensity and rate of spread (Taylor and others 1997). When combined with stand characteristics, surface fire intensity is used to predict potential for crown fire. The Fine Fuel Moisture Code generated by the Canadian Fire Weather Index System is an index of moisture content of litter and other cured fine fuels, and is used as an indicator of ignition potential or the potential for fires to start and spread (B.C. Ministry of Forests 1983). Our measurements of moisture content of needle litter were not significantly different in either treatment from the values predicted from FFMC using Van Wagner's equation, when Fire Danger Class was Low or Moderate, although the values were consistently slightly higher than predicted in the control stand and slightly lower than predicted in the thinned stand (fig. 11; table 3). Predictions of moisture content of needle litter from daily FFMC values improved as fire danger increased (fig. 11) and moisture content was predicted well in both stands when Fire Danger Class was Moderate. FFMC reflects fine fuel moisture content across a fairly wide range of stand conditions within a given fuel type and it appears to be robust enough to predict fine fuel moisture content in both stand conditions we studied.

Table 4—Two-tailed p values from paired sample t-tests comparing needle litter moisture content (α = 0.02) and fuel moisture stick moisture content (α = 0.05).

Danger Class	Control vs. Thinned	Control vs. Predicted	Thinned vs. Predicted	Control vs. Thinned
	- - - - - - - - - - - - - -	*litter*	- - - - - - - - - - - - - -	- - *sticks*- -
Low	0.0003	0.0278	0.0224	<0.0001
Moderate	0.0281	0.0391	0.3021	0.0112

Conclusions

Removing approximately half of the basal area of a mature stand of lodgepole pine in southeastern British Columbia, by thinning from below to uniform 4 m inter-tree spacing, resulted in decreased canopy interception of rainfall and increased within-stand solar radiation, windspeed, and near-surface air temperature. Moisture content of both needle litter and of fuel moisture sticks were most different in thinned and unthinned stands following rainfall, but these differences decreased rapidly as fuels dried. Under moderate fire danger conditions, between-treatment differences were very small and not practically significant. Values for moisture content of lodgepole pine needle litter in both stands were predicted well by the Canadian Fire Weather Index System. Further work is needed to examine physical models of fuel moisture and microclimate under a wider range of stand densities, fuel types and climatic conditions.

Acknowledgments

We would like to thank the B.C. Ministry of Forests and Range (BCMOFR), Protection Branch, Fuel Management Section and the Government of Canada Mountain Pine Beetle Initiative for funding this work; BCMOFR Southeast Fire Centre for assistance with measuring Fire Weather in 2005; John Vallentgoed of the Canadian Forest Service and Jack Selman and Assoc. of Cranbrook B.C. for fieldwork; and, Dr. Nathalie Lavoie (BCMOFR) and Dr. Michael Feller (University of British Columbia) for prompt and helpful reviews of this manuscript. We also wish to acknowledge our former colleague, Bruce D. Lawson for first recognizing the opportunity to do this study.

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Predicting Ground Fire Ignition Potential in Aspen Communities

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***Abstract**—Fire is one of the key disturbances affecting aspen (Populus tremuloides Michx.) forest ecosystems within western Canadian wildlands, including Elk Island National Park. Prescribed fire use is a tool available to modify aspen forests, yet clearly understanding its potential impact is necessary to successfully manage this disturbance.*

Undesirable social consequences of severe, deep burning ground fires include smoke generation and impaired vegetation re-growth. Data on the soil and duff moisture conditions under which ground or subsurface fires may start in aspen are presented, as well as experimental test fire results. Different topographic positions, plant communities and seasons were factored into the research design. The Duff Moisture Code and Drought Code components of the Canadian Forest Fire Weather Index System were calculated and factors including duff moisture content, bulk density and inorganic content measured at the time of ignition. Probability of sustained smouldering ignition models were developed for the aspen forest fuel type, with values of 27 for DMC and 300 for DC at the 50% probability of ignition level. This information will improve the capability to effectively manage aspen using fire in central Alberta.

Introduction

The Duff Moisture Code (DMC) and Drought Code (DC) within the Canadian Forest Fire Weather Index (FWI) System (Canadian Forest Service 1984; Van Wagner 1987) are values of great assistance to fire managers in assessing forest fuel dryness and associated fire risk. Both DMC and DC represent soil duff (i.e. LFH) moisture dryness (Van Wagner 1987), and therefore, its potential to influence fire behaviour. Changes in DMC track moisture in the shallow duff or fibric soil horizon (F-layer), while the DC tracks the humus (H) or deep duff layers as well as heavy downed woody materials. Both indices are determined at noon (standard time) each day during April to October from the standardized weather readings of dry-bulb temperature, 10 m open wind speed, relative humidity and 24 h accumulated precipitation (Turner and Lawson 1978).

Currently there are empirical models correlating the probability of smouldering combustion or ignition and DMC-DC values for select boreal forest types using commercial peat moss as a fuel source (Frandsen 1987, 1991, 1997; Hartford 1989; Lawson and others 1997), but none for trembling aspen. EINP is dominated by trembling aspen (*Populus tremuloides* Michx.) forest. Although these communities may not burn as readily as other boreal forests in the Boreal region (Peterson and Peterson 1992), ground fire may persist in this vegetation under dry conditions for extended periods (Lawson and Dalrymple 1996).

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In this study, the probability of sustained combustion or ignition was examined for soil duff layers in aspen forests of Elk Island National Park, with ignition tests conducted *in-situ*, as per the Lawson and others (1997) field trials. We also determined whether the indices of modeled DMC-DC predict ignition in aspen forest equal to that of duff moisture, with or without soil bulk density and inorganic content considerations.

Materials and Methods

Study Area

EINP is situated 35 km east of Edmonton in central Alberta (approximate Lat. 53° N; Long. 112° E), at the north end of the Beaver Hills,a post-glacial dead-ice moraine elevated 10 to 30 m above the surrounding plains, sufficient to place the area within the Lower Boreal Mixedwood ecoregion (Strong and Leggat 1991). The dominant vegetation of uplands in the Park is trembling aspen, although open grasslands, shrublands, and white spruce [*Picea glauca* (Moench) Voss] forests are interspersed throughout the area (Polster and Watson 1979). Six different aspen plant community types have been identified within the Park (Best and Bork 2004).

The climate of the area is cool-continental, with long, cold winters and short, warm summers (Bowser and others 1962). Annual precipitation over the last 44 yrs at the Edmonton International Airport indicates an average yearly rainfall of 460 mm (Parks Canada 2004). Precipitation in the Park from April to October, inclusive, accounts for 81% of yearly totals (Parks Canada 2004), and has ranged from 220 to 470 mm over the last 10 yrs (Parks Canada 2004). Mean growing season temperatures vary between 5°C in April to 17°C in summer (Rogeau 2004), while the frost-free period is about 100 days (Crown 1977).

Both DMC and DC are re-calibrated annually beginning at 'start-up', either 3 days after snow loss in spring or 3 days after a recorded noon temperature of 12°C (Alexander 1983; Canadian Forestry Service 1984), and are continually updated throughout the fire season until October 31st (Turner and Lawson 1978).

Experimental Approach

The approach used in this study was to develop and test empirical relationships between DMC-DC and ignition trials from various sites throughout the Park. A main calibration site was utilized, involving intensive, repeated sampling and testing to establish a detailed profile of burning success under various DMC-DC levels. Sampling was performed both within *in-situ* soils as found within each plot, as well as within 'rainfall exclusion' treatment areas, designed to exclude precipitation and simulate drought (Van Wagner 1970). Exclusion areas were 3 x 3 m, and tarped 1 m above ground to eliminate soil moisture recharge and to ensure low moisture levels (and high FWI values) were represented in at least a portion of the plots where test fires were conducted. Following initial calibration of codes to the primary ignition plots, relationships between ignition and DMC-DC were subsequently tested on independent replicated plots within each of three main aspen plant community types found throughout EINP (Best and Bork 2004).

Field Sampling

All plots were 20 x 20 m in size and permanently marked. The calibration area was situated within a plant community type encompassing traits similar to the two most prevalent types previously documented within EINP, accounting for approximately 70% of all aspen communities previously investigated within the Park. On average, there were two ignition tests within each plot on each day of sampling. Twelve validation plots were randomly selected from a series of 96 vegetation permanent sample plots (PSP) situated on forested uplands throughout EINP.

Daily fire weather observations were obtained from the Environment Canada (Campbell Scientific) automated weather station, 800 m from the calibration site. Precipitation was also measured locally within and adjacent to the calibration site and at each validation site using a manual rain gauge. Unique fire weather indices (DMC-DC) were calculated for each site using localized precipitation and all other observations were from the weather station.

Ignition Testing and Analysis

Most tests took place during the months of May to August 2004, on a schedule frequent enough to coincide with small increases in DMC-DC and to ensure a series of ignitions ranging from 0 to 100% success at each site. Ignition trials were conducted similar to the method used by Lawson and others (1997). Core samples were taken in each plot as per Nalder and Wein (1998), using a cordless drill and hollow, cylindrical tube auger, 5 cm in diameter. Extracted core samples were separated into 2-cm increments and later oven-dried to determine the moisture content and bulk density of each layer. Core holes from moisture sampling were then filled with smouldering peat moss, obtained from commercial supplies. Peat was heated until approximately ⅔ black in colour and actively smouldering, producing greyish-black smoke. The 5-cm diameter and 12- to 15-cm deep hole generally required about 500 ml of peat moss. Heated moss was carefully placed into the hole, with slight overfilling to compensate for the eventual collapse of peat moss during combustion. Test holes typically smoked for 2 to 5min until a grey ash cover formed.

After 2 h had passed, the peat was carefully removed, making sure not to scrape the sides of the drill hole at the combustion interface. Bare fingers were used to promptly test the perimeter of the hole throughout the 2- to 4-cm and 4- to 6-cm layers for evidence of persistent ignition. The proportion of the cylindrical core found smouldering corresponded to the reported percentage of success or probability of ignition, to the nearest 10%.

All extracted soil core samples were measured for duff moisture and bulk density using the procedure of Lawson and Dalrymple (1996). A representative number of soil core samples were retained for inorganic content determination, following the methods of Kalra and Maynard (1991). A total of 117 trials were carried out, with 64 on the calibration site and 53 on the validation sites. In most areas the 'burning window', ranging from 0% to 100% success, was duplicated at least twice.

Data Analysis

The variables utilized in all analyses included DMC-DC, moisture content (% oven-dry weight basis), bulk density (kg m^{-3}), and soil inorganic content (ash, reported as %). To arrive at one model comparing the probability of ignition success versus the corresponding observed DMC-DC, a non-linear procedure, PROC NLIN (SAS 2001), was used and fitted to a logistic model.

The first analysis involved comparing the probability of ignition versus the DMC or DC only on the calibration plots. Coefficients derived from initialization were run on SAS to check for convergence and derive the B_0 and B_1 values of the estimates. The B_0 and B_1 parameters from SAS were then inserted into a simple non-linear regression model. The standard formula used was:

$$P=\exp(B_0+ B_1*Code)/(1+\exp(B_0+ B_1*Code)), \qquad (1)$$

where 'Code' represents DMC-DC, B_0 the intercept and B_1 designates the slope of the regression coefficients. To confirm the relative accuracy of the calibration equations generated, a linear regression analysis was used to determine the goodness of fit (R^2) and other statistical parameters of the models in relation to the actual probabilities observed.

The second analysis included development of a multivariate non-linear regression model, which included DMC-DC, bulk density (ρ_B) and soil inorganic content (Ash), using the following formula, after Lawson and others (1997):

$$P=\exp(B_0+ B_1*Code+B_2*Ash+B_3*\rho_B)/$$
$$(1 +\exp(B_0+ B_1*Code+B_2*Ash+B_3*\rho_B)) \qquad (2)$$

where 'Code' represents DMC-DC, B_0 the intercept and B_1, B_2 and B_3 designates the slopes as regression coefficients. For the multivariate non-linear regression analysis, the simple equation coefficients B_0 and B_1 were utilized as a starting point, and when combined with the average inorganic content and actual bulk density measurements, as per Lawson and others (1997), used to initialize the approximate B_2 and B_3 coefficients. Only the DMC or DC value was changed at any one time to form the new multivariate models that were checked against the results of the field trial ignition probabilities. Next, these approximate coefficients were inserted into SAS (SAS 2001) along with the actual data set of varying bulk density values and different average inorganic values from 2003 and 2004. Finally, the derived coefficients were run once more with the average bulk density and inorganic values in the multivariate non-linear regression model run with SAS. Multivariate equations were also assessed for goodness of fit (R^2) and other statistical parameters through linear regression with the actual ignition probabilities measured.

The 53 validation site trials were subsequently tested against the calibration models by comparing actual validation ignition success rates (probability values) against the predicted results expected from the simple non-linear calibration models. Testing involved the evaluation of goodness-of-fit (R^2) and other statistical parameters obtained through the use of linear regression with PROC REG (SAS 2001).

Both the calculated moisture content and corresponding DMC-DC values were compared against observed ignition trial results through linear regression with PROC REG (SAS 2001) to determine any differences between predictive capabilities. Finally, results were compared to modelled ignition probabilities from Lawson and others (1997), utilizing the results modelled at the 50% probability level, as suggested by Cruz and others (2003).

Results

Calibration Results

Results of the ignition analysis generated from the calibration site data are provided in table 1, and indicate that both the simple and multivariate models for both the DMC and DC layers were highly significant ($P<0.0001$). However, overall R^2 values were greater, and root mean square error (RMSE) and coefficient of variation (CV) values less for models generated using the DMC layer compared to results for the DC (table 2). While the simple and multivariate models resulted in similar R^2, RMSE and CV within the DMC data, the simple model resulted in a greater R^2 and lower CV than the multivariate model within the DC data (table 1).

Final coefficients for both the simple and multivariate models in the DMC and DC are shown in table 2. Simple and multivariate non-linear models were additionally compared graphically within each of the DMC and DC (fig. 1). Results indicate that the simple model predicted a slightly greater probability of ignition than the multivariate model at a given DMC-DC code, although this difference was more apparent within the DC data (fig. 1). This finding indicates the addition of soil bulk density and inorganic content to the model tended to reduce the anticipated probability of ignition. For example, the simple model indicated a 50% probability of ignition at DMC and DC values of 27 and 300, respectively (fig. 1). In contrast, DMC and DC codes resulting in the same ignition, but using the multivariate model, were 29 and 336. Given that the results from either model were similar, and because

Table 1—Linear analysis of calibration site DMC and DC values, and observed probability of ignitions using simple or multiple regression modelled equations, showing goodness of fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability (Pr>F).

		Linear Analysis			
Code	**Model Type**	**R^2**	**RMSE**	**CV**	**Pr>F**
DMC	Simple Equation	0.74	0.14	16.69	<.0001
	Multiple Equation	0.74	0.15	18.72	<.0001
DC	Simple Equation	0.54	0.23	50.42	<.0001
	Multiple Equation	0.43	0.24	80.93	<.0001

Table 2—Coefficient parameters and standard errors for simple and multiple non-linear models comparing DMC and DC values to the probability of ignition in the aspen fuel type at EINP.

Code	Model Type	B0	SE[a]	B1	SE	B2	SE	B3	SE	F	Pr>F
DMC	Simple[b]	–3.11	0.63	0.12	0.02	–	–	–	–	1008.31	<.0001
	Multiple[c]	2.92	1.38	0.12	0.02	–0.16	0.05	–0.002	0.001	485.68	<.0001
DC	Simple	–8.96	2.22	0.03	0.01	–	–	–	–	147.14	<.0001
	Multiple	7.98	3.03	0.04	0.01	–0.36	0.08	0.0002	0.001	127.55	<.0001

[a] Standard error.
[b] Simple non-linear equation is $P=\exp(B0+ B1*Code)/(1+\exp(B0+ B1*Code))$.
[c] Multivariate equation is $P=\exp(B0+ B1*Code+B2*Ash+B3*\rho B)/(1 +\exp(B0+ B1*Code+ B2*Ash+ B3*\rho B))$.

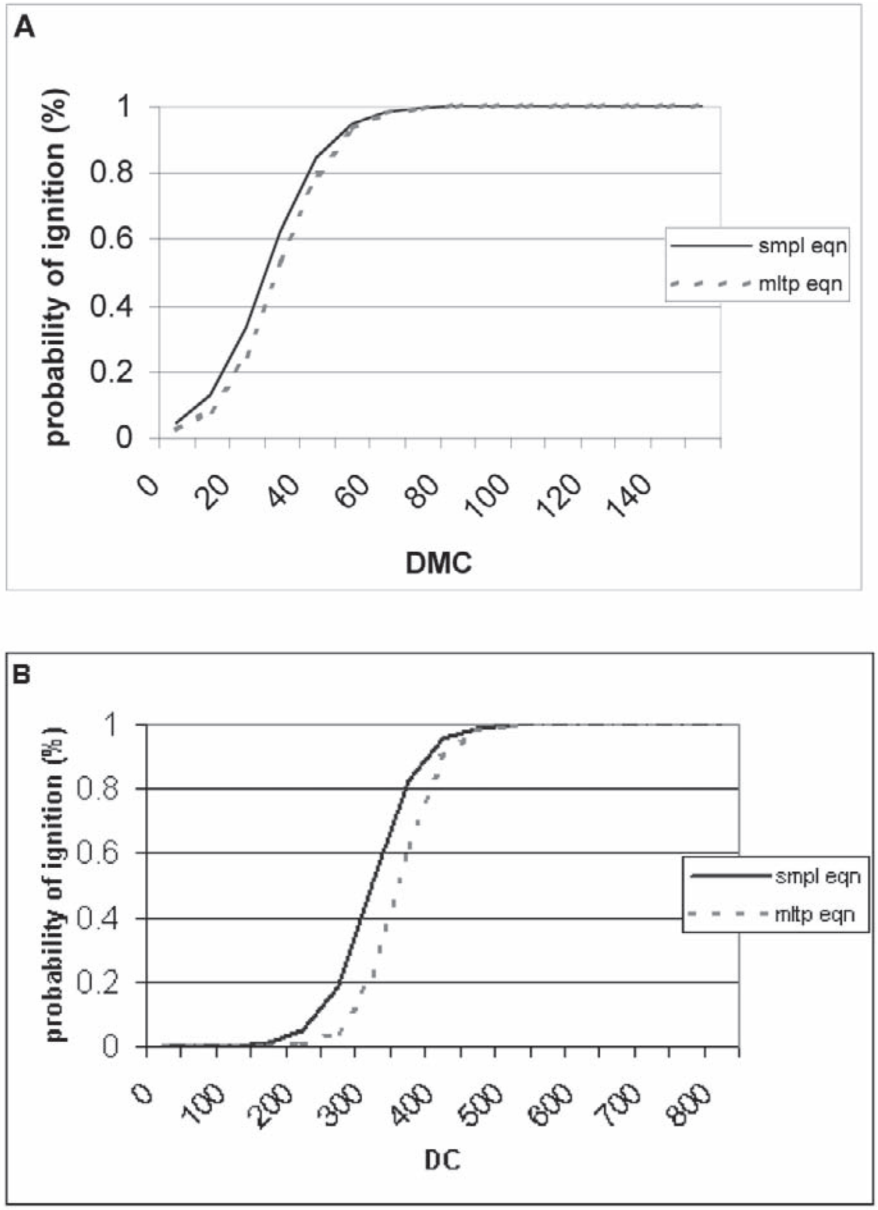

Figure 1—Results of the non-linear analysis fitted to a logistic model showing the probability of sustained ignition against the DMC (A) and DC (B) for simple (smpl) and multivariate (mltp) equations.

inorganic soil data were limited, the simple models were chosen for subsequent application to the validation data.

Validation of Ignition Prediction Models

Ignition probability values observed at the validation trials were compared directly to the values predicted using the simple model developed from the calibration site for both DMC and DC layers. For the DMC, a strong relationship ($P \leq 0.001$) was evident between observed and predicted ignition, but only at the Beaver and Tawayik sites (table 3), with no relationship ($P = 0.52$) at the Goose site. Goodness-of-fit comparisons for the former two were

Table 3—Comparison of the validation observed field burning data to the calibration site modelled results using simple linear regression, showing goodness of fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability (Pr>F).

		Linear Analysis			
Code	**Validation Site**	**R^2**	**RMSE**	**CV**	**Pr>F**
DMC	Beaver	0.49	0.20	31.12	0.0006
	Goose	0.04	0.26	34.67	0.5216
	Tawayik	0.46	0.23	33.85	0.0013
DC	Beaver	0.50	0.11	78.05	0.0004
	Goose	0.54	0.22	49.84	0.0029
	Tawayik	0.33	0.23	80.79	0.0102

relatively strong ($R^2 = 0.46$ to 0.49), with a positive relationship between predicted and observed ignitions (table 3). Results of the DC analysis were similar to DMC, except that a significant relationship ($P \leq 0.01$) was evident between actual and observed ignition at all three validation sites (table 3). Goodness-of-fit values for the three sites were similar ($R^2 = 0.33$ to 0.54) to those observed previously with the DMC.

Comparison of Moisture Content and FWI System Fuel Moisture Codes on Ignition Success

Regressions of ignition success with either moisture content or DMC-DC were compared for each soil layer (table 4). Results from the calibration site and the total pooled data from all validation sites were analysed for both F and H-layers. In all comparisons except the calibration F-layer, FWI values of DMC-DC were superior predictors of ignition than soil duff moisture. FWI values had a higher goodness-of-fit ($R^2 = 0.20$ to 0.53) and lower RMSE (23 to 35) and CV (27 to 89%) than moisture content comparisons. All FWI comparisons were significant ($P < 0.001$).

Table 4—Comparison of observed ignition success versus either moisture content (MC) or the FWI codes of DMC/DC, showing goodness-of-fit (R^2), root mean square error (RMSE), coefficient of variation (CV) and probability (Pr>F) for the calibration site (Allcal) and combined validation data (Allval).

		Linear Analysis			
Soil Layer	**Parameter**	**R^2**	**RMSE**	**CV**	**Pr>F**
F-layer	Allcal MC	0.62	18.94	22.42	<.0001
	Allcal DMC	0.44	23.02	27.26	<.0001
	Allval MC	0.02	33.68	40.00	0.2899
	Allval DMC	0.20	30.37	36.06	0.0007
H-layer	Allcal MC	0.25	40.32	74.47	<.0001
	Allcal DC	0.53	31.98	59.07	<.0001
	Allval MC	0.07	44.14	110.35	0.0570
	Allval DC	0.40	35.45	88.63	<.0001

Comparison of Results to Other Models

Comparison of the modeled values derived here to Lawson and others (1997) indicate the ignition results from EINP were associated with lower DMC-DC values relative to similar ignition probabilities in boreal forest duff types elsewhere. At the 50% probability of ignition, Lawson and others (1997) calculated DMC values between 39 and 58 in upper feather moss and upper sphagnum moss vegetation. Using the lower feather moss fuel type, the Lawson and others (1997) DC value at the 50% probability was 482. In Anderson (2000), the 50% probability of ignition for the DMC layer in the D-1 (leafless aspen) fuel type was calculated near 79, although the logistic regression model utilized in that study was from Hartford (1990).

Discussion

Using the simple ignition models developed in this study, code values of 27 and 300 for DMC and DC, respectively, were determined to approximate the 50% probability of ignition. Incorporating inorganic content and bulk density into multivariate predictive models led to minimal changes in threshold code values (DMC 29 and DC 336 for 50% probability). The addition of physical fuel properties only marginally improved the predictability of ignition models. Both Frandsen (1987) and Lawson and others (1997) developed multivariate equation models for certain duff types; however, neither definitively compared the accuracy of simple and multivariate models. Ignition tests in these studies were also recorded as binary events (yes or no), whereas in the current study a range of probabilities were recorded to a finer resolution (0.0 to 1.0).

Model goodness-of-fit values based on comparison of the validation to calibration data indicated ground fire occurrence could be predicted to some degree from calibrated ignition models. Variation in model accuracy may be explained by the shallow nature of the surface duff profile and substantial inorganic content and bulk density values found in duff layers of the Park.

Validation ignition models for the DC layers, while significant, were found to have a lower R^2 and higher CV than those for the DMC. The shallow depth of the DC layer, coupled with a high inorganic content may explain these observations.

Ignition was under-estimated by calibration models on average at actual ignition levels over 60% for DMC and 20% for DC. Ignition success in the field often increased from less than 20% to over 50% and above, over a very short time interval (days). Ignition also appeared to change rapidly with moisture depletion and changing FWI codes. As a result, effective modelling of ignition remains difficult under rapidly changing environmental conditions, in turn affecting the accuracy of ignition models.

The smouldering threshold (i.e. 50% probability of ignition) for the DMC and DC in ignition trials of Lawson and others (1997) were much greater than that observed in the current study. Lawson and others (1997) also found that a narrow range of moisture separated successful from unsuccessful ignitions, particularly in white spruce duff, somewhat similar to observations within the current study where ignition increased from 20% to more than 50% over a few days.

Conclusions

This research established and tested non-linear models relating DMC and DC to the probability of duff ignition, or ground fire. Overall, simple rather than complex multivariate models were more effective in relating DMC and DC to ignition. During the validation procedure, models developed for the independent calibration site were relatively effective at detecting a change in ignition, although the accuracy of those models remained quite low.

Results of this study indicate that the aspen forest and D-1 fuel type of EINP is quite unique in its properties. Thus, the results of this study are not directly comparable to either that of Frandsen (1987) or Lawson and others (1997) in conifer vegetation types.

Acknowledgments

The authors wish to thank the management and staff of Elk Island National Park for their patience in allowing this research to be carried out and for their assistance in conducting fieldwork. Duff sampling field assistance was also received from Matthew Cacka and the family of the corresponding author. Support for this study was provided by EINP, the University of Alberta, the Canadian Forest Service and FERIC.

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Fire Ecology and Fire Effects

Integrating Fuel Treatments into Comprehensive Ecosystem Management

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Abstract—*To plan fuel treatments in the context of comprehensive ecosystem management, forest managers must meet multiple-use and environmental objectives, address administrative and budget constraints, and reconcile performance measures from multiple policy directives. We demonstrate a multiple criteria approach to measuring success of fuel treatments used in the Butte North Strategic Placement of Treatments (SPOT) pilot project. Located in the Beaverhead – Deerlodge National Forests, Montana, the project addresses multiple issues: altered wildlife habitat affecting sensitive species, grassland conversion to forest, an insect epidemic, water resource concerns, wildland-urban interface development, and wildland fire management. Managers are working with researchers to develop dynamic landscape management strategies. They employ multiple modeling approaches to conduct an integrated assessment of ecological and resource issues relative to multiple management scenarios. Besides evaluating effects of proposed treatments on changes to fire behavior, they also evaluate effects on wildlife habitat, disturbance processes, water quality and economics of treatment alternatives. The intent is to effectively integrate fuel management with Forest Plan goals and comprehensive ecosystem management. This approach offers a structure to use multiple criteria to evaluate success of fuel management activities in the context of other resource objectives.*

Introduction

Recent dramatic increases in wildland fires triggered the commitment of substantial resources to reduce hazardous fuels. The Government Accounting Office (2002) calls for federal land management agencies to develop "consistent criteria to identify and prioritize" areas requiring treatment and "clearly defined outcome-oriented goals and objectives." The urgency to reduce forest fuels creates tension with expectations that forest management must address competing resource objectives while applying the best available ecosystem science. The Healthy Forest Restoration Act of 2003 established a framework to conduct hazardous fuels reduction projects on federal forested lands to protect key ecosystem components, reduce risk to communities and municipal water supplies, improve critical habitat for threatened or endangered species, restore vegetation structure to reflect historic variability, improve commercial value of forest biomass, and address insect infestation. How do managers effectively integrate the complexities of ecosystem science and multiple resource objectives into practical planning strategies?

The scientific basis for comprehensive ecosystem assessment is well established (Grumbine, 1997) and issues of applied ecosystem assessment have been thoroughly discussed (Haynes et al. 1996; Holt 2001; Jakeman and

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Letcher 2003; van der Sluijs 2002). Provisions for conducting environmental impact analysis and managing resources to meet multiple objectives were established in the National Environmental Policy Act of 1969 and National Forest Management Act of 1976, respectively.

Computer-based decision support systems evolved concurrently with ecosystem sciences. Numerous modeling systems seek to transfer ecosystem theory and knowledge into practical management solutions. Many modeling tools focus on resource specific issues such as water quality, wildlife habitat, wildland fire behavior, vegetation processes, management logistics, and economic resource assessment. Many modeling tools coevolved with geographic information systems (GIS) permitting spatially explicit model displays. The need to assess integrated ecosystem components drives development of the emerging field of Integrated Assessment Modeling (IAM) (Jakeman and Letcher 2003; van der Sluijs 2002). In principle, IAM accounts for ecological, social, and economic values where planning environmental and resource management activities. The objective of IAM is to integrate multiple, relevant modeling components into a unified framework to improve how complex environmental problems are analyzed and possible solutions identified.

This paper presents a conceptual framework for a modeling-based assessment and planning procedure that integrates forest fuel treatments with multiple resource objectives. The framework is an example of an IAM currently used for the Butte North Project, Beaverhead-Deerlodge National Forest, Montana. The project is as a pilot of the USDA Forest Service, Strategic Placement of Fuels (SPOT)program. The SPOT program is intended to guide development of a "consistent and systematic interagency approach" to identify and plan treatments on forested acres deemed most critically in need of fuel reduction (Bosworth 2005). The framework is presented in a structured, stepwise format, and provides insight into how integrated assessment modeling is practically implemented. We conclude by describing a "performance report card" for evaluating treatment success based upon multiple resource objectives.

Study Area

The Butte North Project area, located in Silver Bow County, Montana, covers 38,600 ac, 80% of which is managed by the Beaverhead-Deerlodge National Forest (BDNF) (figure 1). In the lower elevations, shallow, highly erodible soils support grass and sagebrush lands. The forested lands above are dominated by lodgepole pine (*Pinus contorta*) with 2,800 ac of Douglas-fir (*Pseudotsuga menziesii*) in drier sites. The area was heavily impacted by mining throughout the late 19th and early 20th century (Lyden 1948). Most of the timber was removed to support mining operations. Commercial logging of lodgepole pine occurred most recently during the 1980's. Many forest roads intersect stream channels. Over 80 residential structures occupy the wildland-urban interface. Small ranch operations run cattle on private lands and federal grazing allotments. The National Forest lands are highly valued for hunting and other recreation. A small municipal water supply reservoir is also located within the project area.

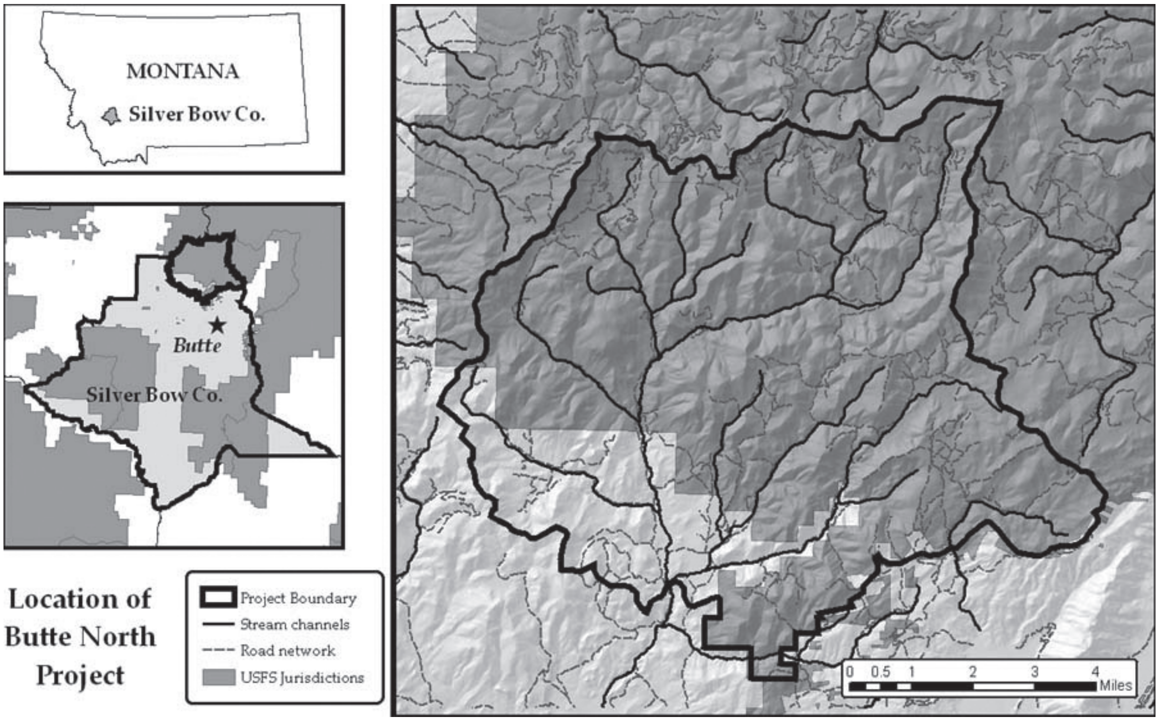

Figure 1—Location of study area within Silver Bow County, Montana.

Current Conditions and Management Issues

The land use history and current environmental conditions result in multiple management issues. Details follow by seven general resource topics as defined by the BDNF managers. These topics are repeated in major sections of the paper as we describe the integrated modeling process.

A. Vegetation: Dense seedling and sapling cohorts occupy stands commercially harvested 20-30 years ago. Conifers continue to encroach upon grass and sagebrush lands. Understory development within Douglas-fir stands increases acres of densely stocked, multi-story vegetation. There are few stands of large mature trees, limiting the potential development of more complex 'old-growth' type vegetation structure. Encroachment and increased vegetation density generally reduces landscape complexity.

B. Insects: Infestations of mountain pine beetles are present and threaten to spread rapidly throughout the conifer forests causing extensive mortality to lodgepole and Douglas-fir stands.

C. Fire and forest fuels: Continuous stands with heavy fuel loading could provide conditions for rapid fire growth. Vegetation on over half of the managed area is classified as Fire Regime Condition Class 3 (FRCC3), indicating that conditions are departed from the historic range of variability and that significant management may be needed for restoration (Hann and Strohm 2003). Fuel loadings in beetle infested areas may increase in the future as infested trees senesce.

D. Watershed: Stream channels are over-widened and contain uncharacteristic volumes of fine sediments, probably from past mining activities and the extensive forest road network. Willow is regenerating poorly, in part due to conifer encroachment and over-grazing in riparian zones.

E. Wildlife habitat: The trend toward lower vegetation complexity probably limits habitat for species which historically inhabited the area. Plans for any proposed management activities must consider habitat for multiple aquatic and terrestrial sensitive species including red squirrel, *Tamiasciurus hudsonicus* (nesting, foraging), lynx, *Lynx canadensis* (den, foraging), black-backed woodpecker, *Picoides arcticus* (habitat), pileated woodpecker, *Dryocopus pileatus* (nesting, foraging), flammulated owl, *Otus flammeolus* (nesting, foraging), northern goshawk, *Accipiter gentilis* (nesting, foraging), fisher, *Martes pennanti* (den, foraging) and West Slope Cutthroat Trout (*Oncorhynchus clarki lewisi*).

F. Social: Dense fuel concentrations proximate to residential structures and within the municipal watershed could threaten lives, property, and a drinking water source should severe wildland fire occur.

G. Economics: Funds to conduct any management activities are limited. Proposed activities must be logistically and economically feasible.

Developing an Integrated Modeling Framework

The core Butte North assessment team consisted of specialists in silviculture, wildlife, GIS, fire and fuel management, hydrology, fisheries, and landscape modeling. Following background research, group discussions, and field reconnaissance, the team defined resource issues and developed a list of possible management objectives. The objectives were translated into landscape components and relationships that could be defined within a GIS and modeling applications. Rules were developed to adapt these components and relationships into assessment logic within the modeling framework. Modeling tools appropriate to resource issues were implemented addressing vegetation, insect spread, fuels and fire, wildlife habitat, and human uses. Modeling results were integrated into a final modeling system which assessed the feasibility and trade-offs associated with multiple objective scenarios. In summary, the IAM process was accomplished through the following steps:

Step 1: Translate Issues to Objectives
Step 2: Translate Objectives to Modeling Logic
Step 3: Build and Integrate Models
Step 4: Define Basis for Scenario Comparison
Step 5: Frame Alternative Scenarios

The IAM process permits visualization of possible consequences of multiple plausible alternatives which may help estimate and confirm anticipated benefits and conflicts. IAM may also reveal unanticipated opportunities and pitfalls. The intent is to provide spatially explicit comparison across a range of alternative scenarios.

Step 1: Translate Issues to Objectives

The core team developed a series of management objectives defined by specific activities, to address the seven identified landscape issues.

A. Vegetation: Implement pre-commercial thinning in stands commercially harvested over the past 2-3 decades. Restore grass and sagebrush lands using slashing and broadcast burning. Reduce Douglas-fir understory vegetation. Protect selected stands with larger stem sizes, passively managing for potential 'old growth' conditions. Monitor spatial arrangement of vegetation activities for changes to the mosaic of vegetation structure.

B. Insects: Thin beetle infested stands to reduce competition among the remaining trees and salvage value of some trees in infested areas.

C. Fire and forest fuels: Reduce forest fuels within stands with highest potential for extreme fire behavior. Reduce vegetation density in FRCC3 areas. Reduce vegetation density in beetle infested areas.

D. Watershed: Limit or prohibit management activities near stream channels, especially where sensitive species are present. Remove conifers encroaching into broadleaf riparian vegetation.

E. Wildlife habitat: Monitor and constrain management activities which alter potential habitat for species of concern. Minimize impacts to currently suitable habitat and favor change which increases suitable habitat.

F. Social: Reduce loading of forest fuel near structures and within the municipal water supply watershed.

G. Economics: Use commercial values from vegetation treatments which yield merchantable timber to generate revenues to fund other, non-commercial resource improvements.

Many of these objectives could be addressed simultaneously through activities within the same landscape area. For example, revenues from harvesting to reduce stand density within insect infested areas could help fund stream restoration projects. Conversely, activities to meet one objective could directly conflict with other resource objectives. For example, mechanical activity to reduce forest fuels could increase sedimentation to streams and alter sensitive wildlife habitat. The challenge of the IAM approach is to define resource relationships sufficiently well to illuminate benefits, trade-offs, and conflicts within the modeling environment.

Step 2: Translate Objectives to Modeling Logic

With objectives defined, the next step was to determine which resource components to model and to identify available data. Each objective was reviewed to determine which physical and landscape attributes best describe the features affected by the objective and how these features relate to the planning landscape. Implicit in these definitions is the requirement that spatial data be available. This is an iterative process which requires dealing with "chicken or egg" logic; prior knowledge of model input requirements may limit data that can be used, while available data may limit which modeling tools may be used (Mulligan and Wainwright 2004). Also, available data may not be sufficient; more data may need to be collected, parameters may need to be estimated from existing data, or alternative modeling approaches may be necessary.

The *minimum modeling unit*, the smallest land area identified as having unique characteristics, was also chosen at this step. The convention defining vegetation stands (hereafter "stands") as a minimum mapping unit logically translated to the minimum modeling unit. All computations and summaries are based upon the attributes of the minimum modeling unit. Attributes were assigned to stands as a single assignment assuming homogeneity for the entire unit or as a percentage of land area occupied by a given feature within the unit. An example of percentage is the portion of a vegetation stand occupied by a stream buffer. The stream buffer is also an example of a management *zone*. Zones may define common jurisdictions, areas with common management objectives, or other classifier useful for planning and analysis.

A. Vegetation: The GIS stands layer which established the minimum modeling unit was a composite of legacy Timber Stand Management Record System (TSMRS) with vegetation updates from Satellite Imagery Land Classification (SILC) data (Redmond and Ma 1996). Each stand was assigned a dominant plant/tree species, vegetation structure class, canopy density class, and habitat type.

B. Insects: The 2005 Aerial Detection Survey (ADS) GIS layer was used to identify stands and label with current beetle infestation (USDA Forest Service 2005).

C. Fire and forest fuels: In addition to assigning FRCC classifications a fire and fuels specialist used expert opinion to translate vegetation data into definitions of fuel characteristics required for fire behavior modeling. Topographic information required for fire behavior modeling was acquired from a digital elevation model and historical weather data was acquired from a nearby weather station.

D. Watershed: Stream buffers were delineated around perennial stream channels after the Inland Native Fish Strategy (INFISH) (USDA Forest Service 2006) guidelines. A riparian recovery zone was established at 50 ft and an activities monitoring/exclusion zone was established at 300 ft. The coincidence of the 300 ft zone was appended to the stands layer as a binary attribute and the portion of a stand occupied by the riparian buffer was assigned to each stand. Areas previously identified as high priority for recovery were assigned as a priority zone.

E. Wildlife habitat: Wildlife habitat modeling required vegetation characteristics acquired from the GIS stand layer.

F. Social: The locations of structures were approximated using the Montana parcel GIS layer (available at: http://nris.state.mt.us/nsdi/cadastral/) to generate a point layer representing building clusters. Points from the GIS were adjusted to match recent aerial photos provided by the BDNF. Stands within the municipal supply watershed were attributed based on a GIS layer provided by the BDNF.

G. Economics: Activity cost estimates were provided by the BDNF. Revenue estimates from potential commercial sales were derived from the transaction evidence appraisal (TEA) procedures of USDA Forest Service Region 1 (2005), explained further in the next section. Estimates of potential harvest volumes were derived from the basic vegetation attributes of the stands layer.

Step 3: Build and Integrate Models

The data describing landscape attributes and management effects were loaded into individual resource models, or sub-models. Using independent sub-models maintains model integrity, greater process transparency, and better description of errors and uncertainties inherent in all environmental modeling (Beven 2006; van der Sluijs 2002). Sub-models may be sophisticated computer programs or very simple rules developed from research or expert opinion. Respective model outputs were organized back into the base GIS and finally compiled into a final Integrated Assessment Model.

A. Vegetation—Successional pathways: Logic for successional pathways following disturbance and management activities was adopted as previously developed from research literature and expert opinion (Chew et al. 2004).

B. Insects—Infestation spread model: Based on current conditions defined by the ADS, the projected spread of the infestation was modeled using a GIS-based approach (Shore and Safranyik 1992) adapted to fit available data. Results of the insect spread modeling were used to construct a future landscape used in the fire behavior modeling to estimate fire behavior 20-30 years in the future assuming increased insect spread and increased fuel loading as dead and dying trees senesce.

C. Fire and forest fuels: Potential fire behavior was modeled using the Treatment Optimization Model (TOM) within the FLAMMAP modeling system (Finney 2002). TOM uses GIS data layers to analyze fire spread behavior assuming fixed ignition sources, and weather and wind conditions. The resulting map suggests the location, orientation, and size of fuel treatment polygons, or TOM polygons, which may most effectively and efficiently change large fire growth. Separate TOM runs were completed using 97-99th percentile weather conditions, prevailing winds from two directions, NW and SW, and two vegetation conditions, current and future bug-infested conditions created by the insect spread model. The GIS stands were attributed to indicate coincidence with TOM polygon.

D. Watershed—Specialist analysis: Watershed analysis was limited to specialist field assessments and GIS attribution of stream buffer zones previously described.

E. Wildlife Habitat—Model of wildlife habitat zones: Wildlife zones were determined by matching GIS vegetation data with the habitat requirements of the species (Hart et al. 1998; Pilliod 2005; Ruediger et al. 2000; Samson 2005). The zones were categorized on a 0-3 scale for habitat quality and the GIS stands were attributed with the suitability rank for each wildlife zone. The wildlife zones values were summed for an overall wildlife habitat quality index.

F. Social model: The wildland urban interface (WUI) was modeled by generating a buffer extending ½ mi from each building cluster point. Stands intersected by this buffer were assigned the WUI zone attribute.

G. Economic model: Timber value was estimated by the TEA method which predicts stumpage value adjusted for sale characteristics and market indicators. Polygons in the GIS vegetation layer were assigned a mechanical treatment method based on proximity to an existing road and mean slope within the polygon; this attribute adjusts the TEA values on a stand by stand basis. Estimates of forest product volumes from mechanical activities were derived by using Forest Inventory and Analysis (FIA) data in the Forest Vegetation Simulator model (FVS) (Dixon 2002) and the Fire and Fuels Extension of FVS (Reinhardt 2003). The modeling results were compiled into a “look-up” table which associates volume estimates from activities with the antecedent vegetation.

Model Integration—Results from each sub-model were compiled first in GIS then into a master IAM system called Multiple-resource Analysis and Geographic Information System (MAGIS). MAGIS is an optimization model designed to solve complex spatial and temporal scheduling problems in natural resource management (Zuuring et al. 1995). The MAGIS modeling system is based on mixed-integer mathematical programming that includes vegetation management and an optional roads component for analyzing access and associated costs and resource impacts (Weintraub et al. 1994). Generally, if a resource can be defined in a GIS and with rules relating the resource to management effects, the resource can be accounted for in MAGIS.

Figure 2 presents a schematic of the model integration structure. The MAGIS model was prepared for sub-model data by defining the attributes to import from the GIS layers. Other definitions were entered for management activities, costs, and rules for vegetation succession, activity outputs, and management activities. *Management regimes* were defined consisting of activities, alone or in series that could be applied to accomplish project objectives. Examples included slashing and broadcast burning to restore grass and sagebrush lands and mechanical thinning in the commercial management zones. With all definitions entered, the attributed GIS vegetation layer was imported to MAGIS.

Step 4: Define Basis for Scenario Comparison

The final step for building an integrated model was to define e*ffects functions*. These establish resource characteristics to be monitored and compared between alternative management scenarios run in MAGIS. These are constructed so that the output of each effects function specifically relates to a project objective. Effects functions commonly summarize acres affected by management actions. They may be viewed as an *accomplishment* meeting an objective (e.g. sum of stream project acres treated), or an *indicator* to be monitored or perhaps constrained (e.g. change in wildlife habitat index or number of acres impacted within the 300 ft stream buffer). Virtually any number of effects functions can be defined limited by project objectives and common sense. Effects functions defined for the Butte North Project include:

A. Vegetation
- Acres of lodgepole plantation thinned (accomplishment)
- Acres of grass/sagebrush restoration candidates treated (accomplishment)
- Acres of multi-story Douglas-fir treated (accomplishment)
- Acres of potential old growth affected (indicator)

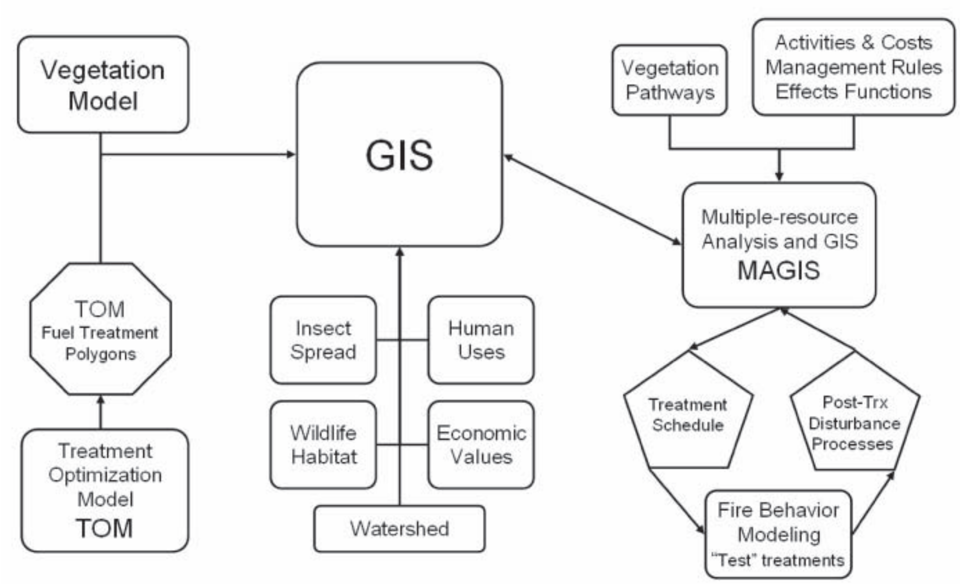

Figure 2—Schematic of model relationships and integration structure.

B. Insects
- Acres treated intersected by TOM polygons in areas of projected insect spread (accomplishment)

C. Fire and fuels
- Acres treated intersected by TOM given modeled fire behavior based on current vegetation (accomplishment)
- Acres treated classified as fire regime condition class 3 (accomplishment)

D. Watershed
- Acres of priority riparian project treated (accomplishment)
- Acres of stands treated containing any 300 ft stream buffer (indicator)

E. Wildlife habitat
- Acres treated containing habitat of key species (accomplishment or indicator depending upon associated affects)
- Index of wildlife habitat value (indicator)

F. Social
- Acres treated containing WUI buffer (accomplishment)
- Acres treated around reservoir (accomplishment)

G. Economics: These effects functions are either accomplishments or indicators depending upon other associated resource effects
- Total costs of activities
- Total product volume
- Total present net revenue

Step 5: Frame Alternative Scenarios

The process of using IAM to define alternative scenarios is similar to developing alternative land management proposals. Different combinations of desired outcomes are compiled, each emphasizing a particular set of resource objectives. A primary scenario goal or *objective function* is determined. Boolean logic is then applied to effects functions to set specific goals and apply constraints. For example, an objective function might be to maximize acres of WUI treated to reduce fuels. Constraints might be set to simultaneously limit impact in the stream protection zone, acres of mechanical treatment in the WUI zone, and budget. The mathematical solver in MAGIS first determines the feasibility of meeting the objective function within the constraints set and then calculates related impacts and outcomes defined by each effects function. Defining scenarios is an iterative and cumulative process. Results from one scenario are analyzed, adjusted, and fed into the next. This process continues until the users believe they have reached an optimal spatial and temporal schedule of treatments to meet objectives. Work on the Butte North modeling continues. Examples of basic scenarios which will be used for the Butte North analysis will include a fire threat reduction option, a wildlife option, and an economic option.

Forest Health Restoration Report Card

The IAM outlined for the Butte North Project demonstrates application of multiple modeling tools for multi-objective, multi-resource analysis. The single issue of fuel reduction does not drive the analysis. Fuels and fire threats are addressed in the context of the other significant environmental and management concerns. The opening assessment question is not, "What is the problem fire?" Instead this approach asks, "What role does fire play as one component of a complex system?" and "What management actions are warranted to address overall forest health?"

Expecting that management accomplishments must be accounted for based on standard performance criteria, the systematic assessment of key resources through the preceding analysis presents a logical foundation for a multiple criteria performance reporting tool. Given that fire and forest fuel will drive budgets for the foreseeable future and that the Healthy Forest Restoration Act establishes the management directives, the prospective tool is entitled: Forest Health Restoration Report Card. Figure 3 presents a working draft concept. The intent is to account for and acknowledge multiple costs and benefits from management activities, to concisely report expected treatments objectives, and to convey this information simultaneously to several audi-

PROJECT NAME: Butte North
LOCATION: Beaverhead-Deerlodge National Forest, Silver Bow Co., MT
PARTNERS: BDNF, MT DNRC
PROJECT SUMMARY:

			Treatment Method				Expected Treatment Effectiveness (yrs)
TREATMENT GOALS	Total	%	RX Fire Ac	%	Mechanical	%	
ACRES TREATED	**1000**	**100%**	**650**	**65%**	**350**	**35%**	
RESOURCE TOPICS							
VEGETATION							
Grass/sage restoration							
DF understory thin							
INSECTS & DISEASE							
FUEL REDUCTION							
FRCC Change	500	50%	250	25%	250	25%	
WATERSHED							
WILDLIFE HABITAT							
SOCIAL VALUES							
Wildland-Urban Interface	350	35%	200	20%	150	15%	20
Water Supply	200	20%	150	15%	25	2.5%	35
WATERSHED	250	25%	50	20%	250	100%	35
TES	50	5%	25	50%	10	20%	15
OLD GROWTH	100	10%	100	100%	65	65%	85
BIOMASS REMOVAL							
FINANCIAL ANALYSIS							
TREATMENT COST	$ (152,500)		$ (97,000)		$ (55,500)		
PRODUCT REVENUE	$89,275		$ 0		$89,275		
NET VALUE	$(63,225)				$33,775		
ECONOMIC IMPACTS							
DIRECT ECONOMIC EMPLOYMENT IMPACTS							
DIRECT ECONOMIC INCOME IMPACTS							

Figure 3—Working prototype for a Forest Health Restoration Report Card. Some cells are intentionally left empty to reflect how the single card can capture the unique character of each project.

ences. The report card should directly reflect the project purpose and need. It should document the expected resource effects, both positive and negative, expected duration of treatment effectiveness, the economic benefits and costs, and any other social effects that have been analyzed. The tool provides a valuable qualitative and quantitative summary of project goals, merits, impacts, and costs; accounts for annual accomplishments comparing treatment targets to actual acres treated; and provides a basis for future project monitoring and outcome-based performance reporting. This tool sets the foundation for measuring success beyond simply reporting acres treated and more robustly captures the value and intent of undertaking fuel and forest restoration treatments.

The report card system may be one tool to help restore public trust, because it clearly demonstrates that multiple resource and environmental concerns were addressed and acted upon. Furthermore, the report card system may provide a basis for more consistent multi-objective planning and monitoring of future projects with a forest health emphasis. Modeling results may be validated and the degree to which intentions are realized is transparent.

Future of Modeling and Performance Measures

Models may help guide decisions, not make them. Models are limited by errors and uncertainty and, as such, are never a substitute for professional judgment and ground verification of planning data. For all the error and uncertainties within the models and modeling processes themselves, we cannot hold off decisions until we have perfect systems. Models provide some measure of simplicity with the hope of greater clarity as we wrestle with inherently and intractably complex systems. Reasonably enough, management of complex systems requires tools that adequately represent this complexity. IAM is one such tool. Our current abilities to integrate resource modeling systems are coarse but will only improve with practice (Jakeman and Letcher 2003) and development of improved IAM tools and logic.

We have outlined a practical procedure for integrating fuel treatments into comprehensive ecosystem management through integrated assessment modeling. This framework provides a tool for systematic analysis of multiple resource objectives within a common planning area. Rather than fire and fuels issues driving the process, this framework provides insight into the relationship between fire, forest fuels, and other resources. The results from this integrated assessment modeling approach offer a structure to develop a multi-criteria performance report card. The outcome may be planning protocols that make better use of ecosystem science and more defensibly meet land management directives.

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Comparison of the Sensitivity of Landscape-Fire-Succession Models to Variation in Terrain, Fuel Pattern, Climate and Weather

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Abstract*—The relative importance of variables in determining area burned is an important management consideration although gaining insights from existing empirical data has proven difficult. The purpose of this study was to compare the sensitivity of modeled area burned to environmental factors across a range of independently-developed landscape-fire-succession models. The sensitivity of area burned to variation in four factors, namely terrain (flat, undulating and mountainous), fuel pattern (finely and coarsely clumped), climate (observed, warmer & wetter, and warmer & drier) and weather (year-to-year variability) was determined for four existing landscape-fire-succession models (EMBYR, FIRESCAPE, LANDSUM, and SEM-LAND) and a new model implemented in the LAMOS modelling shell (LAMOS(DS)). Sensitivity was measured as the variance in area burned explained by each of the four factors, and all of the interactions amongst them, in a standard generalised linear modelling analysis. Modeled area burned was most sensitive to climate and variation in weather, with four models sensitive to each of these factors and three models sensitive to their interaction. Models generally exhibited a trend of increasing area burned from observed, through warmer and wetter, to warmer and drier climates. Area burned was sensitive to terrain for FIRESCAPE and fuel pattern for EMBYR. These results demonstrate that the models are generally more sensitive to variation in climate and weather as compared with terrain complexity and fuel pattern, although the sensitivity to these latter factors in a small number of models demonstrates the importance of representing key processes. Our results have implications for representing fire in higher-order models like Dynamic Global Vegetation Models (DGVMs)*

Introduction

Wildland fire is a major disturbance in most ecosystems worldwide (Crutzen and Goldammer 1993). Fire interacts with weather and vegetation such that forested landscapes may burn quickly whenever fuels are abundant, dry and spatially continuous, especially if there is a strong surface wind (McArthur 1967; Rothermel 1972). The relative importance of variables in determining area burned is an important management consideration although gaining insights from existing empirical data has proven difficult.

Landscape-fire-succession models, that simulate the linked processes of fire and vegetation development in a spatial domain, are one of the few tools that can be used to explore the interaction of fire, weather and vegetation over long time scales. There is a diverse set of approaches to predicting fire regimes and vegetation dynamics over long time scales, due in large part to the variety of landscapes, fuels and climatic patterns that foster frequent forest

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fires (Swanson and others 1997; Lertzman and others 1998), and variation in modeler's approaches to representing them in models.

Systematic comparisons among models, using a standardised experimental design, offers insight into our understanding of the key processes and parameters affecting diverse ecosystems (Dale and others 1985; Rose and others 1991; Gardner and others 1996; VEMAP 1996; Pan and others 1998; Cramer et al 1999) as well as our confidence in the reliability of model predictions (Bugmann and others 1996; Turner and others 1989). The objective of this research is to compare a range of landscape-fire succession models to gain insight into the relative importance of terrain, fuel pattern, weather and climate in determining modeled area burned, and the extent to which findings can be generalized across a range of ecosystem types.

We selected a set of landscape-fire-succession models and performed a comparison on neutral landscapes to identify the relative importance and sensitivity of simulated fire to terrain, fuel pattern, weather and climate. We originally planned to compare results of models from the twelve classification categories of landscape-fire-succession models of Keane and others (2004) but in reality we limited ourselves to models from three classification categories selected from modelers with the time and resources to undertake the complex simulation design. We compared five models including EMBYR (Gardner and others 1996), FIRESCAPE (Cary & Banks 1999), LANDSUM (Keane and others 2002), SEMLAND (Li 2000), and a new application of the LAMOS modelling shell (Lavorel and others 2000). These models may appear functionally similar but they are quite different in many aspects, including a wide diversity in the simulation of fire spread and ignition, representation of vegetation, and the complexity of climate and fire linkages (Cary and others 2006).

This study does not represent an exercise in model validation. Rather, we selected models that have previously been verified and validated, and one new model, and analysed their behaviour with respect to variation in terrain, fuel pattern, weather and climate. A more comprehensive description of the study is given by Cary and others (2006).

The Models

EMBYR is an event-driven, grid-based simulation model of fire ignition and spread designed to represent the landscapes and fire regimes of Yellowstone National Park (Hargrove and others 2000). The pattern of forest succession of lodgepole pine forests is simulated by a Markov model, with fuels sufficient to sustain crown fires developing as a function of forest stand age. The probability of fire spreading from a burning pixel to each of its neighbors is determined by stand age, fuel moisture, wind speed and direction, and slope. An index of fire severity, based on fuel type, fuel moisture, wind speed and the rate that the cell burned, determines whether fire intensity is sufficiently high to cause a stand-replacing fire.

FIRESCAPE simulates individual fire events that are combined into patterns of fire frequency, fire intensity and season of occurrence (Cary and Banks 1999). Daily weather is generated by a modified version of the Richardson-type stochastic climate generator (Richardson 1981) so that serial correlations within a particular meteorological variable and cross correlations between variables are maintained (Matalas 1967). Ignition locations are generated from an empirical model of lightning strike modified from McRae (1992).

The rate of spread of fire from a burning pixel to its neighbors is assumed to be elliptical (Van Wagner 1969) and is determined by Huygens' Principle, although varying topography, fuel load and wind direction result in non-elliptical fires. Head fire rate of spread is according to the fire behavior algorithms of McArthur (McArthur 1967; Noble and others 1980) with fuel loads modeled using Olson's (1963) model of biomass accumulation which has been parameterized for a range of Australian systems.

LAMOS(DS) is an implementation of LAMOS (Lavorel and others 2000) with a contagious spread fire model working on a daily time step. It is a simple model, sensible to daily minimum and maximum temperature, precipitation, fuel amount and slope. LAMOS(DS) contains two principle functions; one to estimate pan evaporation (Bristow and Campbell 1984; Roderick 1999) which, together with precipitation, produces a moisture budget, and a second equation to modify spread probabilities as a function of slope (Li 2000) and intensity. Fire intensity is the product of three linear functions: fuel load ($0 – 1$ kg m^{-2}), moisture (0-200mm) and temperature (5-25°C). Temperature during the course of the fire is interpolated between the daily minimum and maximum by a symmetrical sine function. Fires are assumed to begin when temperature is at the daily maximum. Fuel is consumed in proportion to the resulting intensity.

The LANDscape SUccession Model (LANDSUM) is a spatially explicit vegetation dynamics simulation program wherein succession is treated as a deterministic process, and disturbances are treated as stochastic processes (Keane and others 2002). Fire spread is a function of fuel-type, wind speed and direction, and slope using equations from Rothermel (1972) and Albini (1976). The elements that define the fire regime (for example average fire size, ignition probabilities) are input parameters, whereas fire regime is an emergent property for the other models. Ordinarily, the area burned in LANDSUM would not vary amongst the climate factors, however for this comparison, the probability of ignition success was made sensitive to the Keetch-Byram Drought Index.

The SEM-LAND model (Spatially Explicit Model for LANDscape Dynamics) simulates fire regimes and associated forest landscape dynamics resulting from long-term interactions among forest fire events, landscape structures, and weather conditions (Li 2000). A fire process is simulated in two stages: initiation and spread. The fire initiation stage continues from the presence of a fire ignition source in a forest stand until most trees in that stand have been burned. Once most trees are burned, the fire has the potential to spread to its surrounding cells. The probability of fire spread is determined by fuel and weather conditions and slope using relationships from the Canadian Forest Fire Weather Index system (Van Wagner 1987) and Canadian Forest Fire Behavior Prediction system (Forest Canada Fire Danger Group 1992; Hirsh 1996).

The Comparison Design

The comparison involved determining the sensitivity of modeled area burned to systematic variation in terrain, fuel pattern, climate and weather (Cary and others 2006). It incorporated three types of terrain, two types of fuel pattern, three different climates, and the full extent of weather variability for simulation locations. The simulation landscape was an array of 1000 by 1000 square pixels measuring 50 by 50 meters.

Variation in terrain was introduced by varying the minimum and maximum elevation of the simulation landscape by varying the amplitude of the two-dimensional sine function used to represent terrain. The sine functions had a periodicity of 16.67 km (333.3 pixels). Three landscapes representing flat, rolling and mountainous terrain, with maximum slope values of 0°, 15° and 30° respectively and relief of 0 m, 1250 m and 2500 m respectively were generated (figure 1). The average elevation of each landscape was 1250 m.

Fuel pattern was varied to represent finely clumped and coarsely clumped fuel patterns (figure 2). The finely clumped fuel pattern was comprised of ten by ten pixel (25 ha) clumps of varying fuel ages, whereas the coarsely clumped fuel pattern was comprised of fifty by fifty pixel (625 ha) clumps. Maps of fuel ages were generated by randomly allocating values from the series 0.1, 0.2, 0.3, ...1.0 to both finely and coarsely clumped fuel maps so that values were represented evenly across the landscapes. Ten replicate maps of each fuel pattern type were randomly generated for the model comparison. Fuel maps were transformed differently for each model to produce either fuel load or fuel age related maps that were meaningful to individual models (see Cary and others 2006). The maps of different fuel types were characterised by the same average fuel load or age, however the arrangement of different aged fuels varied between map types.

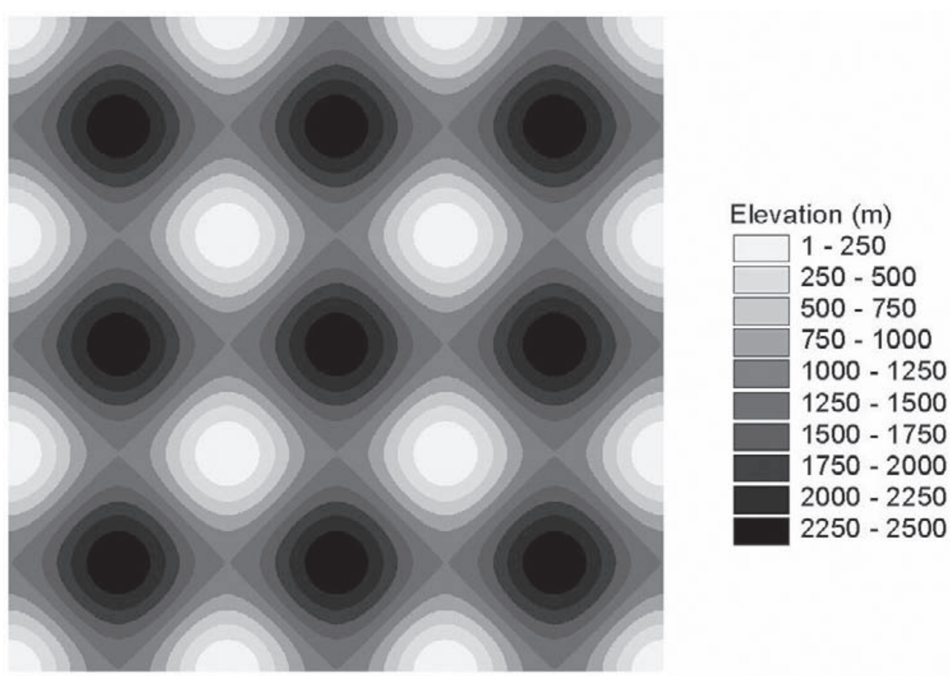

Figure 1—Pattern of elevation in mountainous landscape used in comparison of landscape-fire-succession models.

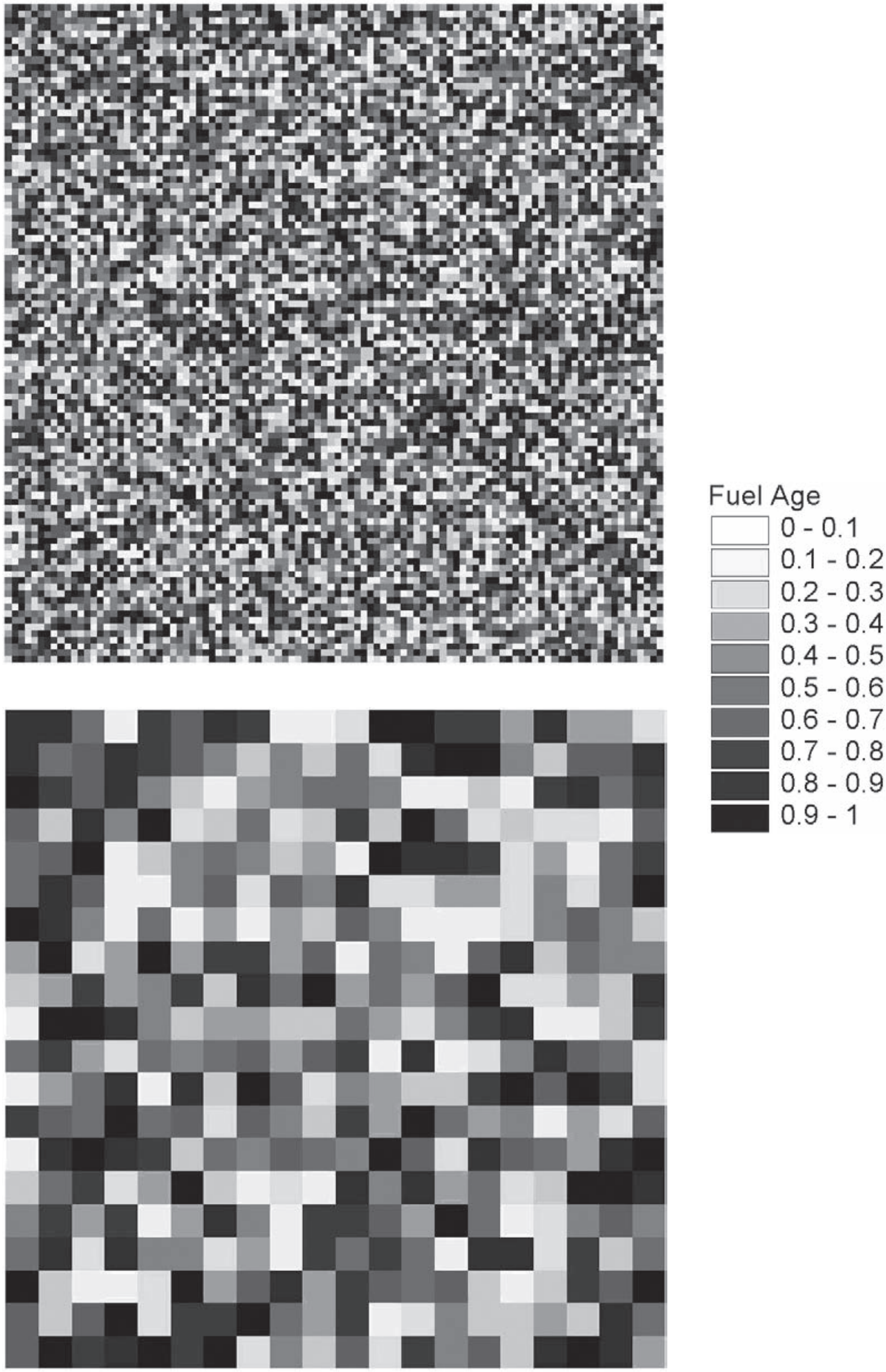

Figure 2—Replicate of each type of fuel pattern map used in comparison of landscape-fire succession models: a) finely clumped (25 hectare patches) and b) coarsely clumped (625 hectare patches) fuel pattern (values range from 0 to 1.0 and are transformed into fuel age or fuel load separately for each model.

Weather and climate are essentially different phenomena at fine temporal scales and were treated as orthogonal. Variation in weather was introduced for most models by selecting ten representative years of daily weather records for the landscape where the model has undergone most rigorous validation (table 1). For EMBYR, weather data from Glacier National Park, MT, was used. The ten weather years were selected so that the distribution of annual average daily temperature and annual average daily precipitation in the selected set best matched the variation in the weather record available (around 40 years for most models) (See Cary and others 2006). Three types of climate were included in the design, including observed, warmer/wetter, and warmer/drier climate. Daily values for the warmer/wetter and the warmer/drier climate were derived from the 10 weather years of observed climate by adding 3.6 °C (mid-range of projected global average temperature increase (1.4 to 5.8°C) (IPCC 2001) to daily temperature, and by decreasing daily precipitation by 20 percent for the warmer/drier climate and increasing daily precipitation by 20 percent for the warmer/wetter climate.

A total of 1,800 year-long simulations were run for each model (except for LANDSUM) from the 180 unique combinations of terrain (flat, mountainous, mountainous), fuel pattern (finely and coarsely clumped), climate (observed, warmer/wetter, warmer/drier), and weather (ten one-year replicates), given that there were ten replicate maps of each fuel pattern. Approximately 20 percent of the LANDSUM simulations did not experience fire and this resulted in a poor estimate of the probability and size of fires, because of the shortness of the simulation periods. This was rectified by performing ten

Table 1—Available weather data for study regions and associated models.

Location	Data type	Variables	Model
Glacier National Park, Montana	42 years, daily observations.	Daily maximum temperature (°C) Daily minimum temperature (°C) Daily precipitation (cm)	EMBYR LANDSUM
Edson, Alberta	34 years (1960 – 1993) of daily observation (observations at 1200 LST) from approximately the 1st April to 30th September, inclusive.	Temperature (°C) Relative Humidity (%) Windspeed (km.h^{-1}) Rainfall (mm) Daily FFMC*, DMC*, DC*, ISI*, BUI* Daily Fire Weather Index Number of days since rain * variables related to Fire Weather Index	SEM-LAND
Ginninderra, Australian Capital Territory	42 years of simulated weather based on Richardson-type weather simulator (Richardson, 1981) modified for all variables required for fire behaviour modelling.	Daily maximum temperature (°C) Daily minimum temperature (°C) Daily west-east wind speed (km.h^{-1}) Daily south-north wind speed (km.h^{-1}) Daily 9 am atmospheric vapour pressure (kPa) Daily precipitation (mm)	FIRESCAPE
Corsica	38 years (1960 – 1997) of daily observations.	Daily average temperature (°C) Daily precipitation (mm) Daily PET (mm)	LAMOS

simulation replicates for each unique combination of terrain, fuel pattern, fuel pattern replicate, climate, and weather replicate, and averaging them to produce a better estimate of area burned. Fires affected fuel load/age within each simulation but, since simulations were for only a single year, no vegetation succession algorithms were invoked. The total area burned per year (m^2) was recorded for each one-year simulation.

The sensitivity of simulated area burned to terrain, fuel pattern, climate and weather was assessed from the variance explained by each of the variables and all possible interactions. Variance explained (r^2) was determined from a fully factorial ANOVA performed in the SAS statistical package. Variance explained is a more meaningful measure than statistical significance when comparing the importance of environmental variables, particularly when dealing with simulated data. It facilitates the comparison of the importance of a range of variables on area burned, across a range of models with different input requirements and calibrated for widely separated landscapes characterised by quite different climate systems and weather syndromes. Plots of residual values against fitted values were constructed for each analysis. Analyses performed on untransformed area-burned data produced residuals which were highly skewed and the variance in residuals that was highly variable across fitted values. Transformation of area burned by the natural logarithm produced patterns of residuals that we considered acceptable for our analyses.

Results

Simulated area burned was more sensitive to climate and weather than to fuel pattern and terrain (table 2). Ln-transformed modeled area burned was considered sensitive to variation in climate for FIRESCAPE, LAMOS, LANDSUM and SEM-LAND while it was considered sensitive to variation in weather for EMBYR, FIRESCAPE, LANDSUM and SEM-LAND. The interaction between these two variables was considered important for EMBYR, LANDSUM and SEM-LAND. For models sensitive to climate, there was a trend for increasing area burned for warmer climates (warmer/drier and warmer/wetter) compared with the observed climate, with the warmer/drier climate being characterised by larger area burned than the warmer/wetter climate in two of four cases (see Cary and others 2006).

Only FIRESCAPE showed sensitivity to variation in terrain (and the interaction between terrain and weather, and that between terrain, climate and weather). Modeled area burned was highest for mountainous terrain and least for flat terrain. Only EMBYR showed sensitivity to variation in fuel pattern (and the interaction between fuel pattern and weather factors). Modeled area burned was higher for the coarsely clumped fuel pattern than for the finely clumped pattern (see Cary and others 2006).

Discussion

The variance in modeled area burned was greater for weather than climate for EMBYR, LANDSUM and SEM-LAND, compared with FIRESCAPE and LAMOS, perhaps because the inter-annual variation between the weather years for these locations was lower than for other sites. Nevertheless, sensitivity of modeled area burned to weather was considered important for four

Table 2—Relative Sums of Squares attributed to different sources of variation in the comparison of sensitivity of ln-transformed area burnt to terrain (Terrain), fuel pattern (Fuel), climate (Climate) and weather factors (Weather), and their interactions. Factors and their interactions are considered important if they explain more than 0.05 and 0.025 of total variance respectively. Factors and interactions considered unimportant are blank. Significant factors and interactions (P < 0.05) are indicated by *.

		Model				
Source	DF	EMBYR	FIRESCAPE	LAMOS	LANDSUM	SEM-LAND
Terrain	2		0.293*			
Fuel	1	0.217*	*		*	*
Terrain x Fuel	2		*			
Climate	2	*	0.418*	0.278*	0.178*	0.370*
Terrain x Climate	4		*			
Fuel x Climate	2	*				*
Terrain x Fuel x Climate	4		*			
Weather	9	0.329*	0.087*	*	0.333*	0.542*
Terrain x Weather	18		0.025*		*	
Fuel x Weather	9	0.031*	*			*
Terrain x Fuel x Weather	18	*				
Climate x Weather	18	0.096*	*	*	0.224*	0.046*
Terrain x Climate x Weath	36		0.025*			
Fuel x Climate x Weather	18	*				
Terr x Fuel x Clim x Weath	36					
Model	179	0.744	0.905	0.401	0.766	0.971

Note that not all significant sources are considered important.
(Source: Cary and others 2006)

out of five models. The overriding importance of weather for fire activity has been highlighted in numerous studies (see Flannigan and Harrington 1988; Swetnam 1993; Bessie and Johnson 1995; Hely and others 2001; Flannigan and Wotton 2001). Our finding regarding the importance of weather across a range of models highlights the importance of adequately incorporating variability in weather into landscape-fire-succession models.

Several authors have provided simulated evidence for increasing area burned or frequency of fire under warmer climates (Clark 1990; Cary and Banks 1999; Li and others 2000; Cary 2002), possibly due to a longer fire season (Stocks et al 1998; Wotton and Flannigan 1993). This is consistent with our general findings. Climate was not considered important for EMBYR although earlier studies have indicated that a wetter climate would result in larger fires (Gardner and others 1996). A possible explanation for the discrepancy is that, in this study, simulations were only one year in length and vegetation succession effects were not incorporated. We are planning new research where simulations will be centuries long, allowing for the importance of vegetation succession to be explored.

Fuel pattern was relatively unimportant, except in the case of EMBYR. Fire spread in EMBYR is partly a function of the nature of fuel in the source and target pixels of any fire spread event. Frequently changing fuel condition in the finely clumped fuel pattern resulted in a decrease in area burned compared with the coarsely clumped pattern. While this is a realistic representation of fire spread, fuel pattern accounts for a comparatively small amount of variance in EMBYR compared to climate and weather in the other models.

Terrain was considered important for FIRESCAPE, despite all models incorporating a similar positive effect of slope on fire spread. FIRESCAPE is the only model that varies weather with terrain. The mountainous terrain provides a greater proportion of the landscape which is warmer and drier (in the "valleys"), compared to the rolling and flat landscapes, given that all landscapes were characterized by an average elevation of 1250 m. Representing the effect of terrain on weather in landscape fire models is fundamental if this aspect of the terrain factor is to influence models results in a realistic fashion.

Our results have implications for representing fire in higher-order models like Dynamic Global Vegetation Models (DGVMs). The relative unimportance of fine scale fuel pattern indicates that coarse scale DGVMs may not need to incorporate pattern of vegetation within simulation cells, although this depends on the importance of vegetation succession on area burned, which was not tested in this experiment. On the other hand, landscape scale pattern in terrain was demonstrated to be fundamentally important using the one landscape-fire-succession model that incorporates the effect of terrain on weather. Also, the general finding of the importance of inter-annual variability in weather (compared with climate) has important implications for the inclusion of fire into DGVMs because an increase in inter-annual weather variability resulted in greater effects on area burned than the climate variable in some cases.

The results from this study are concerned with comparing landscapes where the mean fuel age/load is constant across simulations but varies in the arrangement of fuel (fuel pattern). We are presently using our approach to compare the sensitivity of modeled area burned to variation in approach/extent of fuel management and ignition probability. It also has considerable potential for conducting comparisons amongst groups of other types of models producing variation in landscape dynamics, and for further comparison amongst landscape-fire succession-models.

Acknowledgments

Thanks to the National Center for Ecological Analysis and Synthesis, a Center funded by the National Science Foundation (Grant #DEB-0072909), the University of California, and the Santa Barbara campus, who partly funded this research. We also thank all participants in NCEAS workshops especially Andrew Fall, Carol Miller, Don McKenzie and Mike Wotton, and Russ Parsons, and Dan Fagre who organised a workshop in Glacier National Park. The IGBP Fire Fast Track Initiative are acknowledged for their support of this project.

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Assessing Ecological Departure from Reference Conditions with the Fire Regime Condition Class (FRCC) Mapping Tool

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***Abstract**—Knowledge of ecological departure from a range of reference conditions provides a critical context for managing sustainable ecosystems. Fire Regime Condition Class (FRCC) is a qualitative measure characterizing possible departure from historical fire regimes. The FRCC Mapping Tool was developed as an ArcMap extension utilizing the protocol identified by the Interagency Fire Regime Condition Class Handbook to derive spatial depictions of vegetation departure. The FRCC Mapping Tool requires a biophysical setting layer identifying potential vegetation distribution, a current succession class layer allowing for comparison with historical vegetation, and a landscape layer (assessment area boundaries) as input data. The tool then compares existing vegetation composition for each biophysical setting to previously modeled reference conditions for those types. As described in this paper, spatial outputs characterizing vegetation departure at the succession class, biophysical setting, and landscape levels can be used by land managers to identify restoration objectives and priorities.*

Introduction

Severe wildfires in recent years have prompted Federal action to protect communities and restore landscapes and associated fire regimes (USDA Forest Service 2000). A standardized, relatively simple method of landscape assessment was needed to measure progress in ecosystem restoration (Schmidt et al. 2002). The Fire Regime Condition Class (FRCC) assessment method was developed (Hann et al. 2005) to meet this need, and to evaluate departure from a range of reference conditions at multiple scales. Reference conditions include the median values for abundance of seral stages, as well as an estimate of historical fire frequency and severity on landscapes and are developed for each BpS. FRCC is a classification of the amount of departure of conditions at a given time period (such as current or future) from historical ecological reference conditions (Hann et al. 2005). Current policy direction for federal lands management, embodied in the Healthy Forest Restoration Act of 2003 (P.L. 108-148), requires FRCC assessments as part of pre-restoration planning and post-restoration monitoring.

Because of the prominence of FRCC in legal and administrative direction, a number of national and regional trainings in FRCC methods were conducted in 2003 and 2004, with the aim of improving understanding and implementation of FRCC assessments. FRCC training continues at the local level, and is also available on line at www.frcc.gov. An understanding of these methods is a necessary precursor for effective use of the FRCC Mapping Tool.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Central to the FRCC concept is a classification of landscape integrity relative natural or "reference conditions." We define natural conditions as the range of ecological structure, function, and composition operating on landscapes without post-European settlement influence. Because of uncertainties and lack of information on what this range would be at present, we use the historical range of variation (that prior to European settlement) as an approximation of what the current natural range would be. Given the constraints of currently available data and knowledge, this historical range of variation (HRV) is assumed to represent the best understanding of a properly functioning ecosystem (Landres et al. 1999, Hessburg et al. 1999). When actual historical data are available (tree ring studies, legacy photographs, etc.), the historical range of variation can be described directly, if often incompletely. Usually, however, modeling is required. Modeling this range of historic reference conditions, and then comparing it to current conditions, allows us to infer a departure from conditions presumably influenced by a properly functioning disturbance regime (Cleland et al. 2004).

Moving landscapes closer to the historic range of variation can be useful if the management goal is to restore ecosystems across landscapes. Note, however, that the range of variation is not necessarily the same as a desired future condition. Maintaining wildlife habitat and protecting communities from wildlfire risk are examples where management goals are not necessarily the same as moving landscapes towards HRV.

A simple, intuitive concept in principle, modeling HRV can be fraught with complexity and sources of error. One problem with estimating historic landscapes is that we are generally working with very little data (Gill and McCarthy 1998, Dillon et al. 2005, Marcot 2005). Another problem is that climate change may lead to changing reference conditions; i.e., the historical range of variation becomes obsolete as an approximation of the natural range of variation. Nevertheless, HRV remains our best approximation of a properly functioning system, at least until better models are available.

Dillon et al. (2005) cautioned that modeling HRV has four primary requirements: 1) analyses should be conducted at multiple scales so that important ecological processes are not missed or misrepresented; 2) assessments should consider spatial variation of vegetation patterns across landscapes (see also Arno and Petersen 1983, Johnson and Gutsell 1994); 3) variability can be calculated in several ways, and this should be considered for a more meaningful result (see also Marcot 2005); and 4) consider the role of climate change over time; e.g., climatic conditions during the Little Ice Age (1700-1850), a timeframe often used for the historic range, are very different from those today (see also Millar and Woolfenden 1999).

The FRCC Mapping Tool is a menu-driven GIS extension automating and spatially applying FRCC calculations. As designed and with subsequent refinements, it addresses each of these considerations. The practical outcomes of Mapping Tool use, however, are still unfolding as it is implemented and results evaluated. The Mapping Tool can be easily run at multiple scales, providing that input layers are delineated or can be aggregated at those scales, addressing requirement (1) above. FRCC is based largely on variation in spatial patterns, addressing requirement (2). Throughout this paper, the reader should fully realize departure is calculated using an estimated mean or median value of succession stage abundances. Departure from a range of values would be more meaningful, and methods to develop this are under active consideration (requirement 3). Finally, as for climate change (requirement 4), there is nothing in FRCC that precludes modeling different climate scenarios. As climate change effects on vegetation become better understood and models more widely available, FRCC reference conditions can be adjusted accordingly.

During the initial development of the FRCC methodology, and with subsequent research efforts such as the multi-year LANDFIRE project (www.landfire.gov), reference conditions were modeled to estimate HRV. Specifically, HRV was estimated for vegetative structure and composition, and in terms of fire regime characteristics (fire frequency and severity). Using a combination of literature searches, expert opinion, and simulation modeling, HRV metrics were developed for all major vegetation types, or "Biophysical Settings" (BpS), in the U.S. Biophysical settings are a potential vegetation concept defined using a disturbance-constrained approach; i.e., succession and vegetation development occur within the bounds of historic natural disturbances; non-lethal disturbance frequency and severity can influence successional trajectories (Hann et al. 2005). To date, more than 300 reference condition models provide the basic foundation for diagnosing FRCC at multiple spatial scales.

The FRCC system is an index of departure, with three condition classes. Properly functioning landscapes, defined as exhibiting less than 33 percent departure from the median or average HRV conditions, receive a Condition Class 1 rating. Condition Class 2 represents landscapes with moderate departure (33 to 66 percent departure), and Condition Class 3 lands show high departure (greater than 66 percent). These classes are generally useful for planning and prioritizing ecosystem maintenance and restoration. For example, FRCC data might provide baseline data for pre- and post-treatment planning, monitoring, and accomplishment reporting.

FRCC assessments can be conducted in several ways. Field-based assessments can be made where an evaluator rates the vegetation (succession stage abundance) and fire regime components (current fire frequency and severity) of the landscape using aerial photography, field observation, and fire atlas data. These landscapes are generally in the range of hundreds to thousands of acres. This method is useful for field checking of estimates made at broader scales and for local monitoring. Another alternative is to use the FRCC Mapping Tool with remotely sensed vegetation data in a geographic information system (GIS) to produce maps at various scales. The Mapping Tool evaluates remotely sensed vegetation data to produce spatially specific FRCC diagnoses. A third option, not discussed in this paper, is to download the remotely sensed FRCC map from www.landfire.gov. That data layer, however, was designed for regional and national-scale analyses and may be too coarse for many analyses.

The FRCC Mapping Tool provides an objective, consistent, and spatially specific way to measure post-European settlement changes across multiple geographic scales if suitable data are available. Assessments based on the FRCC Mapping Tool can help managers prioritize landscapes for possible restoration and maintenance activities from fine (e.g., hundreds of acres) to coarse (e.g., millions of acres) scales. Finally, the Mapping Tool is relatively easy to use and understand—not a minor consideration when a standardized method for use at multiple organizational levels is needed.

FRCC Mapping Tool Characteristics

The FRCC Mapping Tool was designed in conjunction with the field-based Standard Landscape Method described in the FRCC Guidebook (Hann and others 2005). In contrast with field-based FRCC assessments, the Mapping Tool is a GIS application that produces multiple spatial layers to analyze pixel- to landscape scale (ranging from hundreds to millions of acres) departure and FRCC.

Both FRCC methods use similar principles to evaluate landscape departure and condition class. Field-based assessments evaluate existing vegetation and fire frequency/severity, whereas the FRCC Mapping Tool currently assesses only the departure of existing vegetation from reference vegetation conditions. To date, the software team developing the mapping tool has not been able to develop a way to effectively evaluate post-European settlement fire frequency and severity for a given landscape. This is primarily because these data layers are lacking or inconsistent for most areas of the country, not because of software limitations. Nonetheless, for many biophysical settings the existing condition indicates changes in fire regimes compared to the reference range.

Because of the similarity between the two FRCC methods, potential users of the Mapping Tool should first seek FRCC certification (see www.frcc.gov). In addition, users should have a firm understanding of geographic information systems (GIS) and experience using raster data and ArcMap (Version 9.0 or later) software. The Mapping Tool software, user guide, and systems requirements can be downloaded at www.frcc.gov.

The FRCC Mapping Tool uses three input layers to produce six output layers. (See Figure 1 for a diagram of the mapping process used in the Tool.) The Mapping Tool also produces a summary spreadsheet known as the Management Report. This report shows the current acres in each BpS succession class, and the area that would need to be converted to restore a landscape with a range of conditions similar to the historical range.

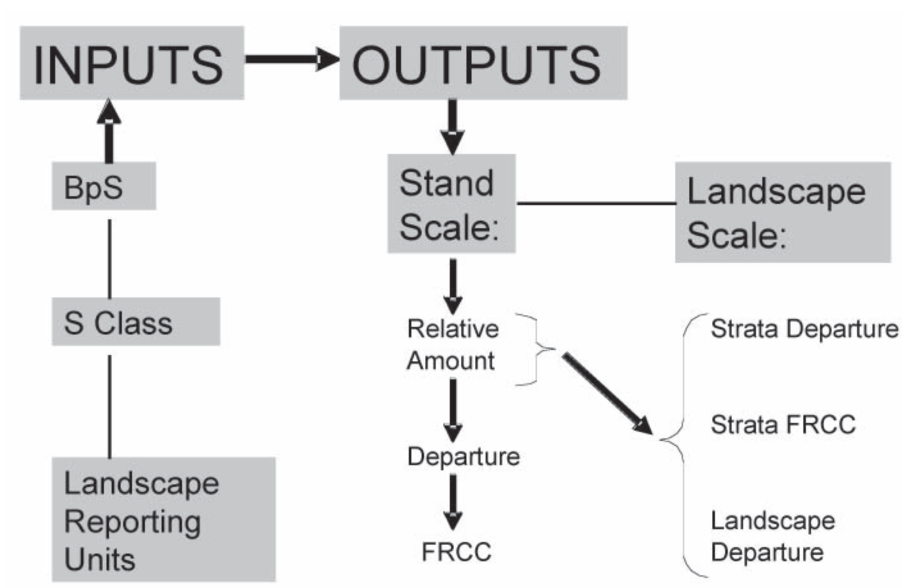

Figure 1—Diagram of the FRCC Mapping Tool process.

Input Data Layers

The Mapping Tool derives its suite of FRCC attributes from three user-provided input layers. These data sources can range widely, from coarse field-level data, to data derived from satellite imagery, to photo-interpreted vegetation mapping with extensive field checking. Because FRCC is a scale-dependent variable (Hann and others 2005), users must first provide a map to support scale-appropriate succession class analysis. This *Landscape Layer* should identify the appropriate spatial scale and boundaries for assessing FRCC. It may vary by BpS or geographic area. The Mapping Tool allows up to three landscape levels for consideration. For example, a tri-level nested hierarchy of area hydrologic units or similar nested classification can be used. When based on hydrologic units, for example, the map units might range from subwatersheds, to watersheds, to subbasins (nested watersheds of increasing area, Figure 2). These hierarchical maps allow the FRCC Mapping Tool to analyze Succession Classes according to ecologically appropriate scales, which differ among fire regimes. For example, a subwatershed scale can be used where small or patchy fires predominated historically (fire regime groups I and II [Hann and others 2005]). Conversely, BpS's influenced primarily by large replacement fires (Regimes IV and V) should be analyzed at the largest landscape scale because large fires can falsely appear to skew the statistical distribution of succession classes for small study areas. Hann and others (2005) have developed guidelines for analyzing FRCC based on fire regime-topography combinations (Table 1).

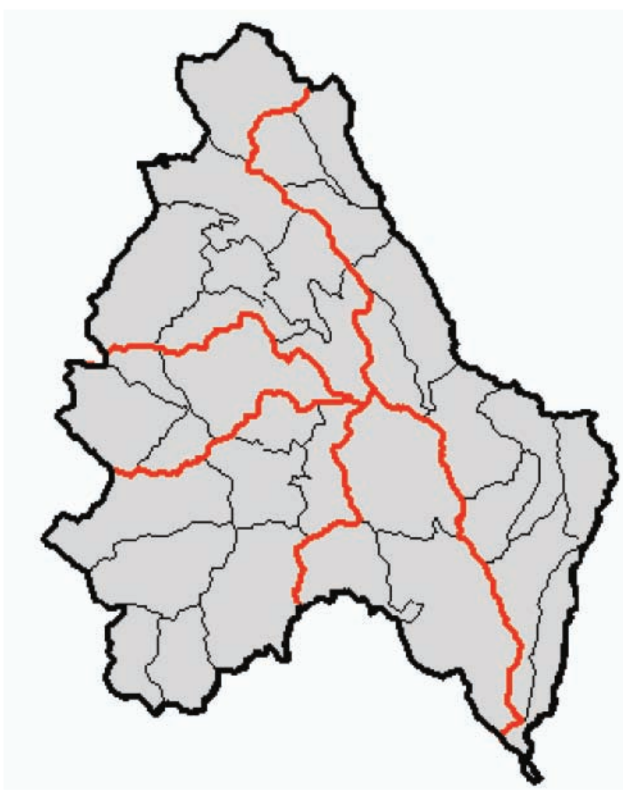

Figure 2—Example of tri-nested landscape hierarchy based on hydrologic units (from Hann et al. 2005). Such ecologically based classifications are useful for FRCC analysis, where potential analysis units range from the subwatershed to the subbasin scales.

Table 1—Scale guidelines for determining FRCC (Hann and others 2005). Suggested analysis area size range is based on dominant fire regime type and is inversely related to slope steepness and land dissection.

Fire regime group[1]	Terrain: Flat to rolling (lightly to moderately dissected)	Terrain: Steep (moderately to highly dissected)
	------------------ *acres* ------------------	
I, II	50-2000	50-1000
III	500-2000	250-1000
IV,	5000-1,000,000	2000-250,000
V (replacement severity)	5000-1,000,000	2000-250,000
V (mixed severity)	50-10,000	50-10,000

[1] I (0-35 yr/low to mixed severity); II (0-35 yr/stand replacement); III (35-200 yr/mixed severity); IV (35-200 yr/stand replacement); V (200+ yr/stand replacement [but can include any severity type]).

To summarize input requirements for the landscape layer, the user must: 1) provide a base map containing up to three nested landscape sizes, such as hydrologic units or ecological units (Winthers et al. 2005), and 2) in an associated table, specify for the Mapping Tool which landscape levels are appropriate for FRCC analysis based on BpS, dominant fire regime types and associated terrain dissection. The Mapping Tool then concurrently analyzes BpS vegetation succession classes according to each user-specified landscape level in the area.

The FRCC Mapping Tool also requires a *Biophysical Settings* input layer, which shows BpS distribution within the analysis area. The Mapping Tool analyzes this layer in tandem with a user-provided Reference Condition table to document the estimated average amount of each succession class historically. For instance, results from a given BpS model might suggest up to 20 percent of the type occurred in the early seral succession class, 40 percent occurred in the mid-seral open class, 10 percent occurred in the mid-seral closed class, and so on.

The LANDFIRE reference condition tables for the entire U.S. will load automatically after installing the Mapping Tool software, or users can develop custom reference condition tables based on local data. These tables must contain three pieces of information for the Mapping Tool: 1) a comprehensive list of all BpS within the study area, 2) reference condition amount (in percent) for each BpS succession class, and 3) the appropriate landscape reporting scale for each BpS type. Determining this scale generally means identifying a scale large enough to encompass the normal range of disturbance (fire) sizes and frequency for the question of interest.

Finally, the user must provide a *Succession Classes* layer showing the current distribution of succession classes within the analysis area. This layer can be generated from local current vegetation layers crosswalked to the appropriate FRCC succession class. This allows the Mapping Tool to compare the current amount of each succession class to the estimated historical amounts, thus assessing FRCC departure and condition class diagnoses. The LANDFIRE project represents a good source of data for succession class and other information. Upon completion in 2009, comprehensive U.S. map coverage will be available for succession classes, BpS, and other layers.

Output Data

To date, the FRCC Mapping Tool produces six output raster (pixel-based) GIS coverages (map layers) describing various Fire Regime Condition Class metrics. The Mapping Tool also generates a report summarizing the raster data. Two additional rasters are now in the final stages of development, as discussed below. For more detailed information on all layers, see the FRCC Guidebook (Chapter 4 in Hann and others 2005).

Output layers generated by the Mapping Tool fall into two groups: those at the BpS/landscape scales and those at the succession class/stand scales. The first group (BpS/landscape scales) includes three layers. The first of these, the *Strata Departure* layer summarizes Departure for each BpS, (or landscape "stratum," Hann et al. 2005). (Note that the soon-to-be-replaced FRCC Guidebook uses the now outdated name "S*tratum S-Class Departure*" for this layer.) The *Strata Departure* layer integrates the landscape strata according to a number of percent Departure classes. The next layer is the "*Strata FRCC*" layer (previously called the "*Stratum S-Class FRCC*" layer) (Figure 3). This data layer classifies the various BpS departure results according to the three FRCC Condition Classes described above. The final raster currently available is the "*Landscape Departure*" layer. Here, the Mapping Tool rates landscape-scale Departure by calculating an area-weighted average of the various strata departure percents, then by generating an overall rating for the appropriate landscape scale. When an area is dominated by large replacement fires, for instance, the tool bases the departure rating on the largest landscape scale defined by the user, such as a watershed occupying tens of thousands of acres.

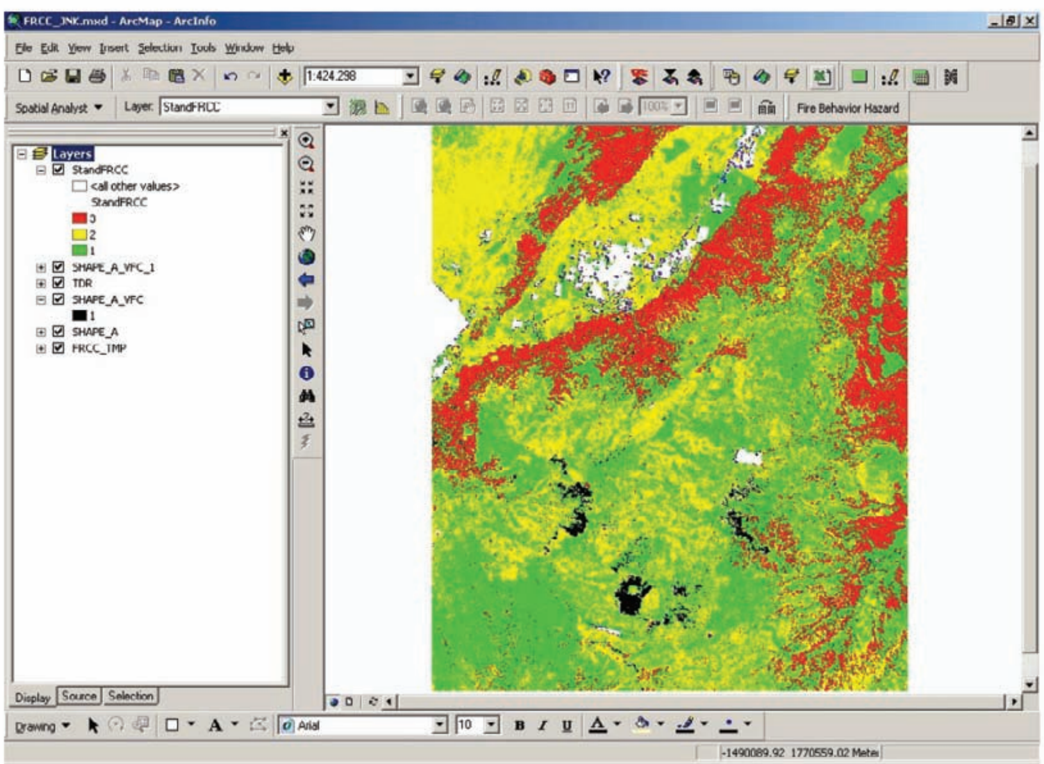

Figure 3—Example of FRCC Mapping Tool output for a hypothetical analysis area. Map shows Fire Regime Condition Class for the various landscape Strata, which typically represent an area's biophysical settings (*Key*: green is Condition Class 1, yellow is Condition Class 2, red is Condition Class 3 [white polygons indicate "No Data"]).

In the second group (succession class/stand scales), the first data layer generated by the FRCC Mapping Tool is the *Succession Class Percent Difference* layer. This output compares the amount of each BpS succession class during the current period to the estimated average amounts for the Reference period. In this case the measurement scale ranges from -100% to +100%, with zero representing similar amounts, negative values indicating deficient amounts, and positive percents representing excessive amounts. That is, the layer shows the most deficient to the most excessive (relative to the historic median) succession classes on today's landscape.

The next output layer is the *Succession Class Relative Amount*. (The current version of the FRCC Guidebook (Hann et al. 2005) uses the now outdated name "Stratum S-Class Relative Amount" for this layer.) This layer simply classifies the percent difference data according to the FRCC Guidebook (Hann and others 2005)(Figure 4). For example, pixels with a percent difference value of between minus 33 and minus 66 percent are "under-represented," whereas values between plus 33 and plus 66 percent are considered "over-represented." Classifying the myriad results from the percent difference layer thus helps users more easily identify which succession classes should be maintained, versus those that could be reduced or recruited, in order to emulate average BpS Reference Conditions.

Finally, the *Stand Condition Class* (FRCC) layer, previously called "*Stand Level FRCC*" (Hann et al. 2005), further classifies the above results. Here, the Mapping Tool rates the relative amount output according to the three Condition Classes mentioned earlier. For example, pixels in the "similar," "under-represented," and "trace" relative amount classes are rated as Stand Condition Class 1. Pixels in the "over-represented" relative amount class are considered to be Stand Condition Class 2, and those in the "abundant" relative amount class are Stand Condition Class 3. This layer was developed primarily to facilitate reporting and accomplishment. We stress this layer should not be used as a proxy for the landscape condition class layer, because the latter is a more appropriate layer for identifying FRCC, a landscape-scale measure. It is better to think of stands as having *membership* in successional stage classes that are either over-abundant, under-abundant, or within the historic range.

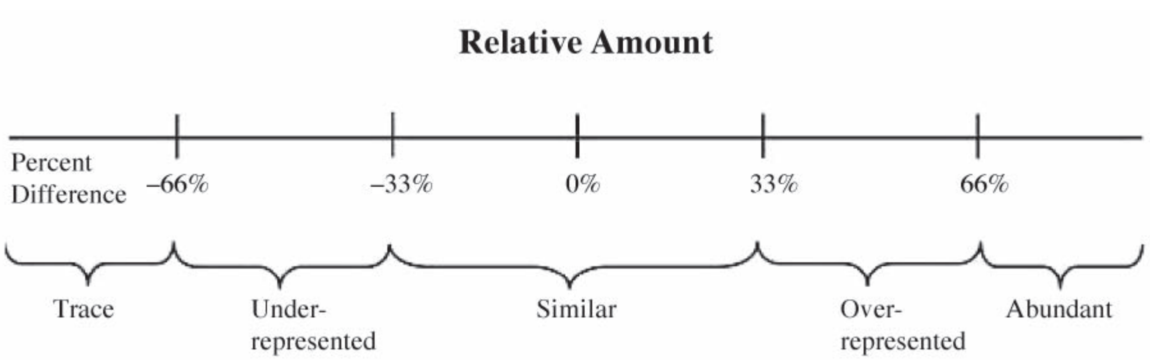

Figure 4—The Percent Difference- and Relative Amount scales used for FRCC assessments.

Software for two additional rasters currently is being developed, yielding an eventual total of eight data layers. Specifically, a *Stand Departure* layer and a *Landscape Condition Class (FRCC)* layer will likely be available by late 2006. The *Stand Departure* layer will base departure at the local (stand) scale on each stands membership in an seral stage abundance class compared to the historic average. The *Landscape Condition Class* layer will generate a single FRCC call for a landscape (delineated by the user) that is the weighted average of its member *Strata Condition Classes*.

The FRCC Mapping Tool also generates a Management Report spreadsheet to accompany the output rasters. The spreadsheet serves as the primary tool for analyzing and interpreting the GIS results, helping to support various planning needs. For instance, the data helps identify the ecological condition of an individual BpS or for multiple BpS in a given analysis area. The GIS data can also help managers identify ecological conditions and prioritize treatments ranging in scale from individual stands to entire landscapes. Such FRCC data can also be useful for fulfilling various reporting requirements, for developing budgets, and for supporting public education.

Mapping Tool Limitations

The FRCC Mapping Tool has several limitations. First, unlike field-based assessments, the Mapping Tool cannot be used to document post-settlement trends in fire frequency and severity. In many cases, however, the remotely sensed vegetation condition serves as an indirect measure of current fire potential, essentially serving as a proxy for those two FRCC metrics. Using remotely sensed data to identify numerous vegetation types and current conditions also can be difficult. Distinguishing between closely related BpS types and among the various succession classes is frequently challenging, particularly when types occupy closely similar terrain. In the western U.S., for example, the distinction between early successional Class “A” in pinyon pine (*Pinus edulis*)-juniper (*Juniperus* spp.) woodlands and similarly grass-dominated succession classes in adjacent sagebrush (*Artemisia* spp.) types can be difficult, especially for broad ecotones. Identifying various types of FRCC-defined “Uncharacteristic” succession classes also can be difficult when using remotely sensed data. Examples include areas invaded by varying amounts of exotic cheatgrass (*Bromus tectorum*), and woodland-grassland ecotones experiencing tree encroachment as a result of post-1900 fire exclusion. To help mitigate such interpretation errors, users of the FRCC Mapping Tool might need to conduct local field sampling to help improve the digital “signatures” for the remotely sensed data.

Management Applications

To date, land managers have used the FRCC Mapping Tool to support various planning activities. Introduced in late 2004 during a number of training sessions in the western U.S., the FRCC Mapping Tool is gaining acceptance and use. Although the Tool has not yet been fully implemented, enough practical experience has emerged that we can highlight several management oriented examples and issues here. As of 2006, the mapping tool has been used to determine FRCC on National Forests throughout much of the Pacific Northwest Region. One of the software’s main strengths as reported by users is the personnel time saved with its use. The Tool has helped automate a GIS process that would otherwise require a number of time-consuming steps. The FRCC Mapping Tool has also helped promote a standardized approach to determining FRCC (Jane Kertis, Siuslaw National Forest, pers. comm.), facilitating communication among land managers.

Improper or inconsistent use of the Mapping Tool, rather than software design and function, seems to be the main issue to date. The Mapping Tool will not run if the input layers do not agree with each other and with the reference condition table. For example, if a BpS on the map layer is not included in the reference conditions table, the software will not run. Hence the importance of consistent input data without errors. Also, using inappropriate landscape input maps can be expected to produce varying degrees of FRCC estimation error for similar vegetation types. Experienced users are currently helping to educate their peers about the FRCC scale issue and the appropriate uses of the Mapping Tool. Instructions on use of the Mapping Tool can be found in the FRCC Guidebook (Hann et al. 2005).

The FRCC Mapping Tool will be used to assess subregions, such as northwest Oregon (Jane Kertis, Siuslaw National Forest, pers. comm.). Similarly, the USDA Forest Service Pacific Northwest Region's standardized existing vegetation mapping effort, known as the Interagency Mapping and Assessment Process (IMAP) also will examine the potential utility of the Mapping Tool for assessing FRCC and related metrics at more local landscape scales than LANDFIRE does. Given the vast amount of area in the U.S. currently in need of ecological assessments, newly emerging GIS software such as the FRCC Mapping Tool will become increasingly important to land managers.

Acknowledgments

The FRCC Mapping Tool was developed by the National Interagency Fuels Technology Team (NIFTT), the technology transfer unit of the National Interagency Fuels Coordinating Group. Both are Federal entities representing the U.S. Forest Service, Bureau of Land Management, Bureau of Indian Affairs, Fish and Wildlife Service, and National Park Service. Additionally, The Nature Conservancy participates as a formal partner in the FRCC/LANDFIRE effort.

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Predicting Post-Fire Severity Effects in Coast Redwood Forests Using FARSITE

Hugh Scanlon[1] and Yana Valachovic[2]

Abstract—*Assessing post-fire impacts in coast redwood (Sequoia sempervirens) forests can be difficult due to rough terrain, limited roads, and dense canopies. Remote sensing techniques can identify overstory damage, locating high intensity damage areas, although this can underestimate the effects on the understory vegetation and soils. To accurately assess understory impacts requires field assessment techniques, which can be expensive for larger burn areas. Where geospatial data for fuels and topography can be combined with weather data using FARSITE, a fire behavior simulation model, landscape fire behavior predictions can be made. Fire behavior outputs can be generated to produce a post-fire predicted landscape map of fire severity. The 2003 Canoe fire burned 4,000 hectares, primarily in old-growth redwood forests in Humboldt County, California. Post-fire sampling of burn impact was assessed using the Composite Burn Index methodology and found to be unrelated to FARSITE produced fire behavior variables using regression analysis. This finding is understandable because basic FARSITE landscape data available for this fire lacked fuel load information for post-combustion analysis. The Canoe Fire had a slow rate of spread, and with the deep fuel beds present; long duration burning was observed. Fire severity, as described by the Composite Burn Index, was greatest in the forest understory. FARSITE was a useful projection tool for perimeter advance and flame lengths associated with the fire front.*

Introduction

The short-term effects of wildfire on vegetation, soils, wildlife, and watersheds are poorly understood in the coastal redwood [*Sequoia sempervirens* (D. Don) Endl.] forests of northern California. The September 2003 4,575 hectare, (11,214 acre) Canoe Fire, ignited by lightning in Humboldt Redwoods State Park, provided a rare opportunity to better understand the mixed effects of fire following logging and over a half century of fire exclusion in old-growth and second-growth forests.

Assessing post-fire impacts in coast redwood forests can be difficult due to rough terrain, limited access, and dense canopies. Remote sensing techniques can identify overstory damage, locating high intensity damage areas, although this can underestimate the effects on the understory vegetation and soils. To accurately assess understory impacts requires field assessment techniques, which can be expensive for larger burn areas.

Where geospatial data for fuels and topography can be combined with weather data using a fire behavior simulation model, landscape fire behavior predictions can be made. Fire behavior outputs can be generated to produce a post-fire predicted landscape map of fire severity.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Methods

The 2003 Canoe fire started in Humboldt Redwoods State Park in Humboldt County, California, burning primarily old-growth and young-growth redwood forests. Stand species included coast redwood, Douglas-fir (*Psudeotsuga menziesii)*, and tanoak (*Lithocarpus densiflorus*) in the overstory. Understory species included suppressed redwood, tanoak, huckleberry (*Vaccinium* sp.) and *Oxalis oregana*. The burn included unlogged old-growth areas, partially logged areas with a residual old-growth component, and previously logged areas that have stands of 60 to 100 year young-growth. A field based fire severity assessment was completed 9 months after the burn using the Composite Burn Index Methodology (FIREMON 2003) and was used to calibrate a map of the fire effects based on remotely sensed data. We tested the prediction ability of the FARSITE (Finney 2004) fire simulator to produce a similar map.

CBI Analysis

An initial fire severity map was created using a remote sensing approach. Pre- and post-fire IKONOS imagery (2002 pre-burn versus 2004 post-burn) was visually compared to delineate fire severity boundaries. Oblique imagery taken after the fire from a helicopter in December 2003 was used to validate three established severity classes. Severity classes were defined as: low with no visible change to the canopy; medium with <50% canopy loss; and high with a >50% loss. The minimum mapping unit was approximately 5 acres and boundaries were drawn with heads-up digitizing.

The forests of the burned area were classified into one of three community types (alluvial redwood, slope redwood and Douglas-fir forests), two management histories (old-growth or second growth stands), and two fire severity types based on observations of canopy conditions, with low representing green canopy conditions, and high with canopy mortality. This design created a factorial of 12 stand types and five replicate plots that were assigned at random using a GIS application. One type, old-growth alluvial high severity did not exist and therefore was excluded. As a result, 55 plots were installed and utilized for comparisons.

The Composite Burn Index (CBI) is a field technique developed by the interagency FIREMON program to identify and quantify fire effects over large areas. FIREMON is designed for repetitive measures. We applied the CBImethodology during the summer of 2004, nine months post-burn in 0.04 hectare (0.1 acre) circular plots. Characteristics were related to individual strata and scores averaged for the whole plot. The strata consisted of a) substrates or soils, b) herbs, low shrubs and small trees < 1 meter tall, c) tall shrubs and saplings 1< 5 m, d) intermediate and subdominants trees, and e) the dominant trees. The color and condition of the soils, the amount and quality of the fuels and vegetation consumed, the regeneration post-fire, the establishment of new seral species, and blacking, scorching and torching of the trees was evaluated.

We used the field data to calibrate or validate the remote sensing results. Our results are presented as an average of the scores for 1) total plot (i.e. all strata) 2) overstory (i.e. only the dominant tree stratum) and 3) understory (i.e. soil to vegetation <5 m tall). The CBI produces a score on a 0-3 basis with 3 as extremely high severity.

NCSS was used to analyze the data using ANOVA and means separation was performed with Fisher's Protected LSD.

FARSITE Analysis

FARSITE is a spatial fire behavior simulation system. The base landscape data was created at the Northern California Geographic Area Command Center, Redding, California in September 2003, and was used during the fire to predict short and medium range fire growth. Slope, aspect, and elevation data are derived from 30-meter resolution USGS Digital Elevation Models. The fuel model layer was derived from the California Department of Forestry and Fire Protection's Forest and Rangeland Assessment Program remote sensing data. Crown canopy values were estimated by H. Scanlon during the fire. No fuel loading data for post-frontal combustion analysis was available.

Weather data for analysis are derived from the nearby Eel River Remote Automated Weather Station (RAWS) and a portable RAWS.

The Eel River RAWS was used hourly for all wind data. The portable RAWS was deployed in the fire area from September 23 to October 1. These stations were used to develop the diurnal cycle of maximum temperature—minimum relative humidity, minimum temperature—maximum relative humidity for the fire.

In the early stages of the fire, perimeter data was estimated visually by aircraft and are therefore sparse and imprecise,. No CBI data sample plots were within these initial fire areas. As the fire increased in size, fire perimeters were determined primarily using helicopter mounted thermal imaging technology. Usually only one perimeter was generated at the end of each flight day. The daily fire perimeter was used as an ignition starting point for FARSITE, and the burn was projected for at least 48 hours. Initially, a 6 hour daily burning period was used since the fire advance was initially slow. This was extended to a 10 hour active burning period by the second week of the fire. Additional ignition was added where perimeter conrol firing operations are known to have been used and actual fire advance was not reasonably predicted by model.

Where the fire was projected to advance, FARSITE predicted the following values for each 30 m x 30 m raster cell: time of fire arrival from run initiation; rate of spread; flame length; fireline intensity: heat per unit area. Raster output from FARSITE was imported to ESRI ArcMap for compilation and analysis. For each overlapping CBI sample site and FARSITE raster cell, the resulting fire behavior values were evaluated against the corresponding fire intensity for the understory, overstory, and combined CBI values using linear regression (Microsoft Excel 2003).

Results and Discussion

The Canoe fire produced a complex mosaic of fire effects, with the majority of the burned area classified as low or low-moderate severity, based on remote and field calibrated data. Results of the remote evaluation (Ikonos imagery and aerial photos) were well correlated with the field established CBI ratings for the overstory, but significantly under-estimated the fire severity observed in the understory. The Canoe Fire had a slow rate of spread, and with the deep fuel beds present, long duration smoldering burning was observed. Some patches of high severity effects were observed along the ridges where fire intensity was the greatest.

Since fire severity was under-estimated in all but the high severity areas using remote sensing, modeling the fire using FARSITE had some potential to provide better prediction for these sites. As applied, FARSITE only modeled the advancing fire front, not the long duration burning following the front's passage.

The Composite Burn Index (CBI) results were found to be unrelated to FARSITE produced fire behavior variables using linear regression analysis. The FARSITE outputs of fireline intensity, flame length, heat per unit area, rate of spread, and reaction intensity were poor predictors ($r^2 < 0.10$) and not significant for field derived understory, overstory, and combined CBI values.

Knowing that the longer these models project into the future, the more inaccurate they become, we reassessed our data to use only those CBI plots where the fire arrived within 48 hours, then 24 hours of the run initiation. The linear regression fit did not improve substantially. Review of scatter plot diagrams did not suggest improvement by using transformation functions (Figure 1).

Finding the fire behavior outputs as unrelated to the CBI results is understandable because the basic FARSITE landscape data lacked fuel load information for post-combustion analysis. The fire burned for a long time after the passing of the fire front, which we were unable to model. FARSITE was a useful projection tool for perimeter advance and flame lengths associated with the fire front.

Several additional factors contributed to the poor correlation of fire intensity predictions to field observations. Fire perimeters were usually determined between 1900 and 2100 hours for any given day, generally near the end of the active burning period. The next day's projected progression did not begin until 1100, about 14 hours after the last known fire location. In this area, two

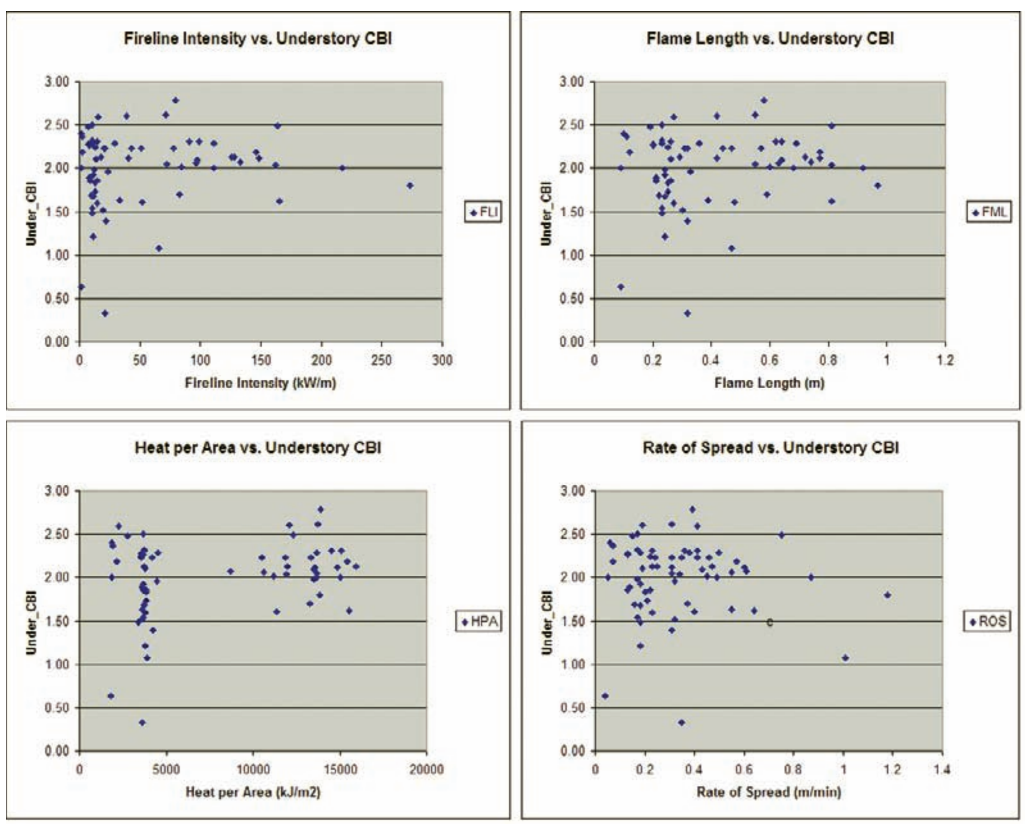

Figure 1—Scatter plot diagrams of fire behavior output versus understory CBI values.

separate burning periods were observed – one during peak fire conditions, and a second beginning at 0100 hours for the upper slopes. The FARSITE simulator is not designed to handle a two-burning period situation, since it relatively uncommon.

Fire control actions also influenced the burn response. In most areas, control lines were established, followed by a firing operation to blacken in the perimeter prior to the arrival of the main fire. We attempted to include these operations in the modeling. However, the records were sparse for when and where these actions were taken and may not have been applied at the correct time or date. Aerial ignition spheres were also used in the fire control operation to accelerate interior burn out in some areas. Higher severity was observed in some of these areas (southeastern portion of the fire) than were predicted by the model.

Differences in winds were not likely a major factor. The dense canopy cover tends to reduce the wind effect in most burn areas. Winds only had substantial effects on exposed ridgelines. Those areas were not used in the CBI assessment. Other error may have been introduced in determining and mapping CBI plot locations (plots landing in the wrong raster cell), and inaccurate assessment of fuel models. However, fuels, topography, and weather did not vary substantially within the immediate area of a plot in either the field, or as modeled. Post-fire vegetation was assessed in the FIREMON process, challenging the accuracy of the remotely sensed fuel model data.

Conclusions

With improved pre-fire data we believe that FARSITE could assist in predicting the landscape effects of fire. Additional research and fuel load data is needed to produce better modeling. Users are cautioned to have a good understanding of model limitations before applying the results. Predicting understory impacts of fire across large areas will remain a challenge without improved remote sensing techniques.

Acknowledgments

We are grateful for the funding provided by Save-the-Redwoods League and for the project assistance provided by Humboldt Redwoods State Park.

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Microsoft Excel 2003 Statistical functions.

Measuring Ecological Effects of Prescribed Fire Using Birds as Indicators of Forest Conditions

Nathaniel E. Seavy[1]**, John D. Alexander**[2]

Abstract—*To evaluate the ecological effects of prescribed fire, bird and vegetation surveys were conducted in four study areas of the Klamath National Forest where prescribed fires are being used for management. Bird and vegetation data were collected at sites treated with prescribed fire and nearby untreated control sites. Data were collected at stations from 2000 (pre-treatment) to 2004 (1-4 years post treatment). The treated sites ranged from 9 to 30 ha, and during the course of the study 25-73% of each area was treated with prescribed fire. Over this time period, there was no consistent change in the volume of vegetation in either the tree or shrub strata. Similarly, there was no measurable effect of prescribed burning on the composition of the overall bird community. Spatial variation and annual variation in abundance appear to be more important than the change induced by prescribed burning at this scale and intensity. The abundance of eight individual species that have been identified as conservation focal species for coniferous forests was also investigated. There were no consistent changes in the abundance of these species that we could attribute to the application of prescribed fire. These results suggest that the prescribed fire applied in these treatment units had negligible effects on landbird community composition.*

Introduction

Biodiversity and ecosystem function may be closely linked to historical fire regimes. These regimes have been altered by fire suppression policies implemented in the 20th century (Agee 1993). In an attempt to restore fuel conditions created by historical fire regimes (i.e. mixed-severity; Huff and others 2005), management agencies are using prescribed burns and mechanical fuels treatments that mimic the effects of natural fire. However, the ability of these management activities to mimic the effects of natural fire on habitat structure and animal populations is not well understood (Tiedemann and others 2000). For example, prescribed fire treatments may fail to create the range of habitat conditions used by birds after naturally occurring wildfires (Smucker and others 2005).

Like many national forests across the west, the Klamath National Forest in northern California is currently using prescribed fire as a tool to reduce fuels and improve forest health (S. Cuenca, personal communication). However, the ability of prescribed fire to achieve the desired ecological effects is largely uninvestigated (Tiedeman and others 2000; Huff and others 2005). Monitoring is essential to evaluate the ability of fire-related management activities to achieve desired ecological conditions (Huff and others 2005). One approach to designing monitoring projects is to focus on groups of organisms that can provide cost-effective information about ecological conditions of interest

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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(Vos and others 2000; Gram and others 2001). Birds are an effective tool for monitoring because: (1) many species are easily and inexpensively detected using standardized sampling protocols; (2) species respond to a wide variety of habitat conditions; and (3) accounting for and maintaining many species with different ecological requirements can be used to implement landscape scale conservation strategies (Hutto 1998). Changes in the abundance of bird species associated with desired habitat conditions can thus be used to gauge the ability of management actions to maintain or improve that habitat condition and provide inferences about which habitat conditions are contributing to these changes.

To evaluate the impacts of prescribed burning in the Klamath National Forest, we compared vegetation structure and bird abundance over a five-year period. The objectives of this project were to (1) describe the effects of prescribed burning on vegetation structure and bird community composition and (2) evaluate if these effects are consistent with the ecological goals of coniferous forest management.

Methods

Study Sites and Sampling Design

Our study site was on the Klamath National Forest in northern California (fig. 1). The forest vegetation in the area of these prescribed fires is diverse (Whittaker 1960) and includes both conifer and hardwood species. Dominant conifers include Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), incense-cedar (*Calocedrus decurrens*), and white fir (*Abies concolor*). Dominant hardwoods include tanoak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), canyon live oak (*Quercus chrysolepis*), California black oak (*Q. kellogii*), Oregon white oak (*Q. garryana*), and big-leaf maple (*Acer macrophyllum*). The relative composition of these species varies with elevation, aspect, and soils. Generally, these forests correspond to the Douglas-fir, Mixed Evergreen Hardwood, or White Fir Types described by Huff and others (2005). Fire-related studies in these vegetation types show a mix of fire severities, frequencies, and sizes typically characteristic of low and moderate-severity fire regimes (Agee 1991; Wills and Stuart 1994; Taylor and Skinner 1998, 2003). Over time, such mixed-severity fires create forests with multiple age classes, often with Douglas-fir or ponderosa pine as an emergent canopy above various hardwoods.

Working with a fire planner and district biologist form the Klamath National Forest, we identified four study areas where a series of control burns were to be implemented (fig. 1). Using maps of planned prescribed fire treatments, we established groups of stations (sites) where fire treatments were planned (treated sites), and where they were at least 1000 m from where fires were planned (control sites). Stations were established at least 250 m apart. For all analyses we consider sites as independent replicates and generated a single measurement for each site by averaging across stations.

The application of prescribed burns within the study areas was patchy. Sometimes, burns were applied such that stations were located along their edges or just outside the boundaries of burns. As a result, it is difficult to use a simple dichotomous classification of treated vs. untreated stations. Furthermore, stations were surveyed each year, but between surveys new treatments were applied. As a result the proportion of treated area around the points increased throughout the course of the study. To quantify the proportion of

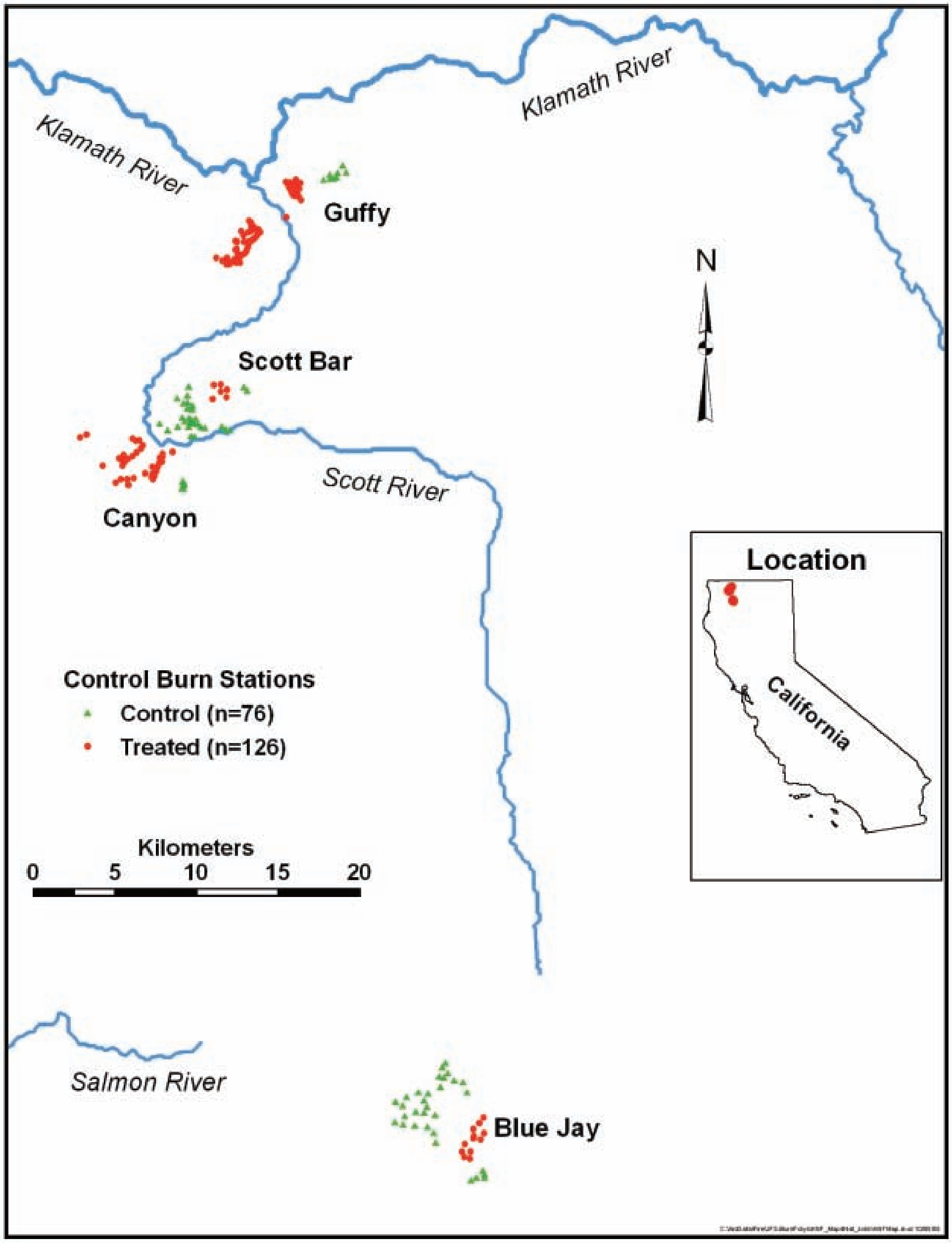

Figure 1—Map showing the location of four study areas where we studied the effects of prescribed fire on bird communities in the Klamath National Forest in northern California. Triangles represent stations at treated sites, and circles represent stations at control sites.

each treated site that was burned, we used a geographical information system to create a 50 m buffer around all points that fell within 50 m of a polygons that had been treated between 1999 and 2004 and then calculated the percent of this area that was treated in each year of the study (table 1).

Data Collection

Vegetation sampling—Vegetation structure was measured at all stations in all years of the study. We used a relevé method (Ralph and others 1993) to collect vegetation data at each station on variable radius plots. Within these

Table 1—Four study units in then Klamath National Forest, California, where prescribed burning was applied between 2000 and 2004. Location of sites are identified in Figure 1.

Area	Site	Number of stations	Total area (ha)[1]	Percent treated[2]				
				2000	2001	2002	2003	2004
Blue Jay	treated	12	9	0	0	18	25	25
	control	31						
Scott Bar	treated	6	5	0	0	0	0	71
	control	8						
McGuffy	treated	69	53	33	33	33	33	59
	control	8						
Canyon	treated	39	30	53	62	64	66	73
	control	29						

[1]Number of ha encompassed by a 50 m buffer around the points in each unit.
[2]Cumulative percent of the buffer-defined area that was treated for each year.

plots, we recognized two vegetation layers: a tree layer (generally >5 m), shrub layer (generally >0.5 m and <5 m). For each layer, we visually estimated height of the top of the tree layer (canopy height) and the bottom of the tree layer (canopy base height). We also estimated shrub height and shrub base height. For each layer, we recorded total cover of all vegetation in each layer as one of six cover classes (0, 0 to 5, 5 to 25, 25 to 50, 50 to 75, and 75 to 100 percent) and used the center point of each cover class as the measurements.

Breeding season point counts—Bird abundance was evaluated using standardized point count methodologies (Ralph and others 1993). Five-minute bird counts were conducted between sunrise and 1000 PDT on each station, and all landbird species seen and heard were recorded. The distance to each individual was estimated to the nearest meter. Counts were conducted only on days when the wind was <20 kph and it was not raining. All observers were experienced and had been trained for distance estimation and species identification. Only birds detected ≤50 m of each point were used in the analysis. This criterion was chosen to reduce the possibility of double counting individuals, including detections that were outside of treated or control areas, and alleviate biases introduced if detection rates differed between treated and control areas (Schieck 1997; Siegel and DeSante, 2003). Flyover detections were excluded from the analysis. We restricted our analysis to passerines and woodpeckers, and excluded four species (Common Raven, American Dipper, Violet-green Swallow, and American Crow) that we expected would be highly influenced by habitat characteristics unaffected by prescribed fire.

Data Analyses

Vegetation structure—We used the relevé data to generate indices that represented the volume of vegetation of the tree layer and shrub layer. The volume of the tree layer was calculated by subtracting the canopy base height from the canopy height, and then multiplying this distance by the total cover value for the tree layer. The same method was used to calculate an index for the volume of the shrub layer. Within each year, we averaged all measurements within each site, and used this single tree and shrub layer value in all subsequent analyses.

To describe the difference between vegetation volume of treatment and control sites, we used:

$$d = \log(V_{treatment}/V_{control}),$$

where *d* describes the difference between the vegetation volume (*V*) in the control sites and treatment site. When there is no difference between control and treatment sites *d* = 0, when treatment sites have greater vegetation volume than controls, *d* is positive, when treatment sites have less vegetation volume *d* is negative. Because prescribed fire was expected to raise the canopy base height and reduce shrub cover, we predicted that *d* would become increasingly negative over the course of the study.

Bird community composition— For each site and year we calculated average abundance (individuals/station) of all bird species and used these values in a species x site matrix. We then tracked the movement of each site in ordination space to evaluate the degree to which the bird community composition changed over the course of the study. Because our four areas covered a wide range of elevations and habitats, we expected substantial spatial differences in bird community composition. Therefore, we analyzed two sets of birds; 'all birds' included all the passerines and woodpeckers that were detected during the study and 'core birds,' which was a subset that was restricted to species that were detected at all sites in at least one year of the study. We evaluated changes in bird community composition through time using detrended correspondence analysis (DCA) conducted in PC-ORD (McCune and Mefford 1999).

Abundance of coniferous forest focal species—To investigate species-specific responses to fuels treatments we selected 'core' birds that were identified by either the California or Oregon/Washington Partners in Flight coniferous forest conservation plans (Altman 2000; CalPIF 2002). Within each year, we averaged the number of individuals detected per station, and used this single value for each site in all subsequent analyses. Similar to the analysis of vegetation volume, we described the difference in bird abundance between treated and untreated sites as:

$$d = \log(A_{treatment}+1/A_{control}+1),$$

where *d* describes the difference between bird abundance (*A*) at control sites and treated sites. Because some species were not detected at some sites in some years, we used Naperian (N + 1) logarithms.

Results

Application of Prescribed Fire

Prescribed fires were applied at all four sites over the five years of the study (table 1). At two sites (Guffy and Canyon) a third to half of the area had already been treated before the study began, however, in both these areas treatments continued throughout the course of the study (table 1), thus we would expect the trajectory of changes at these areas to be similar to the other areas. In most of the sites we monitored for several years after the first treatments were applied, with the exception of the Scott Bar site, where we collected a single year of post-fire data.

Vegetation Structure

We found no evidence that the volume of live vegetation in the tree layer was consistently reduced at treated sites; in each year the difference between the treated and control areas was roughly symmetrical around 0, and there was no suggestion that this measurement had consistently decreased at any of the four areas (fig. 2). Our results for the volume of the shrub layer were similar (fig. 2), in that there were no sites that showed a consistent pattern of change between treated and control sites through the course of the study. In both the first and last year of the study, the measurements of the difference in total shrub cover of treated and untreated sites was symmetrically distributed around 0 (fig. 2).

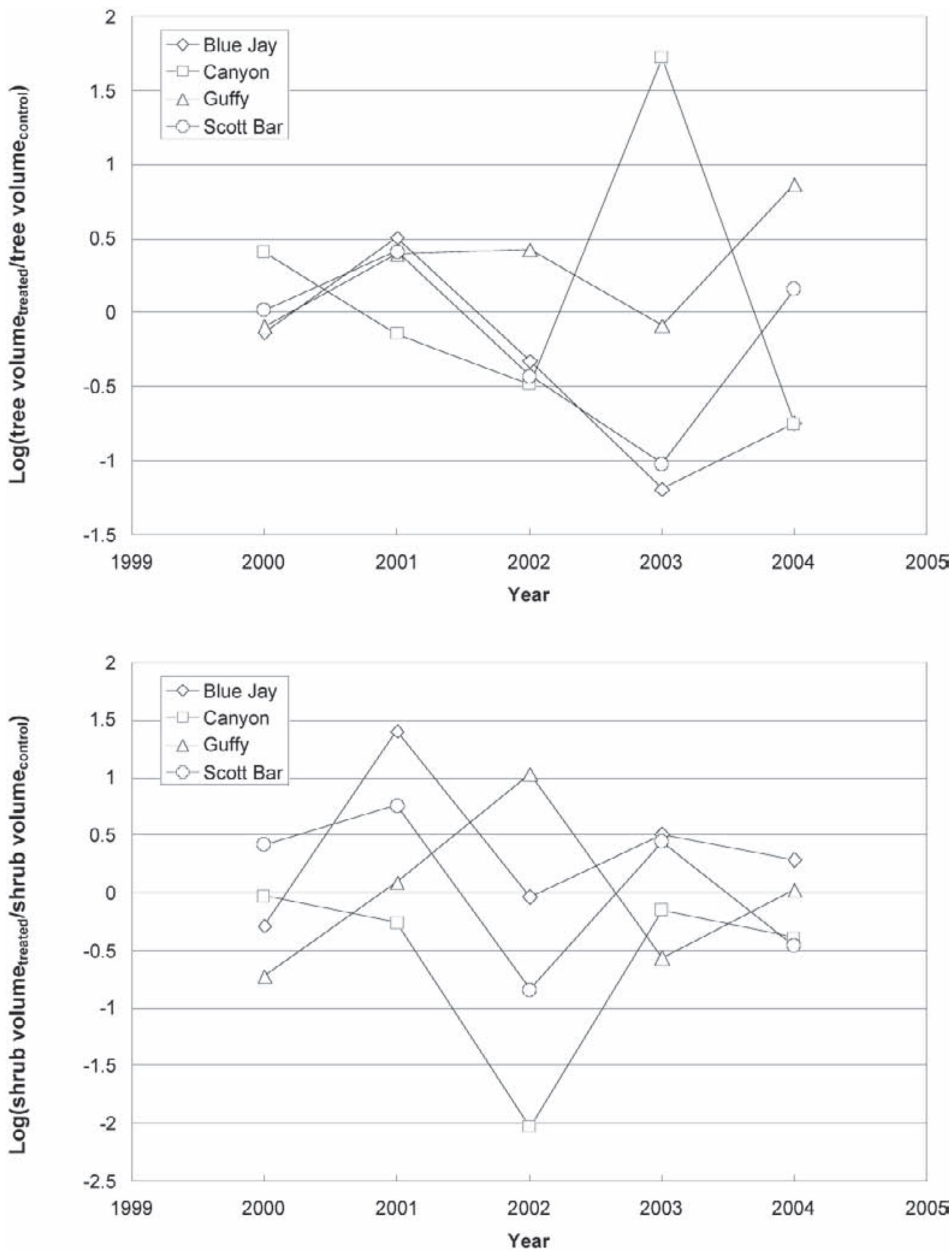

Figure 2—Log response ratios comparing vegetation characteristics of treated and control sites from the four study areas over the five-year study period.

Bird Community Composition

For ordinations of both 'all birds' and 'core birds' most of the variation in the original multidimensional space was captured in the first two axes (table 2), therefore, we limited out our interpretation to these axes. Ordination of bird communities for the treated and untreated units demonstrated substantial variation in bird communities among sites (fig. 3). In particular, the Canyon control site and Blue Jay treated site were substantially different from all the other study sites. Furthermore, it was not uncommon for sites from the same area (e.g., compare Guffy treatment to Guffy control) to be more different than sites from different areas (e.g., Guffy treatment versus Scott Bar control). These spatial patterns remained roughly the same for ordinations of all birds and core birds (fig. 3). Although there was substantial year to year variation in bird communities, both in treated and control units, there was no apparent directional movement in ordination space associated with treatments. For instance, although treated units Canyon and Blue Jay both moved during the study period, they moved toward each other, suggesting that if there was an effect of prescribed fire, it had the opposite effect in these two units.

Abundance of Focal Species

For the eight Partners in Flight coniferous forest focal species that we investigated, we could discern no obvious changes in abundance that occurred as a result of treatment (fig. 4).

Discussion

Our results suggest that the effects of prescribed fire on vegetation structure and bird community composition have been minimal in these areas of the Klamath National Forest. We found no evidence that prescribed fire treatments were associated with a persistent decrease in the volume of vegetation in the tree or shrub layer. There was substantial year to year variation, and some of these changes may represent short term changes from recent treatments, but these effects did not appear to persist, or accumulate, over the course of the study.

Similarly, our ordination results for the bird community show no evidence of a directional change in bird community composition that is unique to the treated areas (fig. 3). Even in the absence of overall community effects, we

Table 2—Coefficient of determination for the correlation between bird community detrended correspondence analysis (DCA) ordination distances and relative Euclidean distances in the original multidimensional space.

	All birds		Core birds	
DCA Axis	**Incremental R^2**	**Cumulative R^2**	**Incremental R^2**	**Cumulative R^2**
Axis 1	0.39	0.39	0.39	0.39
Axis 2	0.35	0.74	0.40	0.79
Axis 3	0.04	0.79	0.04	0.83

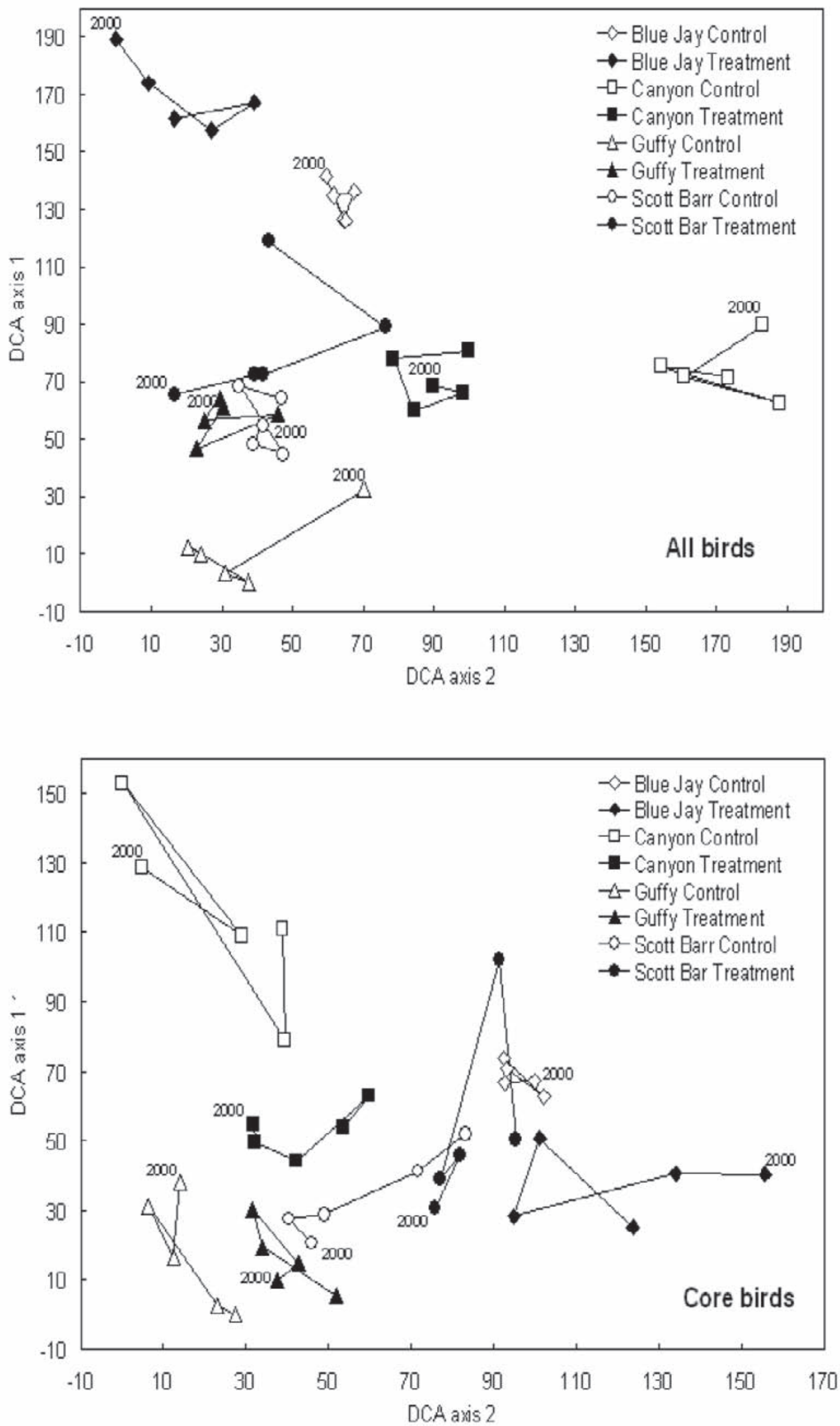

Figure 3—Ordination plots of DCA scores for bird communities at treated and untreated sites in the Klamath National Forest in northern California.

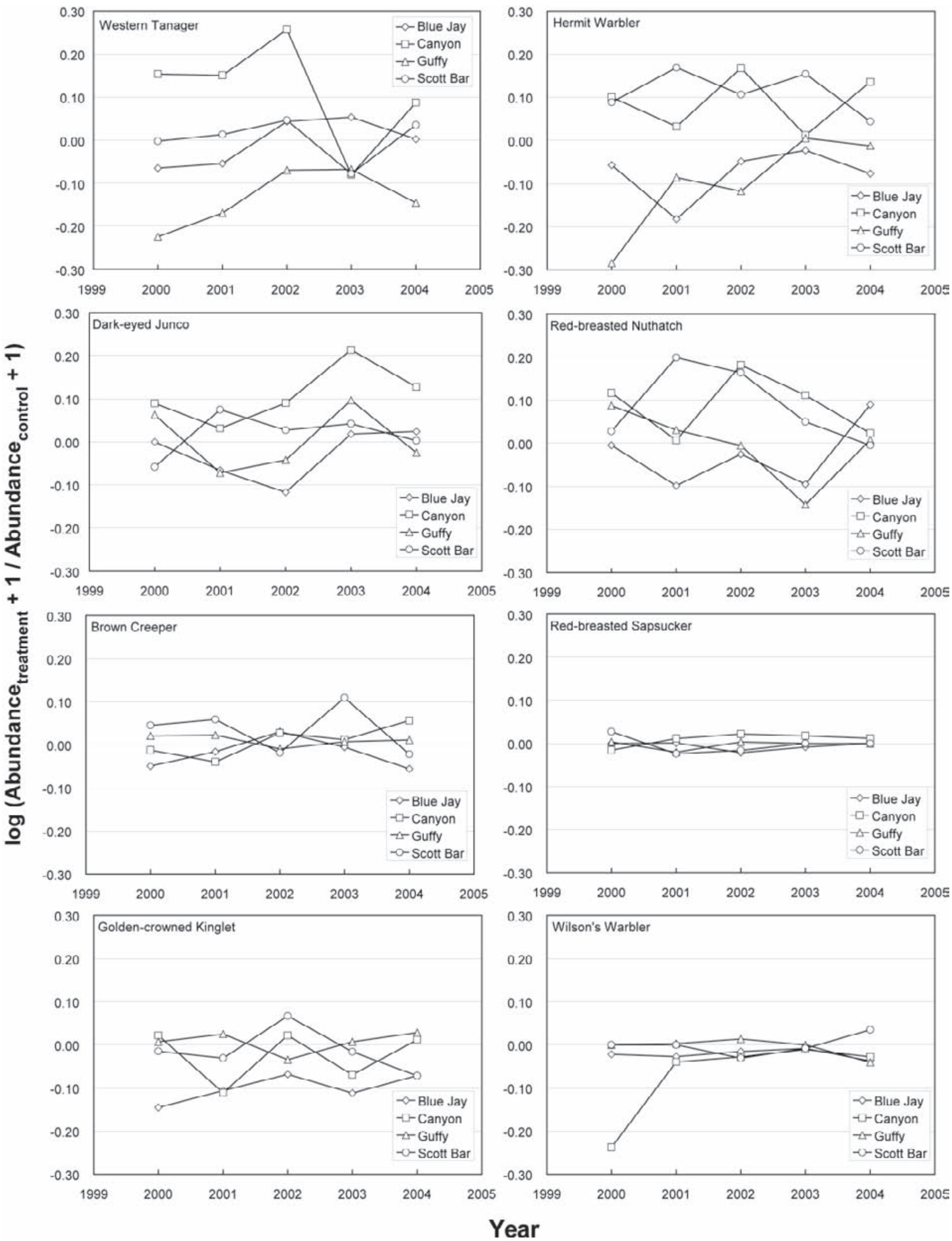

Figure 4—Log response ratios comparing bird abundance of treated and untreated sites from the four study areas over the fire-year study period.

may still be concerned about the effects of prescribed fire if they change the abundance of individual species that are of particular conservation concern. However, our analyses of the Partners in Flight focal species for coniferous forests showed no consistent trends for these species to become either more or less abundant after treatment.

There is limited evidence that fuels reduction projects in the western United States can be implemented in such a way that they are consistent with the goals of wildlife conservation and ecosystem health (Tiedemann and others 2000; Huff and others 2005). However, this study, and a similar study comparing thinned and unthinned mixed-conifer forests in the Sierra Nevada (Siegel and DeSante 2003), suggest that in conditions were prescribed fire has little effect on the volume of live vegetation, such treatments may have relatively minor consequences for bird communities. However, if the goal of these treatments includes restoring conditions in such a way that it changes the quality of wildlife habitat, our results suggest that prescribed fire in the Klamath National Forest would need to be modified to achieve the desired conditions.

Acknowledgments

We thank S. Cuenca and T. Grenvic for logistical support and numerous field assistants for their help in conducting field work. Comments from C.J. Ralph and S. Janes greatly improved the paper. This project was funded by the Joint Fire Sciences Program project 01B-3-2-10 and the US Forest Service Region 5 Partners in Flight program.

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Monitoring Changes in Soil Quality from Post-fire Logging in the Inland Northwest

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Abstract*—The wildland fires of 2000, 2002, and 2003 created many opportunities to conduct post-fire logging operations in the Inland Northwest. Relatively little information is available on the impact of post-fire logging on long-term soil productivity or on the best method for monitoring these changes. We present a USDA Forest Service Northern Region study of post-fire logged sites using a variety of methods to assess changes in soil productivity and site sustainability after timber harvesting activities. The disparate soil and climatic conditions throughout the Northern Region made it an ideal area to study post-fire logging operations. Our results indicate that post-fire logging during the summer creates more detrimental disturbance (50% of the stands) than winter harvesting (0% of the stands). In addition, on the sites we sampled, equipment type (tractor > forwarder > rubber-tired skidder) also influenced the amount of detrimental disturbance. Number of sample points is a critical factor when determining the extent of detrimental disturbance across a burned and harvested unit. We recommend between 80 and 200 visual classification sample points, depending on confidence level. We also provide a summary of methods that will lead to a consistent approach to provide reliable measures of detrimental soil disturbance.*

Introduction

During the last century, wildfires in the western USA have been viewed by many land managers and the public as catastrophic events (Kuuluvainen 2002). Until recently, fire suppression has been used to control the extent of these fires, but now stand-replacing fires are occurring on many Federal lands in the western USA. Consequently, the standard policy on many National Forests has been to harvest fire-killed trees for economic value before they decay (Lowell and Cahill 1996; McIver and Starr 2001). Proponents and opponents of post-fire logging are abundant (Beschta and others 2004; Sessions and others 2004; Donato and others 2006), but one critical issue of concern to each group is the impact of this practice on the soil resource.

Wildland fires can impact more than 10,000 ha of forest land at one time and, combined with post-fire logging, significant soil impacts can occur. Loss of surface organic matter and nutrients from the fire, increased decomposition from increased insolation, decreased soil porosity, increased erosion, and compaction may all combine to alter site productivity after wildfire and post-fire logging activities (Poff 1996). There are no specific methods that directly assess the impact of post-fire logging on soil productivity, but many methods for measuring proxies exist (see Burger and Kelting 1999; Schoenholtz and other 2000). Measures of wood production, net primary productivity, or changes in some specific soil properties (e.g. bulk density, forest floor depth,

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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cover type, etc.) can all be readily determined, but the link between forest management, soil properties, and site sustainability is not easily obtained.

Historically, maintenance of soil productivity on public lands in the USA has been governed by the Multiple Use Sustained Yield Act of 1960, the Forest and Rangeland Renewable Resources Planning Act of 1974, and the National Forest Management Act of 1976. As an outgrowth of these policies, each USDA Forest Service Region developed soil quality standards and guidelines, which were designed to act as a first warning of reduced site productivity after harvest and site preparation operations. The general concepts and the basis for the various guidelines are described in Griffith and others (1992). Lacking better methods, these standards and guidelines have also been used to evaluate soil productivity changes after wildfire and post-fire logging.

Concern about an accurate assessment of soil properties has expanded because of the growing public interest in the consequences of forest management practices on soil quality and its productive capacity (Burger and Kelting 1999; Schoenholtz and others 2000). Worldwide initiatives including the Helsinki Process (1994) and the Montreal Process (1995) have resulted in the development of criteria and indicators for monitoring sustainable forestry practices at broad levels (Burger and Kelting 1999). Recently, progress has been made on developing a common approach to soil monitoring in northwestern North America (Curran and others 2005). The key questions are: What do we measure and what does it mean? The literature is rife with examples of how a soil chemical, physical or biological property may contribute to changes in biomass production, hydrologic function, or ecosystem sustainability (see Schoenholtz and others 2000 for a summary). However, as budgets and personnel dwindle, land managers need a visual assessment of disturbance that can be completed quickly, efficiently, and easily by either field soil scientists or others trained in the assessment process (Curran and others 2005).

Wildfires and post-fire logging generate unique soil surface conditions. Visual disturbance criteria estimate the amount of detrimental disturbance and may need to be specifically designed to encompass the impacts of both fire and logging. Therefore, the objectives of our study were to: (1) determine the magnitude and areal extent (as defined by current soil quality standards) of detrimental disturbance from wildfire and post-fire logging across the Northern Region of the USDA Forest Service, (2) determine the most appropriate spatial sampling design methods for assessing the magnitude of soil impacts, and (3) develop visual criteria that can be used following post-fire salvage harvests to assess disturbance across disparate soil and climatic regimes.

Methods and Materials

Site Descriptions

In the summer of 2004 and 2005, post-fire logging sites were located on the Custer, Helena, Bitterroot, Kootenai, Lewis and Clark, Flathead, and Lolo National Forests (Table 1). Thirty-six stands were sampled over 2 field seasons; 20 had been post-fire winter logged and 16 were post-fire summer logged. Sites were selected by local soil scientists in areas that had recently burned in a wildfire (2000, 2002, or 2003) and had subsequently been logged. If available, we selected three replicate units on each forest, which had similar slope, aspect, soil type, and logging practices.

Table 1—Post-fire logging study site characteristics.

Season of harvest	Logging method	National Forest	Year burned	Year of harvest	Elevation (m)	Parent material	Surface soil texture
Summer	Tractor	Custer	2002	2003	1200	Sandstone	Loamy sand
	Tractor	Helena	2000	2003	1700	Metasediments	Sandy loam
	Tractor	Helena	2000	2002	1700	Metasediments	Loamy sand
	Forwarder	Lolo	2000	2005	1400	Metasediments	Loamy sand
	Forwarder	Flathead	2000	2002	1900	Quartzite	Sandy loam
Winter	Tractor	Bitterroot	2000	2002	1750	Granitic	Loamy sand
	Tractor/RTS[1]	Flathead	2000	2002	1150	Limestone	Silt loam
	Tractor	Helena	2000	2002/03	2500	Metasediments	Sandy loam
	Tractor	Helena	2000	2002	1700	Metasediments	Loamy sand
	Tractor	Lewis & Clark	2001	2003	2200	Limestone	Silt loam
	Forwarder	Kootenai	2000	2003	1600	Glacial till	Silt loam
	Forwarder	Lolo	2000	2005	1500	Metasediments	Loamy sand

[1] RTS= Rubber tired skidder.

Soil Indicator Assessment

In each post-fire logging unit, a 100 point systematic grid and a 100 point random transect were established from a fixed corner point. At each grid and transect point, we described the soil surface cover (e.g. rill erosion, forest floor, bare mineral soil, rocks, etc.) and the presence or absence of platy structure in the underlying mineral soil in 1 m^2 plots. Once the soil surface had been described, we assigned a soil disturbance category to each plot (Table 2), based on the classification systems of Howes (2001) and Heninger and others (2002). In addition to a visual classification, soil strength was determined at each sampling point using a RIMIK CP40 recording penetrometer (Agridry, Toowoomba, Australia).

Statistical Analysis

Chi-square tests for homogeneity were used to evaluate the relationships between disturbance class and soil texture, parent material, season of harvest, and harvest method. Chi-square tests for homogeneity were also used to evaluate relationships between detrimental soil disturbance, soil texture, parent material, season of harvest, and harvest method. Analysis of variance was used to examine relationships between soil strength and soil texture, parent material, season of harvest, and harvest method. All analyses were performed using SAS 9.1.

Results

In this study, there were no significant differences between the grid and random transect methods when visually assessing soil disturbance after fire and post-fire logging ($p < 0.001$). Therefore, data from both the grid and random transect were pooled for subsequent analyses.

Table 2—Description of soil condition classes used.

Condition class	Identifying features
0	Undisturbed forest floor
1	No evidence of past equipment operation, but records of harvesting No wheel ruts Forest floor intact No mineral soil displacement
2	Trail used by harvester (ghost trails) Faint wheel tracks and ruts Forest floor intact No mineral soil displacement and minimal mixing with forest floor
3	Trail used by harvester and forwarder Two track trails created by one or more passes Wheel tracks are >10 cm deep Forest floor is missing/partially intact
4	Skid trails existed prior to reentry and reused Old skid trails from 20th century selective harvest Recent operation had little impact on old skid trail Trails have a high level of soil compaction Evidence of mineral soil displacement from trails
5	Old and new skid trails present Mineral soil displacement from area between skid trails Forest floor is missing

In the USDA Forest Service Northern Region, a stand is considered detrimentally disturbed if greater than 15% of the area is in disturbance class 3, 4, or 5 (Table 2). Of the stands we sampled, 50% of the summer-logged sites and no winter-logged sites had more than 15% of the sampling points in the detrimental disturbance categories (Table 3). The relationship of logging season and detrimental disturbance is significant ($p < 0.0001$) and is primarily characterized by platy structure on skid trails or cow trails.

Table 3—Average soil disturbance after summer and winter post-fire logging.

Season of harvest	National Forest	Number of stands	Amount of Disturbance	
			Not detrimental	Detrimental
			percent	
Summer	Custer	4	72	28
	Flathead	3	77	23
	Helena	3	96	4
	Lolo	4	91	9
Average			**84**	**16**
Winter	Bitterroot	3	97	3
	Flathead	3	90	10
	Kootenai	3	97	3
	Lewis & Clark	3	92	8
	Lolo	2	99	1
	Helena 1	3	92	8
	Helena 2	3	87	13
Average			**93**	**7**

There is a significant relationship ($p<0.0001$) between site parent material and the areal extent of detrimental disturbance. Metasediments, limestone, and granitic parent materials were the least detrimentally disturbed with 75% of the visual classification points being in class 0 or 1.

Surface soil strength was generally not related to disturbance class; however, some exceptions occurred at the 2.5 cm depth. The exceptions were two stands on the Helena National Forest ($p = 0.0312$; $p = 0.0236$) and two stands on the Flathead National Forest ($p = 0.0235$; $p = 0.0033$). These four stands are unique as there was no relationship between surface soil strength, harvest season, type of equipment, or total areal extent of disturbance. However, all four of these sites were burned in 2000 and post-fire logged in 2002. The time between post-fire logging and sampling could have been enough for some soil recovery before soil monitoring occurred.

For all sites, there is a significant relationship ($p < 0.0001$) between visual disturbance class, areal extent of detrimental disturbance, and harvest method. In 66% of the forwarder harvested units, 85% of the rubber-tired skidder units, and 45% of the tractor units, we detected less than 15% areal extent of detrimental disturbance. Many of the sampling sites classified as not detrimentally disturbed had less exposed bare mineral soil than detrimentally disturbed units ($p < 0.0001$). On sites with a significant portion of soil cover, many had live plants, forest floor, moss and lichens present, which may likely indicate soil surface recovery after post-fire harvesting.

Discussion

Severe wildfires greatly impact below-ground ecosystems, including development of water-repellent soils (DeBano 2000) and decreased evapotranspiration (Walsh and others 1992), which can lead to overland flow of water and significant soil erosion. Additionally, the loss of forest floor material reduces water storage in the surface mineral soil (McIver and Starr 2001). The subsequent cumulative effects of fire followed by logging in such a landscape have been difficult to measure (McIver and Starr 2001). Soil surface conditions after post-fire logging is highly influenced by management decisions, which determine equipment type and harvest season. Regardless of disturbance origin (fire or logging), soil productivity in a given area may be influenced by site characteristics (topography, parent material, revegetation, and climate), logging method, and construction of additional roads or skid trails. Our visual disturbance classes (0-5) along with a quick presence or absence survey of key factors (platy or massive structure, forest floor displacement, rut, sheet, rill, or gully erosion, mass movement, live plant, forest floor, wood debris <3″ or >3″, or bare soil) can determine if a harvest unit will meet soil quality guidelines. However, our disturbance classes need to be modified to include soil burn impacts associated with severe wildfires. Removal of surface organic matter may not be detrimental to site productivity unless it is coupled with a change in color in the mineral soil (Neary and others 1999).

Detrimental disturbance was least with rubber-tired skidders, greater when using forwarders, and the most with tractors. In addition, the number of stands with detrimental disturbance was significantly decreased when logging operations occurred during the winter. This is similar to work by Klock (1975) in which he found that tractor skidding over exposed mineral soil caused the greatest amount of detrimental disturbance (36%), followed by cable skidding (32%), and tractor skidding over snow (10%).

Eighty-two percent of our stands were categorized as not having a detrimental soil disturbance after post-fire logging. The remaining stands that approached or exceeded the 15% areal extent of detrimental soil disturbance may require amelioration before other management activities are considered. Detrimental soil disturbance ratings are generally higher after wildfire and post-fire logging when compared to green timber sales, since both wildfire and post-fire logging sites generally lack understory vegetation and forest floor (Klock 1975). Ground-based logging can mitigate some detrimental impacts by leaving logging residue on site or by delaying harvesting until after killed trees drop their needles after a wildfire to establish some forest floor. Both measures provide additional protection from erosion (Megahan and Molitor 1975).

Compaction of the surface soil is also a common concern after ground-based logging operations (Froehlich 1978; Adams and Froehlich 1981; Clayton and others 1987; Page-Dumroese 1993; Miller and others 1996), and surface soil disturbance is more evident immediately post-harvest. Using visual classification categories, we were able to distinguish impacts of summer and winter logging, the influence of parent material, and harvest methods. In some cases, our visual assessments were a direct indication of changes in soil physical properties (e.g. platy or structure) or in surface properties (e.g. displacement of surface organic matter, churned mineral soil, or ruts), and could be used as a surrogate for more intensive sampling. However, the time elapsed between the wildfire and logging activities, and the time between post-fire logging and soil monitoring can be important factors in the degree of detrimental disturbance measured. For instance, on sites with several years between the fire and logging and then another time period between logging and monitoring, some revegetation would likely occur and deposit plant litter on the soil surface. Plant establishment could improve some soil physical properties and influence whether a sample point is categorized as detrimental (class 3) or not detrimental (class 2). The short times between fire, logging and monitoring (1 year between each) may be a reason the Custer National Forest had 28% detrimental disturbance, compared to the Helena National Forest (3 years between fire and logging, and 1 year between logging and monitoring) with only 4% detrimental soil disturbance.

Soil resistance, as measured using a penetrometer, could be easily evaluated on many sites, but the influence of rocks, roots, and low soil moisture, later in the growing season limited its usefulness as tool to make compaction comparisons among sites. However, the use of the penetrometer within one area of similar soil characteristics during a time when soil moisture is fairly high (near field capacity) is feasible for monitoring changes in soil penetration resistance (Utset and Cid 2001).

Management Implications

For our study, we used 6 visual disturbance categories (classes 0-5) to describe areas that had been burned by wildfire and subsequently logged. These visual disturbance classes described combinations of soil disturbance that recur across each harvest unit and can be a relatively quick and easy method for quantifying soil disturbance (Howes et al. 1983). However, season of logging, equipment used, and time between disturbance activities and monitoring were important variables that determine the extent of detrimental disturbance. The visual classification measurements do seem to be an easy, inexpensive method for timely monitoring, and with more data collection, can likely be correlated with long-term vegetation growth. Visual classifications that encompass burn conditions of the soils (charcoal, mineral soil discoloration and ash deposition) are also needed to refine the disturbance assessments, which would make them more useful to forest managers and soil scientists.

Our data indicate that at the 95% confidence level, a sample size of approximately 200 sample points in a 10 ha unit would detect 15% (±5%) detrimental disturbance (Table 4 and unpublished data). A site with 5% detrimental disturbance would only need 75 sample points; whereas a site with a high proportion (>30% of the unit) of detrimental disturbance would need 340 sample points at this confidence level. A confidence level of 80% would significantly lower the number of samples needed. For instance, a site with little disturbance (<5% of the unit) would need only 32 sample points, but a site with a large amount (30% of the unit) of disturbance would need 139 sample points. Using either random transects or grid points are appropriate strategies for laying out monitoring points for similar wildfire burned and post-fire harvested sites when using our visual classification method.

In the USDA Forest Service, soil assessment of management impacts is typically linked to site productivity through soil quality standards (Page-Dumroese and others 2000). However, these standards are not site-specific, do not specify collection of baseline data, are not always linked to changes in biomass production or carbon accumulation, and, in many cases, the monitoring techniques are cumbersome, lengthy, costly and require some laboratory analysis. Reliable assessment of soil disturbance and the link to site productivity is critical. Visual classifications have been used throughout the Pacific Northwest by the B.C. Ministry of Forests (Forest Practices Code Act 1995) and Weyerhaeuser Company (Scott 2000), but have not been linked to tree growth. To date, visual classification systems only describe surface soil conditions, and have not been validated to response variables that are ecologically important (e.g. tree growth, survival). A necessary step in the acceptance of any visual soil disturbance criteria is to develop direct evidence that there is a change in site function, productivity, or sustainability (Curran and others 2005). Our test of visual criteria for assessing soil disturbance after wildfire and logging operations could be used to determine areal extent of detrimental impacts within a harvest unit.

Although visual classifications are not directly linked to ecosystem functions at this time, it is generally recognized in the northwestern USA that surface organic matter can help maintain site productivity (Page-Dumroese and others 2000; Jurgensen and others 1997; Harvey and others 1981).

Table 4—Sample points needed to detect 15% areal extent of detrimental disturbance in a 10 ha unit at different confidence levels (±5%).

Confidence level	Sample points needed
95%	196
90%	139
80%	84

Existing studies such as the North American Long-Term Soil Productivity (LTSP) study, established in the USA and Canada, are investigating the effects of OM removal and compaction on soil productivity (Powers and others 2004), but fire was not included as a disturbance variable. However, the physical removal of surface OM on LTSP study sites generally resulted in lower mineral soil C pools and reduced N availability 10 years after treatment, and tree growth was reduced on low productivity sites (Powers and others 2005). Additionally, tree growth declined on compacted clay soils and increased on sandy soils, but was strongly related to control of the understory vegetation. Recently, the Fire and Fire Surrogate study was started by the USDA/USDI to evaluate the effects of mechanical fuel reduction treatments and prescribed fire-severity on above- and below-ground productivity in a variety of forest ecosystems across the USA (Weatherspoon 2000). Both of these sources of information are needed to complement monitoring data to help develop post-fire harvesting methods that maintain adequate amounts of OM and limit soil compaction to maintain soil productivity.

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The Relation Between Forest Structure and Soil Burn Severity

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***Abstract**—A study funded through National Fire Plan evaluates the relation between pre-wildfire forest structure and post-wildfire soil burn severity across three forest types: dry, moist, and cold forests. Over 73 wildfires were sampled in Idaho, Oregon, Montana, Colorado, and Utah, which burned between 2000 and 2003. Because of the study's breadth, the results are applicable for understanding how forest structure relates to post-wildfire soil burn severity within Rocky Mountains forests. This paper discusses a burn severity classification that integrates fire intensity, fire severity, and post wildfire response; and discusses the relations wildfire setting (fire group), tree crown ratio, tree canopy cover, surface fuel condition, and tree size have with different soil burn severity outcomes.*

Introduction

Although canopy bulk density, fuel models, canopy base height, and other forest metrics have been related to fire behavior using physical laws, controlled experiments, and models (Graham and others 2004, Peterson and others 2005), there is limited information to indicate how forest structure influences or is related to burn severity (what is left and its condition) after a wildfire event (Broncano and others 2004, Loehle 2004, Weatherspoon and Skinner 1995). Moreover, the uncertainty of these relations is unknown, preventing forest managers from communicating their confidence in fuel treatments that may reduce the risk of wildfires and their effects. Without these estimates, managers and forest stakeholders could have a false sense of security and a belief that if a wildfire occurs after a fuel treatment the values they cherish (for example, homes, wildlife habitat, community water sources, sense of place) will be protected and maintained both in the short- (months) and long- (10s of years) term.

In 2001, we began to define and quantify the relation between forest structure and soil burn severity and determine the uncertainty of the relations (Jain and Graham 2004). Although other studies have quantified this relationship they often were limited in scope and applicability (Cruz and others 2003, Martinson and Omi 2003). To avoid these shortcomings, we designed our study to sample many different wildfires (73) that burned throughout the inland western United States over multiple years. Because of the study's scope, it incorporated a large amount of variation in forest structure as well as disparity in burn severity after extreme wildfires. The data we collected came from wildfires that burned in the moist, cold, and dry forests between 2000 and 2003. By including wildfires that burned throughout the inland

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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western United States occurring over multiple years, we were able to include a variety of weather (that occurred during the fires) and physical settings in our sampling. The relations between forest structure and soil burn severity and the uncertainty of these associations after intense and severe wildfires will provide information that can be used for informing fuel management decisions throughout the moist, cold, and dry forests of the inland western United States.

Methods

We visited 73 areas in Montana, Idaho, Colorado, Oregon, Utah, and Arizona burned by wildfires between 2000 and 2003 (fig. 1). These wildfires occurred in three forest cover types: dry (ponderosa pine, *Pinus ponderosa* and Douglas-fir, *Pseudotsuga menziesii*), moist (western hemlock, *Tsuga heterophylla*, western redcedar, *Thuja plicata*, grand fir, *Abies grandis*, white fir, *Abies concolor*) and cold (lodgepole pine, *Pinus contorta* and subalpine fir, *Abies lasiocarpa*) forests throughout the inland western United States. Since not all forest burned in a single year, we included multiple years and multiple geographic regions in our data collection (fig. 1). All areas were sampled the summer after they burned, except areas in Flathead and Lincoln counties in Montana and the Diamond Peak complex of fires in Idaho, which burned in 2000. These wildfires were sampled the second summer after they burned.

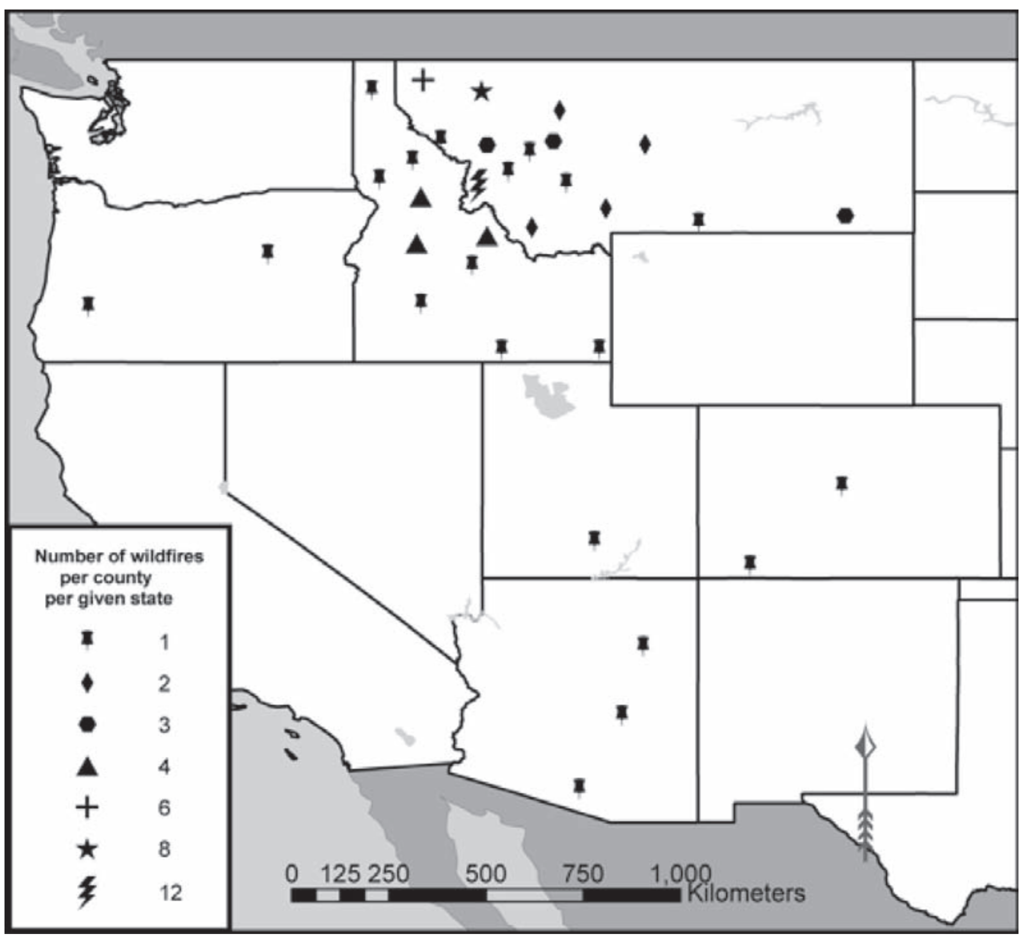

Figure 1—Distribution of the seventy-three wildfires sampled between 2001 and 2004.

Sampling Designs

We used three sampling designs to capture the variation in burn severity occurring at different spatial scales. Intensive sampling occurred in 28 wildfires that burned between 2000 and 2003. Extensive sampling revisited previously established Forest Inventory and Analysis (FIA) plots within 61 wildfires that burned in Montana and Idaho in 2000 and those burned in Montana during 2001 and two wildfires were visited using focused watershed (142 ha to 6,480 ha) sampling.

Intensive Sampling

For each selected wildfire (28 fires), we used stratified random sampling to ensure the variation in forest structure, physical setting, and weather were represented. Our sampling stratification began with forest cover (dry, moist, and cold), followed by burning index (two classes), slope angle (two classes), canopy height (two classes), and stand density (two classes). In establishing the sampling frame, forest cover type described the broad-scale vegetation. We used fire progression maps, local weather data, and the most applicable fuel model for each stand within a fire perimeter to calculate Burning Index (Bradshaw and Britton 2000). We split our sampling at the median burning index for all stands burned by a particular wildfire. The physical settings of the stands were placed into two strata: those with slope angles less than or equal to 35 percent and those with slope angles greater than 35 percent. The Hayman fire in Colorado and Flagtail fire in Oregon had moderately steep topography where we used a 25 percent slope angle to differentiate the two classes. Nested within slope class, stands were divided into sapling to medium sized trees (≤12.5 m) and mature to old trees (>12.5 m). Within height class, two density stratum were identified: those with canopy cover ≤35 percent and those with canopy cover >35 percent. All stands within a fire perimeter had an equal probability of being selected. We randomly selected a stand if it 1) met the sampling criteria, 2) had an opportunity to burn, 3) did not have any confounding factors (evidence of suppression activities), and 4) was at least 100 m by 100 m in size.

Extensive Sampling

Interior West Forest Inventory and Analysis staff have randomly located permanent forest sample plots throughout the forests of the western United States. Several of these plots burned in 2000 and 2001 (61 wildfires). Wildfires that burned in Idaho and Montana in 2000, all wildfires that burned in Montana in 2001, and the wildfires that burned in Utah and Arizona in 2003 were revisited. Because FIA plots were distributed across spatially defined grids and the burned areas varied in size and location, the number of plots burned by the fires varied considerably. As a result, some burned areas had multiple FIA plots sampled after a wildfire while other areas only had one plot revisited.

Focused Watershed Sampling

The focused watershed sampling occurred within forests burned by the Quartz and Diamond Peak fire complexes in Idaho and Oregon in 2000 and 2001. Using GIS based maps, we delineated the watersheds burned by these two wildfire events and subsequently defined a 60-m riparian zone along each side of the stream reaches. Areas outside the riparian zone within each watershed were defined as the upland zone. A minimum of twenty-five plots were randomly located within both the upland and riparian zones using a complete spatial randomness (CSR) Poisson process (Diggle 2003). Using this approach, spatial autocorrelation was avoided (Cressie 1991).

Data Collection

Our intention was to develop a continuous variable or post classify the burn severity of the forest floor. To do so, fine resolution descriptors of soil burn severity were synthesized from past burn severity characterizations to develop the burn severity indicators. Our soil burn severity concentrated on what was left after the fire and not what was consumed (DeBano and others 1998, Key and Benson 2001, Ryan and Noste 1985, Wells and others 1979). For each randomly located plot, physical setting descriptors (aspect, slope angle, topographic position, and elevation), a general stand description (species composition, number of stories, and horizontal spacing), and stand origin (past harvest evidence and regeneration treatment) were recorded. Forest floor characterization included total cover and the proportion of total cover dominated by each char class (unburned, black, grey, or orange colored soils) on a fixed radius plots (1/741 ha). These included new litter (deposition since the fire), old litter (present previous to the fire), humus, brown cubical rotten wood (rotten wood at or above the soil surface), woody debris less than or equal to 7.6 cm in diameter, woody debris greater than 7.6 cm in diameter, rock, and bare mineral soil.

Physical Setting, Fire Weather, and Forest Structure—Fire behavior and burn severity, for the most part, are determined by physical setting (location, topography, juxtaposition, and so forth), fuels (live and dead vegetation), and weather (both short- and long-term). We used the individual fire to reflect the broad scale physical setting. For each burned area we obtained hourly weather observations that occurred during the wildfire. Data from remote automatic weather stations (RAWS) located in the county where each wildfire burned were summarized into daily reports using Fire Family Plus 3.0 (Bradshaw and McCormik 2000). The weather data included relative humidity, maximum temperature, wind speed, and fuel moistures of 1-, 10-, 100-, and 1000-hour fuels. Because the exact day and time a specific plot burned was undetermined, we summarized the weather data to the specific fire. Weather data was unobtainable for some fires located in remote wilderness areas (4 fires).

We used the Forest Vegetation Simulator (FVS) and its Fire and Fuels Extension (FFE) to characterize pre-wildfire forest structure (Wykoff and others 1982, Reinhardt and Crookston 2003, Dixon 2004). Forest structure characteristics included stand density indices, characteristics associated with fire behavior (surface fuels, canopy bulk density, canopy base height), and other miscellaneous stand characteristics (Reinhardt and Crookston 2003). In addition to these FFE-FVS derived forest characteristics we estimated canopy base height directly from our data and described total cover which included canopy overlap as suggested by Crookston and Stage (1999). Also, rather than using quadratic mean diameter (QMD) to describe stem dimensions, we used stem diameter at breast height (d.b.h.) (1.4 m) weighted by basal area[1].

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[1] Basal area weighted diameter breast height (d.b.h.-in) is ∑ ((d.b.h.*individual tree basal area (ft^2) * number of trees for each d.b.h. class) divided by ∑ (number of trees * individual tree basal area (ft^2).

There are several ways to characterize overstory density such as basal area per unit area, trees per unit area, percent cover, canopy bulk density, relative stand density index, total cubic volume per unit area, and total standing biomass. To avoid collinear variables as predictors, we used canonical correlation for data mining and our expertise to determine which variables had promise for identifying the relation between forest structure and soil burn severity. For density we chose total canopy cover with overlap, for tree size we used basal area weighted d.b.h., average height, and species composition was broadly defined as dry, moist, or cold forest. To describe the forest canopy we used canopy base height (total height minus uncompacted crown length then averaged for plot), and uncompacted crown ratio (fig. 2).

Classifying Burn Severity—Figure 3 illustrates a model we used to develop our soil burn severity classification. The fire literature provided knowledge on fire intensity by describing the heat pulse into the soil (for example, Baker 1929, Debano and others 1998, Hungerford and others 1991, Wells and others 1979). However, the amount of fuel consumed by a fire event also reflects fire intensity. Therefore, we incorporated fire severity into our burn severity classification (for example, Debano and others 1998, Key and Benson 2001, Ryan and Noste 1989) and finally, we included ecological responses

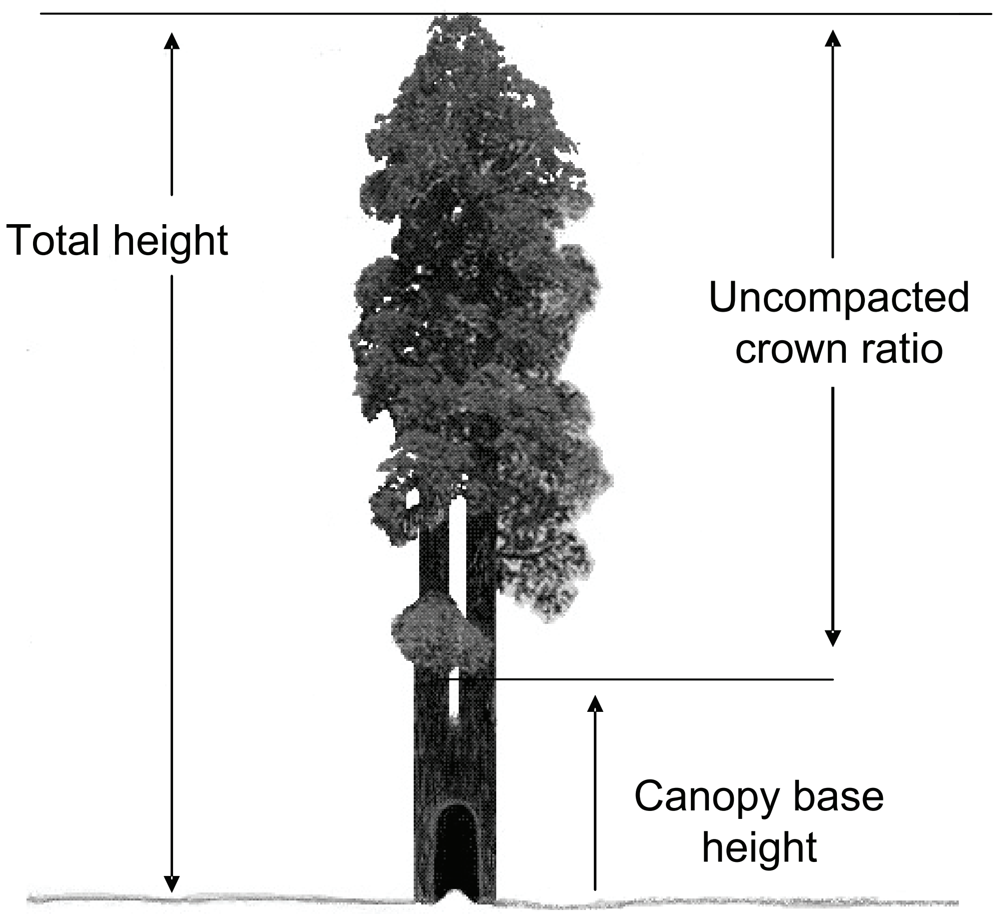

Figure 2—Illustration of how we measured uncompacted crown ratio and canopy base height (total height minus length of uncompacted crown ratio).

that likely occur after a wildfire (for example, changes in wildlife habitat, alterations in soil productivity, changes in soil erosion potential) (Debano and others 1998, Neary and others 1999). As a result our soil burn severity (what is left) classification linked fire intensity, fire severity, and the ecological response (fig. 3).

The classification included six levels of soil burn severity (fig. 4). The factors in the soil burn severity include proportion of litter, mineral soil, and exposed rock present after a fire and their dominant char class, defined as unburned, black char specific to mineral soil, and gray and orange char specific to mineral soil (Wells and others 1979, Ryan and Noste 1989, Debano and others 1998) (fig. 4). The soil burn severity levels included: 1) sites that contained greater than 85 percent litter cover, all char classes, 2) 40 to 85 percent litter cover, all char classes, 3) less than 40 percent litter cover and mineral soil is dominated by black char, 4) less than 40 percent litter cover and mineral soil is dominated by grey or white char, 5) and mineral soil is dominated by black char and no litter cover, and 6) no litter cover and mineral soil is dominated by grey or white char (fig. 4). Wildfires and their "goodness," or lack there of, depends on the values at risk and the biophysical setting and the management

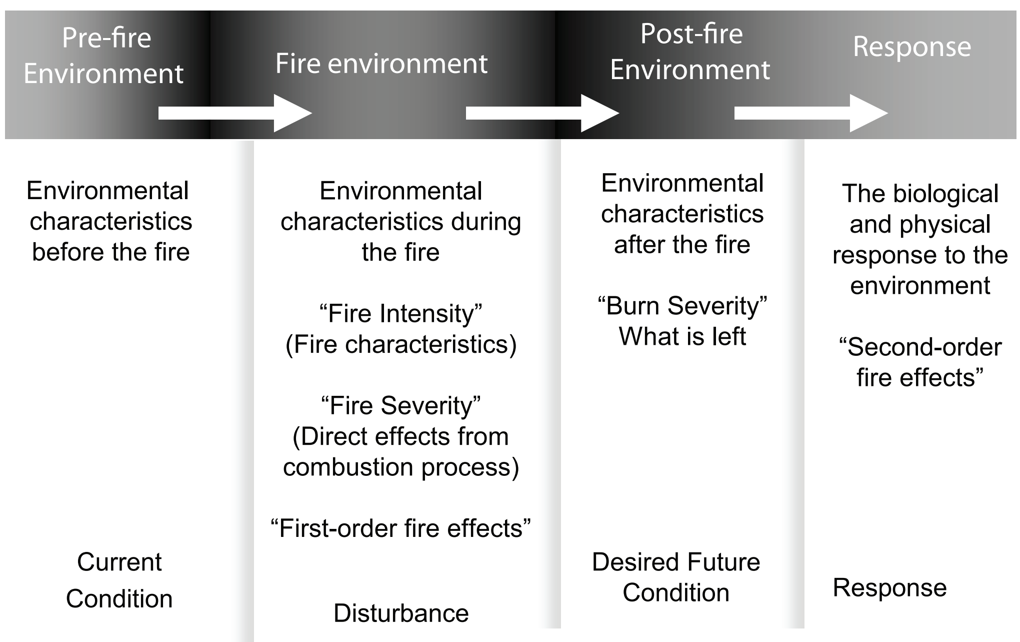

Figure 3—The fire disturbance continuum, of which there are four components, describes the interpretation of different factors involved in wildfires (Jain and others 2004). The first component, the pre-fire environment, includes forest vegetation and state of the environment (moisture levels, amount of biomass, and species composition). This can also be referred to as the current condition just prior to the fire event. The second component, the fire environment, is the environment during the fire event, where fire intensity and fire behavior are characterized in addition to fire severity. Changes to forest components from the fire are also referred to as first-order fire effects. The third component is the environment after the fire is out, referred to as the post-fire environment. This is the environment created by the fire but also is a function of the pre-fire environment and is characterized by what is left after the fire. We refer to this as burn severity. In some cases when fuel treatments are being applied to create a more resilient forest, this could be referred to as the desired condition. The last component is the response, often referred to as second-order fire effects.

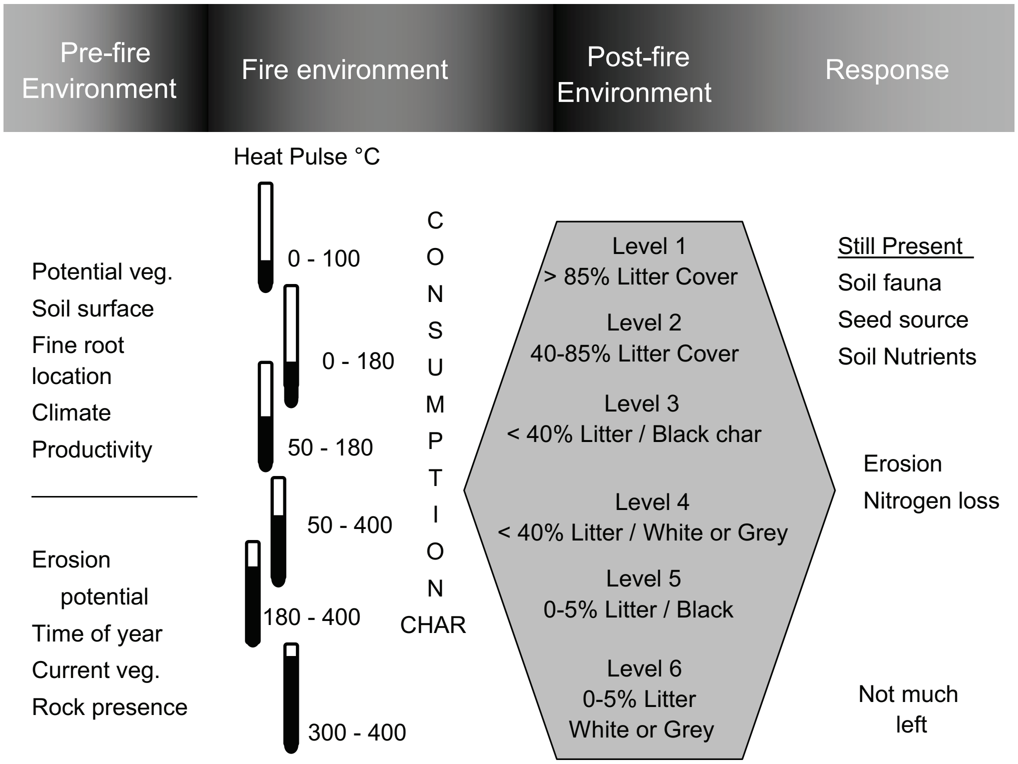

Figure 4—Within the post-fire environment, the soil burn severity classification includes six levels. Going from left to right, a range of temperatures associated with the fire event correspond to the probable indicator of what is left after a fire. For example, to maintain litter cover, the heat pulse into the ground had to be between 0 and 1000 °C. When surface litter is left, often soil fauna are still alive, which often occurs when within a fire severity context, a possible description, is less than 15% of surface litter is consumed. In contrast, by level 6 soil burn severity, the heat pulse into the ground had to exceed 3000 °C in order to create white ash or a grey charred soil appearance (Hungerford and others 1991). The char in each burn severity level refers to the dominant char present after the fire.

objectives for a given setting. Therefore, our six levels of soil burn severity do not depict a value but rather describe a continuum from an unburned forest floor to one in which fire has appreciably altered the physical and biological conditions of the forest floor.

Analysis and Interpreting Results

We combined our six levels of soil burn severity into three levels to ensure our observations were relatively evenly distributed among the different severity classes. Level 2 burn severity (combined level 1 and 2, fig. 4) consisted of areas with greater than 40 percent litter cover ,and the forest floor could vary from unburned to areas exhibiting black char. Level 4 (combined levels 3 and 4, fig. 4) soil burn severity described areas where less than 40 percent litter cover existed and the exposed mineral soil was either black or grey in color. Level 6 soil burn severity (combined levels 5 and 6, fig. 4) described sites where there was minimal litter cover and the exposed mineral soil was black, gray and/or orange colored, or there was an abundance of exposed rock.

We identified relations between forest structure and soil burn severity using a nonparametric classification and regression tree technique (CART) (Breiman and others 1984, Steinberg and Colla 1997). Figure 5 shows a thirteen-outcome classification tree predicting soil burn severity as a function of pre-wildfire forest structure. Outcomes 1 through 13 (shaded) show number of observations correctly classified, total number of observations, and the conditional probability of certainty. Forest characteristics occurring at the top of a classification tree were clearly related to burn severity compared to characteristics that appeared later in the tree. For example, wildfire groups (groups of individual fires) were often the most important in differentiating soil burn severity, followed by uncompacted crown ratio, total cover, and weighted basal area d.b.h. (fig. 5). In addition, the classification tree identified thresholds

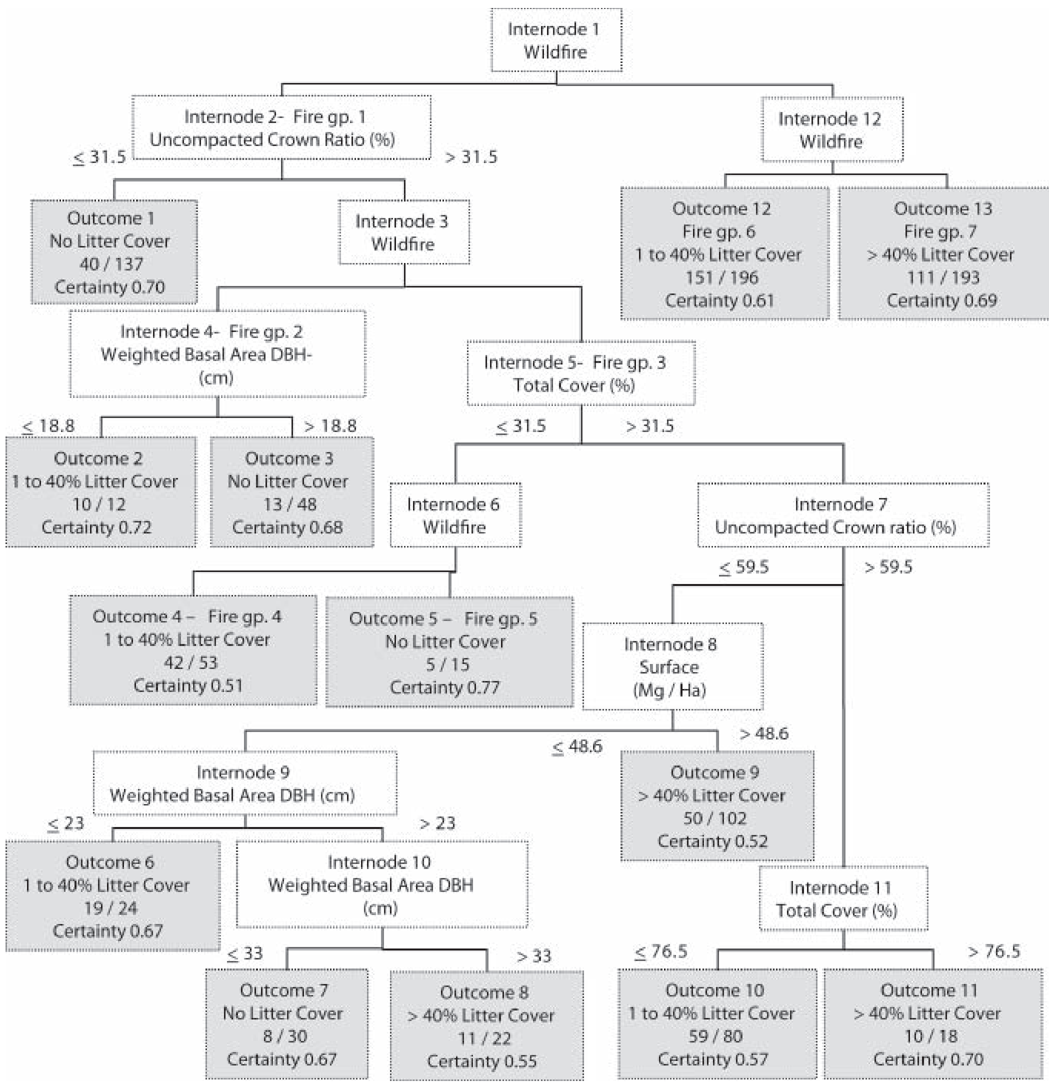

Figure 5—Classification tree for predicting soil burn severity resulting from CART analysis. Shaded areas reflect different predicted outcomes. Each outcome contains the soil burn severity, the number of correctly classified observations versus the total number of observations in the outcome and a conditional probability referred to as "certainty." The internode is where splits occurred based on either fire group or forest structure threshold. Numbers to the left and right of the node indicate the forest structure threshold used in predicting a particular outcome.

at which a forest structure characteristic became related to soil burn severity. In our classification, trees with uncompacted crown ratios ≤31.5 percent were highly related to low litter soil burn severities (level 6, outcome 1) (fig.5). In contrast, trees with uncompacted crown ratios >31.5 percent, differentiated (internode 3) into several outcomes (2 – 8) later in the CART classification. The CART analysis displays conditional probabilities (certainty) of an event happening predicated on earlier classifications. For example, the 0.70 probability of soil burn severity level 6 occurring in outcome 1 is dependent not only if trees have uncompacted crown ratios ≤31.5 percent but also the condition needs to occur within fire group 1 (fig. 5).

Results and Discussion

Our results show that soil burn severity (what is left after a wildfire) is strongly related to general wildfire conditions. That is, we identified seven groups of fires showing similarities when related to soil burn severity (fig. 5). The strength of these relations is exemplified in that fire group 7 only (1 outcome) contained sites with level two soil burn severity (> 40% litter cover, outcome 13). Similarly, fire group 6 only contained sites with level 4 soil burn severity (1 to 40% litter cover, outcome 12). The 56 wildfires in these two groups predominantly burned in the moist and cold forests (figs. 5, 6).

The wildfires in group 3 (outcomes 4 – 11) by far had the greatest diversity in soil burn severity of the wildfires we visited, and the stand structural characteristics often influenced the soil burn severity. Within this fire group total stand cover (internode 5, 31.5%, fig. 5) was an important soil burn severity differentiating characteristic. Stands with the lower canopy covers (≤31.5%) differentiated into two additional fire groups (internode 6, fire groups 4 and 5) and resulted in level 4 (1 to 40% litter cover, outcome 4) and level 6 (no litter cover, outcome 5) soil burn severities (fig. 5). Several of the soil burn severity outcomes (6 – 8) occurring in fire group 3 were related to tree size (weighted d.b.h.) and surface fuel amounts (fig. 5). The wildfires creating these burn severities tended to occur in the dry forests (fig. 6). Also within fire group 3 total cover (internode 11), after uncompacted crown ratio (internode 7), became an important structural element influencing soil burn severity (fig. 5). That is, stands burned in the moist and cold forests with total cover less than 76.5 percent tended to have level 4 (1 to 40% litter cover) soil burn severity and stands having excess of 76.5 percent cover tended to have level 2 soil burn severity (>40% litter cover) (fig. 5). These outcomes (10 and 11) most frequently occurred when wildfires burned the moist and cold forests (figs. 5, 6).

The differentiation of soil burn severity as a result of fire group most likely reflects wildfire characteristics such as fire duration, surface fuel moistures, heat produced, physical setting (for example slope angle, aspect), and geographic location (elevation, landscape position, watershed orientation and juxtaposition). In addition, these results emphasize the importance of observing many wildfires occurring in different years (weather), among many forest types (composition, potential vegetation), and across geographical areas (for example, northern Rocky Mountains, central Rocky Mountains) in order to understand the relation between wildfires and forest structure and how they may determine soil burn severity (Van Mantgem and others 2001).

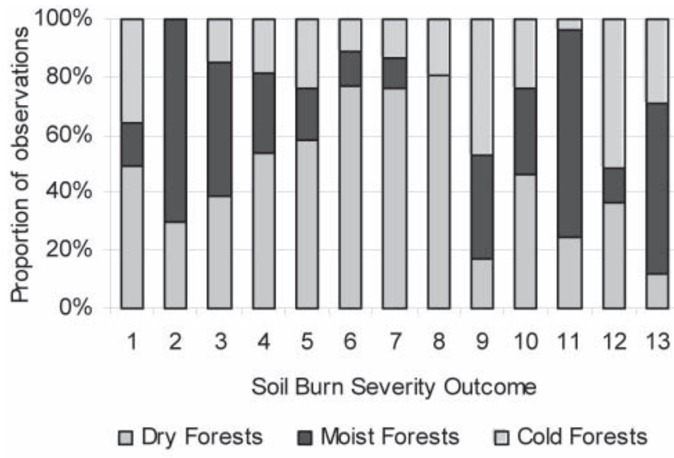

Figure 6—The distribution of forest type within each soil burn severity outcome (see fig. 5). Dry forests are ponderosa pine and/or Douglas-fir cover type. Moist forests are either western hemlock, grand fir, western redcedar, or white fir cover types. Cold forests are subalpine fir and/or lodgepole pine cover types.

Canopy base height, uncompacted crown ratio, and surface fuel conditions most often determine whether a fire will transition from the surface to a crown fire and as a result determine tree burn severity (Scott and Reinhardt 2001, Graham and others 2004, Peterson and others 2005). In contrast, soil burn severity depends on the amount of heat generated on the soil surface, the conduction of heat into the soil layers, and the heat's duration (DeBano and others 1998, Neary and others 1999, Wells and others 1979). These processes are strongly related to the amount of surface fuels, their structure and composition, their moisture content, the pre-fire environment, and the fire environment (fig. 4). Stand characteristics such as tree canopy cover, canopy cover distribution, uncompacted tree crown ratio, and forest composition interact and influence the amount, composition and distribution of live and dead ground-level vegetation (Barnes and others 1998, Oliver and Larson 1990). Therefore, we were not surprised that within a fire group, the most common forest characteristics related to soil burn severity were uncompacted crown ratio, (internodes 2, 7), total cover (internodes 5, 11), tree size (internodes 4, 9, 10), and the amount of surface fuels (internode 8) (fig. 5). Often, these forest characteristics worked in concert and hierarchically to produce a given soil burn severity. For example, for burned over soils to exhibit a level two burn severity (outcome 9) was predicated on sites occurring within fire group 3, trees on the site containing uncompacted crown ratios between 41.5 and 59.6 percent, total canopy cover on the site was less than 31.5 percent, and the surface fuel amounts had to exceed 49.6 Mg ha^{-1} (fig. 5). These results illustrate how overstory characteristics can influence soil burn severity within a group of wildfires and most likely these soil burn severities were related to the amount and condition of ground-level vegetation present when the wildfires burned.

The length of tree crowns in relation to the height of the trees (crown ratio) surprisingly had a strong (differentiated early in the CART analysis) association with soil burn severity, especially with wildfires occurring in group 1 (fig. 5, outcome 1). Fires burning stands with uncompacted crown ratios $\leq$31.5 percent tended to have no litter cover left after the fires burned, resulting in a level 6 soil burn severity (fig. 5). Many of the stands having this soil burn severity were multi-storied (60 of 127 sites had 3 stories or more) with Douglas-fir trees dominating the dry forests and lodgepole pine trees dominating the cold forests. The trees burned had high canopy base heights (>10 m), the stands averaged 1,900 trees ha^{-1} ($S_{\bar{x}}$ = 196), the mean canopy cover was 40 percent ($S_{\bar{x}}$ = 3) and tree diameter (weighted basal area d.b.h.) was less than 19 cm ($S_{\bar{x}}$ = 1). These results suggest that stands containing trees with short crowns occurring primarily in the cold and dry forests most likely influenced the composition, amount, distribution, structure, and moisture content of the surface fuels. The relatively high tree density may have suppressed surface wind speeds, favoring slow fire spread rates that could have combined with the ground-level vegetation conditions and forest floor surface layers (duff) to favor long duration surface fires. These burning conditions are often attributed to leaving no surface organic matter on a site after a fire and creating black or grey colored mineral soil (Debano and others 1998, Key and Benson 2001, Ryan and Noste 1989).

Stands within fire group 1 and containing trees with uncompacted crown ratios exceeding 31.5 percent differentiated into a multitude of soil burn severities depending on further fire groups, tree diameter, canopy cover, and surface fuel amounts. Within fire group 1 soil burn severity was related to total canopy cover in a subset of wildfires (internode 5, group 3). When burned, the denser stands (cover >76.5%) with crown ratios exceeding 59.5 percent tended to have greater than 40 percent litter cover or level two soil burn severity (outcome 11, fig. 5). Stands exhibiting this soil burn severity usually contained 3 or more canopy layers with mean canopy cover exceeding 90 percent ($S_{\bar{x}}$ = 3) and canopy base heights exceeding 4 m ($S_{\bar{x}}$ = 0.6). This soil burn severity most often occurred within moist forests which tend to have high moisture contents in the surface fuels as a result of the deep and closed canopy conditions. In fact the 1000-hour fuel moisture contents occurring in stands exhibiting this soil burn severity averaged 15.5 percent and were greater than those observed in stands exhibiting the other outcomes (fig. 7). These results indicate that apparently because of the high fuel moistures, moist forests can be relatively resilient to wildfire, even if they contain multiple canopy layers, dense canopy cover, and low canopy base heights.

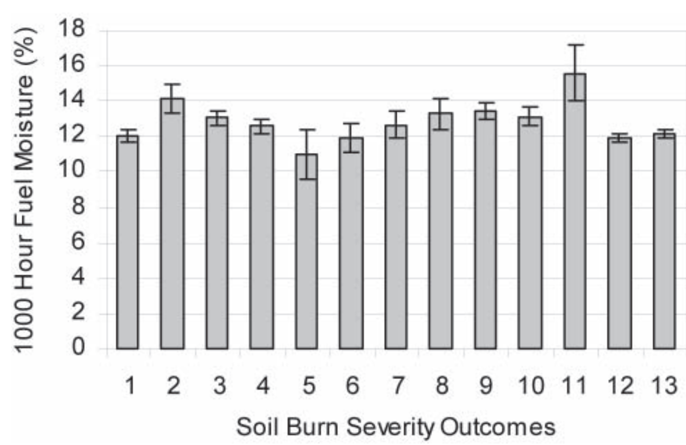

Figure 7—Average fuel moisture and standard errors for the 1000-hour fuels occurring in the stands for each soil burn severity outcome (see fig. 5).

Tree crown ratio appears to influence many stand characteristics that relate to soil burn severity and its influence varies by fire group and canopy cover. After uncompacted crown ratio and canopy cover, the amount of surface fuel becomes influential in determining soil burn severity. However the larger amounts of surface fuels do not readily translate into greater soil burn severity when the forests burned. For example, when wildfires burned stands with crown ratios exceeding 31.5 percent and less than 59.5 percent, canopy cover exceeding 31.5 percent, and containing surface fuels in excess of 48.6 Mg ha^{-1}, level 2 soil burn severity (>40% litter cover) was observed (outcome 9, fig. 5). The moist and cold forests typified this outcome, which historically tend to accumulate large amounts of surface woody debris (80 Mg ha^{-1}, $S_{\bar{x}}$ = 2.5).

After uncompacted crown ratio, canopy cover and the amount of surface fuel, tree size (d.b.h.) becomes a determinant of soil burn severity. The dominance of large trees on a site appear to create conditions that moderate soil burn severity. Soil burn severity level 2 was observed in stands that were dominated by large trees (46 cm, $S_{\bar{x}}$ = 1.0 basal area weighted d.b.h.) even though they contained an average of 40 Mg ha^{-1} ($S_{\bar{x}}$= 0.6) of surface fuels (outcome 8, fig. 5). The canopy cover was moderate (60%, $S_{\bar{x}}$ = 3), as was the canopy base height (7 m, $S_{\bar{x}}$ = 0.6) of stands exhibiting this soil burn severity. This outcome was distributed across the dry forests in strands containing tree densities ranging from 700 to 2,100 trees ha^{-1}. In contrast, level 6 (no litter cover) soil burn severity was observed in predominantly dry forest stands similar to those occurring in outcome 8, except tree diameters were less than or equal to 33 cm. Stands exhibiting this burn severity averaged 28 cm (weighted by basal area) in diameter and contained 1,000 to 2,200 trees ha^{-1}. The mean canopy cover of the stands was 61 percent and the tree canopy base height averaged 4 m ($S_{\bar{x}}$ = 0.5).

These two contrasting soil burn severity outcomes differentiated by tree diameter most likely are related to the tree juxtaposition and variation in density of trees occurring within the stands, especially in ponderosa pine forests, large trees tend to be distributed irregularly often occurring in clumps (Graham and Jain 2005). This irregular horizontal structure would tend to perpetuate variable surface fuel amounts and create a diverse fuel matrix. As a result, surface fires burning fuels in these conditions would most likely result in variable soil burn severities which on the average would be low (level 2). However, small diameter (for example 28 cm) and most likely mid-aged stands, particularly when excluded from fire, tend to develop with more horizontally uniform distributions. As a result, the surface fuels and burning conditions would also be uniform in these stands and may have resulted in surface fires with long residence times.

Small trees (d.b.h.), after uncompacted crown ratio, canopy cover, and the amount of surface fuel were related to level 4 soil burn severity (fig. 5, outcome 6). The dry forest stands dominating this outcome (fig. 5, outcome 6) had 62 percent canopy cover, which was similar to that of the stands occurring in outcomes 7 and 9, but the stands contained more trees (2,000 to 2,800 trees ha^{-1}). Canopy base heights were relatively low (2 m) and average tree height was 13 m ($S_{\bar{x}}$= 1).

The range of soil burn severities occurring among outcomes 6, 7, and 8 illustrate how stand development within dry forests influences soil burn severity. The small diameter young forests when burned tended to create level 4 soil burn severities (outcome 6), the stands with mid-sized and likely mid-aged trees when burned tended to create level 6 soil burn severities (outcome 7, fig. 5), and when stands containing large and old trees burned, level 2 soil burn severities were created (outcome 8, fig. 5).

In fire group 2, which is a subset of group 1 fires, tree size was second only to uncompacted crown ratio in explaining soil burn severity. Again, diameter most likely reflects a developmental stage of the stands exhibiting the two contrasting burn severities. Stands with the smaller and younger trees (<18.8 cm, weighted basal area d.b.h.) had level 4 burn severity compared to the stands containing the mid-aged and larger trees (>18.8 cm weighted basal area d.b.h.) which exhibited level 6 burn severity (no litter). These findings were similar to those illustrated in outcomes 6 and 7 except these outcomes occurred in fire group 2 and outcomes 6 and 7 occurred in fire group 3 (fig. 5). The moisture content of the 1000-hour fuels in stands occurring in outcome 2 was 14 percent ($S_{\bar{x}}$ = 1) and 11 percent ($S_{\bar{x}}$ =1) for the 1000-hour fuels within stands occurring in outcome 3.

Thinned stands, plantations, and others exhibiting management typified stands in outcomes 2 and 6. The forest floor conditions of stands in these outcomes most likely resembled those associated with stand initiation structural stages. These early structural stages frequently contain moist and robust layers of ground-level vegetation. Because these stands were managed, the surface fuel matrix was modified through slash disposal and site preparation activities resulting in a discontinuous fuel bed. Particularly, in the cold and moist forests, crown fires would burn around these areas and most often there was evidence that firebrands landed in these stands but the surface fuel conditions prevented sufficient fire from developing that could create a smoldering fire. Therefore, these results indicate that high stand densities and low canopy base heights do not necessarily lead to severely burned soils and other factors such as developmental stage may also influence soil burn severity.

After uncompacted crown ratio (>31.5%) and total canopy cover (<31.5%) the fire setting (fire group) became an important predictor of soil burn severity (fig. 5). Two fire groups differentiated, one expressing level 4 soil burn severity (outcome 4, fire group 4) and one expressing level 6 soil burn severity (outcome 5, fire group 5). Both outcomes had similar representation from cold, moist and dry forests (fig. 6) and the stand densities of both were low (292 trees ha^{-1} for outcome 4 and 312 trees ha^{-1} for outcome 5) when compared to stand densities occurring in the other outcomes. Also, for both outcomes canopy base heights were near 6 m and the uncompacted crown ratios for both were above 60 percent. The greatest difference in the stands occurring in the two outcomes was the setting (for example topography, geographic location, watershed juxtaposition and so forth) in which they occurred. Outcome 5 consisted of observations from the Hayman and Missionary Ridge fires in Colorado and the Ninemile fire in Missoula County, Montana. Outcome 4 included observations from the Alpine, Bear, and Blodget fires in Ravalli County, Montana and the Flagtale fire in Grant County, Oregon. The stands burned by wildfires in outcome 4 also had higher 1000-hr fuel moistures (12.5%) than stands burned by the fires in outcome 5 (11%) (fig. 7). In addition, the average wind speeds occurring during the fires in outcome 5 tended to be higher (7 to 8 miles hour^{-1}) when compared to the winds blowing during outcome 4 fires (4 miles hour^{-1}). The different burning conditions (for example fuel moisture, wind speed, location, and so forth) exemplified in these two outcomes probably had a greater influence on soil burn severity than forest structure, given that both outcomes had very similar structural characteristics.

There are several factors (for example, weather, type of vegetation, fuel moisture, atmospheric stability, physical setting, ladder fuels, surface fuels) that influence fire behavior and burn severity, and forest structure is only one (Agee 1996, Graham and others 2004). Therefore, we did not expect forest structure to fully explain all of the variation present in soil burn severity after a wildfire. However, through our study and the analysis we performed, we were able predict soil burn severity as a function of pre-wildfire forest structure with probabilities far greater than what would have occurred randomly. These variables were not only hierarchally related to soil burn severity, but together they very readily predicted three levels of soil burn severities. Because we identified three levels of soil burn severity, a random probability of a given soil burn severity occurring would be 0.33. Therefore, any probability exceeding 0.33 of the complete CART tree correctly classifying a particular soil burn severity indicates the addition of forest structural characteristics were significantly related to soil burn severity. The variables, in order of importance, fire group, uncompacted crown ratio, weighted basal area d.b.h., total cover, and surface fuel amounts classified level 2 soil burn severity (>40% litter cover) with a 0.46 probability, level 4 soil burn severity (1 to 40% litter cover) with a 0.40 probability, and level 6 (no litter cover) soil burn severity with a 0.57 probability.

Conclusion

Undoubtedly intense fire behavior is a primary concern for forest management throughout the western United States and fuel treatments to modify this fire behavior are a primary concern (Graham and other 2004). However, in most circumstances what a fire leaves behind in terms of soils, homes, and trees is as important, if not more important than fire behavior. Therefore, fuel treatments need to be designed and implemented as to modify burn severity and the traditional thinned forest with high canopy base heights may not result in the desired burn severity.

One size does not fit all. Therefore, we would suggest that fuel treatments be designed to consider burn severity as well as fire behavior. In particular, biophysical setting (fire group, forest type, locale, potential vegetation type, and so forth) needs to provide context for planned fuel treatments. Secondly, tree canopy base height (reflected in uncompacted crown ratio) needs to be considered when designing fuel treatments, although high canopy base heights do not always reduce soil burn severity. Similarly, reducing total forest cover does not necessarily reduce soil burn severity; rather its interactions with the biophysical setting, canopy base height, and surface fuel amounts and conditions most likely determine soil burn severity. The last characteristics that we identified as having a relation with soil burn severity, were tree diameter and surface fuel amounts.

The robust data we accumulated from wildfires that burned throughout the western United States in recent years did not greatly simplify our understanding of the relations between forest structure and soil burn severity. Nevertheless, we did identify several interactions between forest characteristics and soil burn severity that have fuel treatment management applications. A significant factor of this work is the estimate of the certainty a forest structure (fuel treatment) will have in modifying soil burn severity. The conditional probabilities (certainty) we identified of forest structure or fire setting (fire group) influencing soil burn severity always exceeded 0.50 and occasionally exceeded 0.75 (fig. 5). In addition, the approach we took in identifying the relations between forest structure and burn severity, and the level of certainty we provided, was conditional on the circumstances in which the forest characteristic occurred. This kind of information will be of value when communicating the importance forest structure (fuel treatments) has on determining the aftermath of wildfires. This paper and the analysis and results we reported are a continuation of our work in understanding how forest structure interacts with wildfires, their biophysical setting, and burning conditions to create a particular burn severity.

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Economics and Biomass Utilization

Design and Objectives of FTM–West Model

Peter J. Ince[1] **and Henry Spelter**[2]

Abstract—*The FTM–West ("fuel treatment market" model for U.S. West) is a dynamic partial market equilibrium model of regional softwood timber and wood product markets, designed to project future market impacts of expanded fuel treatment programs that remove trees to reduce fire hazard on forestlands in the U.S. West. The model solves sequentially the annual equilibria in wood markets from 1997 to 2004 and projects annual equilibria from 2005 to 2020 using detailed assumptions about future thinning programs and market trends. FTM–West was designed specifically to account for economic complexities that stem from unconventional size distributions of trees and logs removed in thinning operations (compared with conventional timber supply in the West). Tree size directly influences market value and harvest cost per unit volume of wood; log size influences product yield, production capacity, and processing costs at sawmills and plywood mills. FTM–West provides a tool to evaluate future market scenarios for large-scale fuel treatment programs with various thinning regimes that may have varying costs and yield wood with divergent size class distributions. The model provides a capability to analyze and project how much harvestable wood the markets can absorb from thinning programs over time and the regional timber price and timber harvest impacts of expanded thinning under various assumptions about fuel treatment program subsidy or administrative costs, variations in thinning regime, or alternative projections of future product demands across the spectrum of products ranging from wood fuel to lumber, plywood, and wood fiber products.*

Introduction

Decades of fire suppression, reduced timber harvests on public lands since the 1980s, and a build-up of standing timber inventories in fire-prone forested regions of the western United States have created conditions susceptible to catastrophic wildfires. Expanded programs of systematic stand density reduction through mechanical thinning on public lands may reduce fuel build-up. Timber market consequences of such programs depend on the scale of program and the type of treatment regime. This paper describes the design and objectives of an economic model that can project timber market impacts of expanded fuel treatment programs in the U.S. West.

The "fuel treatment market" model for the U.S. West (FTM–West) employs the Price Endogenous Linear Programming System (PELPS). PELPS is a general economic modeling system developed originally at the University of Wisconsin (Gilless and Buongiorno 1985, Calmels and others 1990, Zhang and others 1993) and more recently modified for applications at the Forest Products Laboratory (Lebow and others 2003). PELPS-based models employ the technique of spatial equilibrium modeling (Samuelson 1952), with periodic (for example, annual) market equilibrium solutions obtained by economic optimization. Solutions are derived by maximization of consumer and producer surplus, subject to temporal production capacity

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constraints, transportation and production costs, and price-responsive raw material supply curves and product demand curves, all of which can be programmed realistically to shift over time and respond to endogenous shifts in market conditions. FTM–West employs the FPL version of PELPS (called FPL–PELPS), Lebow and others (2003) and earlier PELPS publications provide further mathematical details about the modeling system. PELPS has been used fairly widely for partial market equilibrium models of timber and forest products for many years (for example, Buongiorno and others 2003, Zhang and others 1996, ITTO 1993).

Structure of FTM–West

Forest sector market models commonly include structural features of wood product markets, such as a regional market structure with regional product demand curves, regional timber supply curves, interregional transportation costs, and regional production capacities and manufacturing costs. Those general structural features were included also in FTM–West. In addition, FTM–West was designed with other features to account for economic complexities that can arise with utilization of wood from fuel treatment programs, which may have a more divergent distribution of volume by tree size class than does conventional timber supply (for example, wood from fuel treatments may have a larger fraction of volume in smaller trees than conventional timber supply).

General Design Features

Among general design features, FTM–West included demands for more than a dozen forest product commodities encompassing the full spectrum of forest products produced from softwood timber in the U.S. West, three product demand regions, eight production or supply regions, and estimated wood supplies from conventional timber supply sources and from future fuel treatment programs (assumed to be primarily softwoods). Table 1 summarizes the regional and commodity structure of the model.

The model included demand only for forest products produced from softwood timber in the U.S. West, a partial representation of total U.S. and global demands for forest products. Fairly simple demand curves were specified in the model based on an assumption that demands for all products are inelastic (price elasticity of demand ranged from –0.3 to –0.8 among the various products). Aggregate demand quantities for each product were equated to product output data for the U.S. West in the base year (1997) and proportioned to each of the three product demand regions using estimates of regional shipments

Table 1—Regional and commodity structure of FTM–West model.

Supply/production regions	Demand regions	Demand commodities
Coast PNW (OR, WA)	U.S. West	Softwood lumber & boards
Eastern Washington	U.S. East	Softwood plywood
Eastern Oregon	Export market	Poles & posts
California		Paper (five grades)
Idaho	*Supply commodities*	Paperboard (three grades)
Montana	“Pines”	Market pulp
Wyoming–South Dakota	“Non-Pines”	Hardboard
Four-Corners (UT, CO, AZ, NM)	(trees, logs, chips)	Fuelwood

from the West. Product output was based on data published by industry associations, such as WWPA (various years) for lumber, AF&PA (2005) for pulp and paper, and APA–The Engineered Wood Association (various years) for plywood. FTM–West was designed to derive annual market equilibria sequentially over a 24-year period, 1997 to 2020, which permitted testing and calibration of model solutions against overlapping historical data (to 2004). Demand curves were shifted each year based on historical shifts in production in the U.S. West (1997 to 2004), and the model was programmed with a set of assumed future growth rates in regional demand (2005 to 2020) for each forest product commodity. Demand growth rate assumptions matched recent Forest Service Resources Planning Act (RPA) Assessment projections (2005 draft RPA timber assessment report).

Similarly, simple supply curves were used to model conventional softwood timber supply in each of the eight supply regions, while exogenous estimates of wood supply from treatment programs (upper bounds on harvest quantity and harvest costs) were introduced as policy or program variables. Estimates of wood supply from fuel treatment programs were obtained from the Fuel Treatment Evaluator, FTE v. 3.0 (Skog and others 2005). Most conventional timber supply in the U.S. West is currently obtained from timber harvest on state and private forestlands, subjected mainly to even-aged timber management. Thus, inelastic supply curves were used for conventional timber supply (with an assumed price elasticity of 0.7). Conventional timber supply curves were programmed to shift over time in direct proportion (1:1 ratio) to net growth in softwood timber inventory volumes on state and private timberland within each supply region. Annual net growth in state and private timber inventories are computed in the model by deducting from standing timber inventories the harvest volumes from the preceding year and adding timber volume growth based on recent growth rates in each region (Smith and others 2004). Thus, FTM–West incorporated techniques similar to those used in the Forest Service RPA Assessment to model conventional timber supply (that is, inelastic supply curves shifted over time in proportion to projected net growth in timber inventories).

In addition to supply and demand curves, FTM–West incorporated estimates of manufacturing capacities for the various products in each of eight production regions, manufacturing cost data, and transportation cost data (for wood raw material and product shipments). A feature of PELPS is that production capacities shift over time in response to projected market conditions, and in FTM–West we used a representation of Tobin's *q* model to project regional capacity change as a function of the ratio of shadow price (or value) of production capacity to cost of new capacity (Lebow and others 2003).

Structural Complexities in Wood Utilization

Beyond general elements of model structure, FTM–West incorporated some unique features to account for economic complexities that were known to be associated with utilization of wood from fuel treatments. Specifically, it was known that the size-class distribution of wood harvest (the distribution of wood volumes by tree diameter class) may be significantly different for wood removed in fuel treatments than for conventional timber supply. Also, it is fairly well known that timber market value and harvest costs per unit volume are highly dependent on tree size class or diameter, whereas mill production capacity, processing costs, and product yields also vary with log diameter, particularly at lumber mills and plywood mills.

Divergent Sizes of Trees and Logs—In recognition of divergent size classes of trees harvested, both the conventional timber harvest and the exogenously specified wood harvest from fuel treatments were modeled in FTM–West by 2-inch (5-cm) diameter classes, ranging from trees <5 inches d.b.h (diameter at breast height) to trees >15 inches d.b.h. Thus, all wood supply is disaggregated into seven tree size classes, each of which can assume a unique market value in the FTM–West model. Furthermore, each tree size class yields different proportions of logs (by 2-inch log size class) along with variable quantities of wood chip raw materials. Estimates of actual log and chip volume yields were derived for each tree size class and for each of the eight supply regions based on recovery data from regional utilization studies conducted at the Forest Service Pacific Northwest (PNW) Research Station (compiled from mill studies by Dennis Dykstra, PNW Station).

Figure 1 illustrates divergent distributions of harvest volume by tree size class as estimated for conventional timber harvest in the U.S. West (in 1997) and for two fuel treatment thinning program regimes (derived from the FTE program; Skog and others 2005). Both the even-aged TFB (thin-from-below) treatment regime and the uneven-aged SDI (stand density index) treatment regime yielded proportionately more volume in smaller trees (size classes less than 9 inches d.b.h.) than did conventional timber harvest, but the SDI treatment also yielded more volume in larger trees (>15 inches d.b.h.).

Figure 2 illustrates the West-wide average log and chip recovery potential from each tree size class (averages for all eight regions in FTM–West). In general, smaller trees can yield only small logs and a high proportion of volume in wood chips, whereas bigger trees can yield more volume in larger logs (which have generally higher value) and a smaller proportion of volume as chips.

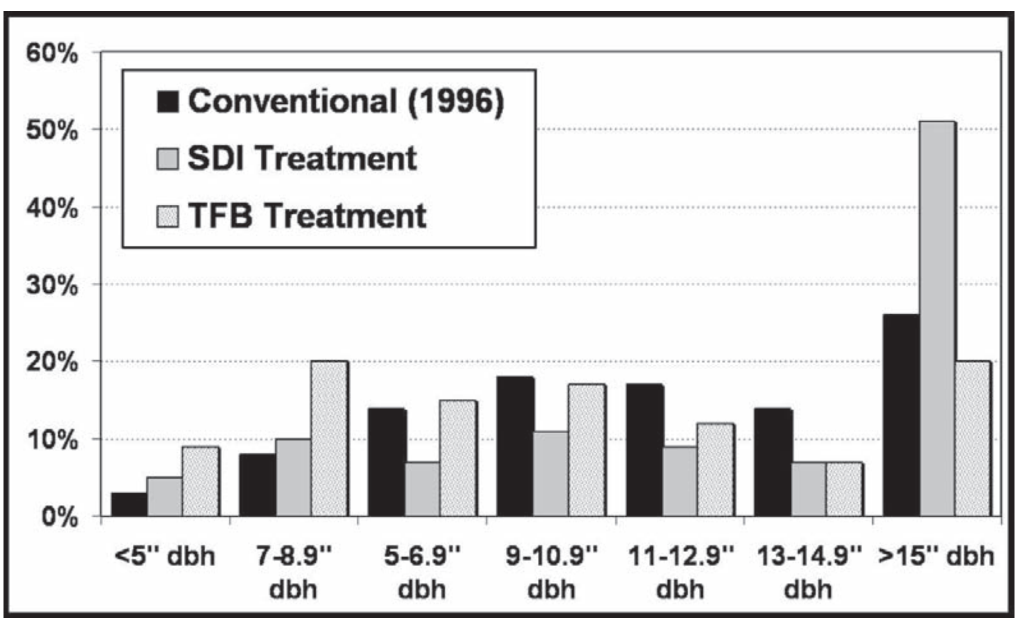

Figure 1—Estimated volume distributions by tree size class for conventional timber harvest and for wood from fuel treatment regimes on federal lands in U.S. West.

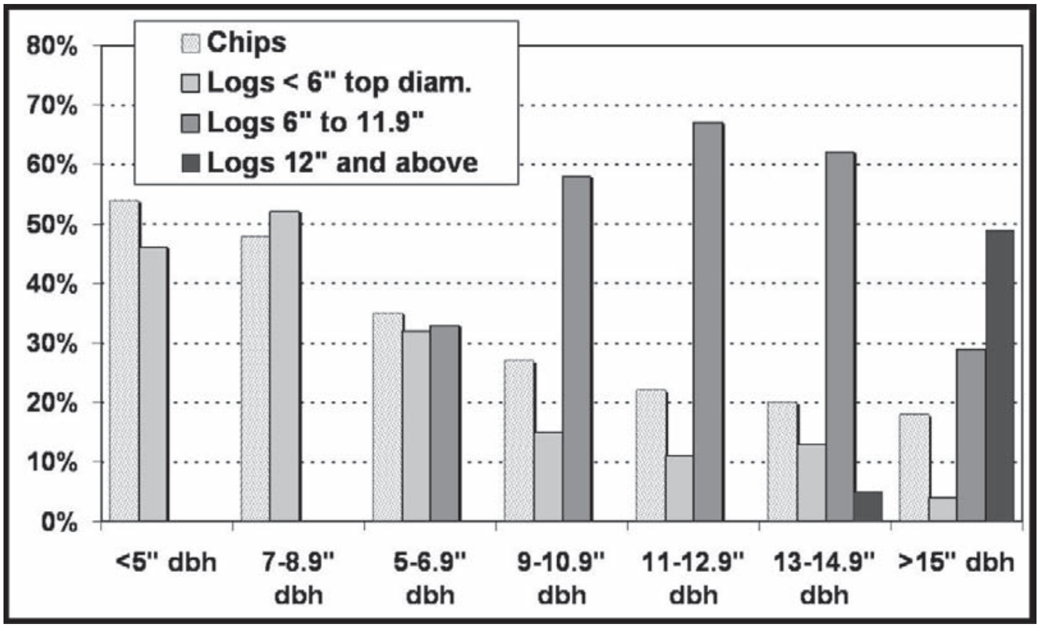

Figure 2—West-wide average log and chip recovery potential (percentages of cubic wood volume recoverable as chips and logs of various sizes) for different tree diameter classes.

Variable Stumpage Values and Variable Harvesting Costs—Harvesting costs per unit of wood volume vary with tree size class due to efficiencies gained in harvesting larger trees with more wood volume per tree or per log harvested. Thus, in addition to modeling wood supply in FTM–West by size class of trees and logs, we used harvest cost models to estimate harvesting costs for each tree size class. Harvesting costs for wood removed in fuel treatments were estimated by the FTE program (Skog and others 2005) using the calculation routine from *My Fuel Treatment Planner* (Biesecker and Fight 2005). Timber harvesting costs for conventional timber supply were estimated by tree diameter class using a conventional timber harvest cost model by Keegan and others (2002).

For the simulated fuel treatment programs, we adopted a policy assumption that fuel treatment managers on federal lands would require removal of all tree size classes marked for thinning, based on an assumption that fuel treatment policies would not allow "high-grading" or just the removal of bigger and more valuable trees. Under that policy assumption, the harvesting and transportation costs applied to all wood from fuel treatments are the volume-weighted average costs across all tree size classes. Note that average costs for fuel treatments (across all size classes) were estimated to be higher than conventional timber harvesting and transport costs in the West.

Figure 3 shows our West-wide averages of wood harvesting costs, wood transport costs to mill, and stumpage costs in dollars per thousand cubic feet (MCF) as assumed or as estimated in the FTM–West model. Costs for conventional timber supply are differentiated by tree diameter class, with notably higher estimated stumpage values for larger trees (2005 equilibrium values).

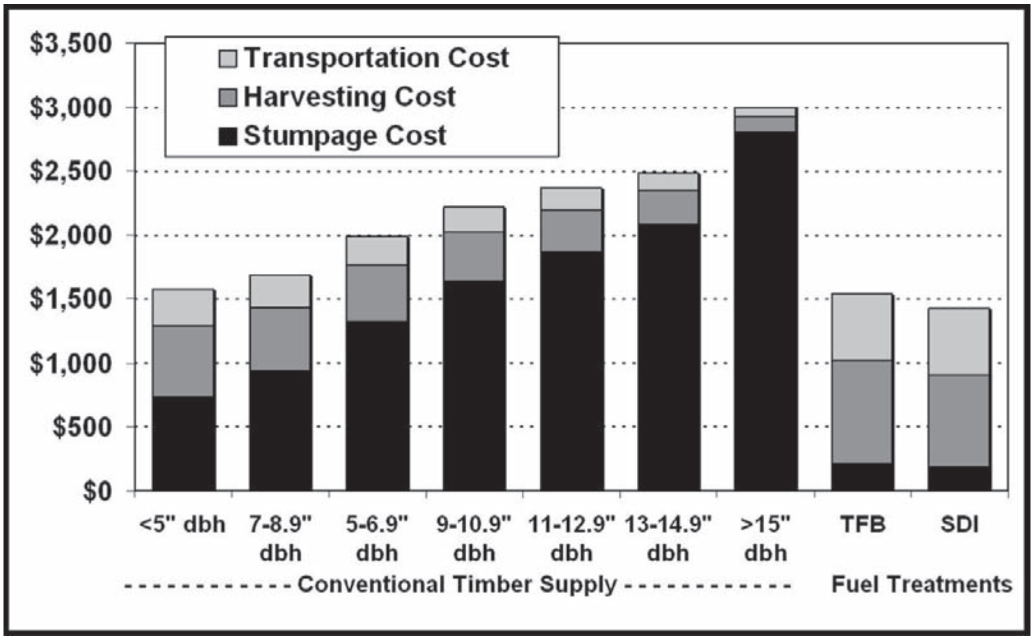

Figure 3—West-wide averages of 2005 delivered wood costs ($/thousand cubic feet) by tree diameter class for conventional timber harvest and wood from fuel treatments, including stumpage cost (2005 equilibrium values computed by FTM–West), harvesting cost, and transportation cost.

In our fuel treatment program scenarios we assumed a hypothetical harvest fee (equivalent to stumpage fee) of $500 per acre, representing a nominal fee for administrative costs. That fee translates to $214/MCF harvested for the TFB thinning program and $188/MCF for the SDI program.

As illustrated in figure 3, the assumed harvest fees (stumpage costs) for the hypothetical fuel treatment programs are considerably lower than the estimated stumpage market values for conventional timber supply in the region, but the estimated harvest and transportation costs for the fuel treatments are considerably higher than those for the conventional timber supply. In essence, we assumed that the hypothetical fuel treatment programs would offer wood to the market at low stumpage fees that would compensate somewhat for the higher harvest and transport costs of fuel treatments. This is purely a hypothetical assumption, and future fuel treatment programs might potentially charge higher or lower fees. Note also that harvest and transportation costs shown here are averages that include costs for both logs and chips delivered to mills.

Variable Product Yields and Variable Sawmilling Capacity—Sawmill capacities are generally constrained by primary saw rigs that break down logs at the front end of sawmills. Primary breakdown saws (or "head rigs") are typically designed to process logs within certain size ranges, some designed to process small logs and some designed to process large logs. Small log mills run logs end-to-end at fairly constant speed, and within a feasible range of equipment design, a larger log yields more product because each cut generates more volume (Fight 2002). In contrast, large log mills may not process logs in one pass but may require multiple passes before logs are sufficiently broken down to permit further processing, which results in unproductive dead time between passes. Furthermore, the larger cross-sectional areas of cuts usually require a slower feed rate with large logs. Thus, effective lineal throughput of logs at large log mills is less than that of small log mills, but the greater volume of wood in each lineal foot more than compensates for the slower feed rate.

In general, sawmill output capacity is determined by (1) the lineal feet of logs that the sawmill is capable of processing in a given amount of time (throughput), (2) the volume of wood contained in each lineal foot of log throughput, and (3) the lumber recovery factor (LRF), which measures yield of lumber in board feet from each cubic foot of log throughput. However, parameters (2) and (3) are strongly influenced by log diameter, and thus lumber output capacity of sawmills varies with the size of log inputs. Product recovery per cubic foot of log input for both lumber and plywood generally increases with log size. Figure 4 is a plot of estimated lumber recovery (in board feet) and plywood recovery (in square feet) per cubic foot of log input by log diameter as estimated for the FTM–West model (Williston 1981).

Sawmill industry mill capacities are conventionally reported in board feet of lumber output rather than lineal feet of log throughput (for example, see Spelter and Alderman 2005). To estimate equivalent sawmill capacities in lineal feet of log throughput, we started by obtaining wood consumption data by log size, available for the states of Washington (Larsen and Aust 2000) and Oregon (Ward and others 2000). In each state the volumes of logs processed by sawmills, expressed in board feet, were provided for four log size classes, as shown for the state of Washington in table 2, row 1.

We then estimated a corresponding distribution of tree harvest volume by tree diameter class (d.b.h.) that would produce a mix of logs (table 2, row 2) exactly matching the actual survey data on log size distribution (table 2, row 1). To do this, we started with data on log recovery volumes from

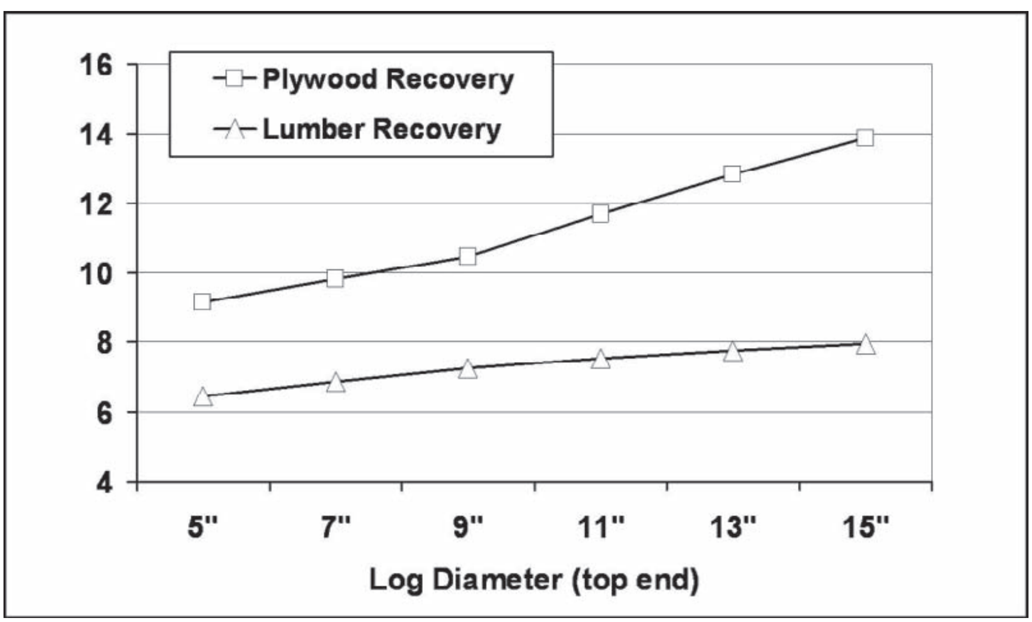

Figure 4—Estimated lumber recovery (board feet) and plywood recovery (square feet) per cubic foot of wood input by log diameter.

Table 2—Log volumes in coastal Washington.

Log diameter class (top end diameter) (inches)	<5	5–10	11–20	21+	Totals
Log volumes (log scale), actual survey data (million board feet)	124.4	908.8	812.0	137.4	1982.7
Log volumes derived from assumed tree harvest (million board feet)	124.5	908.8	812.0	137.4	1982.7
Derived lineal feet of logs (millions)	170.2	541.1	127.2	6.1	844.6
Average cubic feet per lineal foot	0.164	0.457	1.345	3.447	0.553
Derived cubic feet of logs (millions)	27.9	247.4	171.0	21.2	467.4
Average board feet (log scale) per cubic foot	4.46	3.67	4.75	6.49	

field studies conducted over the years at the Pacific Northwest Research Station, as compiled and analyzed by Dennis Dykstra. By an iterative process, we varied the numbers of trees within each tree diameter class until the derived log volumes matched the survey data (table 2, row 2). Then, multiplying numbers of trees by lineal feet of logs from each tree gave derived estimates of lineal log throughput consistent with reported log volumes (table 2, row 3). Regional industry throughput capacity in lineal feet was derived by dividing the estimated lineal throughput by the observed regional capacity utilization ratio (derived from WWPA lumber output data and capacity data from Spelter and Alderman 2005) Thus, we obtained estimates of lineal log throughput capacities at sawmills in western states and FTM–West regions that were equivalent to lumber output capacity in those states and regions. Similarly, multiplying the number of logs by the cubic volume of each log produces estimates of the equivalent cubic foot volumes of mill throughput (table 2, row 5).

To model sawmill capacity in relation to log size, we had to estimate the relationship between lumber output and log size for a given regional log throughput capacity. In other words, we assumed that sawmill capacity is constrained primarily by the lineal log throughput capacity of mill head rigs, but variation in log size can result in marginal shifts in lumber output capacity. Again, for each log size, two variables connect log throughput to equivalent board feet of lumber output: cubic volume of wood in an average lineal foot of log throughput (what we term the V factor) and lumber recovery factor (LRF), the board feet of lumber yielded by a cubic foot of log throughput. Given industry throughput capacity in lineal feet, along with the V and LRF factors, the theoretical board foot capacity for each log size class can be determined. However, portraying lineal throughput capacity as invariant with respect to log size is unrealistic. As logs get bigger, at some point the log breakdown requires multiple passes through the head saw and/or feed speeds must be decreased (Williston 1976). Because we do not have mill capacities by feed speed limits, we approximated this aspect of sawmilling by introducing an arbitrary log speed adjustment factor, effectively speeding processing up for smaller logs and slowing it down for larger logs. This adjustment resulted in a realistic representation of how sawmill throughput would respond to changing log diameters and produced throughput capacities from which board foot capacities were derived by multiplying by the V and LRF factors, as shown in table 3.

Table 3—Board foot lumber output capacity as a function of log size for given log throughput capacity (lineal feet of log throughput).

Log size class (inches)	Capacity (lin. ft)	Adjustment for log speed (%)	Adj. cap. (lin. ft)	V	LRF	Capacity (board ft)
<4	844.6	73	1,461	0.15	6.33	1,387
4–5.9	844.6	52	1,284	0.27	6.44	2,233
6–7.9	844.6	24	1,047	0.51	6.87	3,668
8–9.9	844.6	7	904	0.65	7.25	4,260
10–11.9	844.6	–6	794	0.91	7.54	5,448
12–13.9	844.6	–15	718	1.30	7.77	7,252
>14	844.6	–32	574	2.52	8.20	11,861

It is self-evident that the V factor (cubic volume per lineal foot of log throughput) increases with log size because the wood volume in a lineal foot increases by the diameter of the log squared. The LRF also increases because the share of edgings and slabs becomes a smaller fraction of total volume as logs increase in size (fig. 1).

Variable Manufacturing Costs—In a similar vein, the V and LRF factors affect non-wood manufacturing costs. A mill's labor costs and capital costs, for example, are invariant with respect to the size of a log that is momentarily being processed, and thus they are marginally fixed costs relative to log throughput but variable with respect to product output. Varying log size marginally affects lumber output, and thus fixed costs will be written off against varying volumes of product output. Thus, manufacturing costs per board foot of lumber output vary in FTM–West by log diameter class.

To estimate how manufacturing costs vary with log size class we first developed estimates for each region of average industry non-wood costs (labor, energy, materials, supplies, overhead, and depreciation) per unit of mill output. Multiplying the unit cost estimates by the base year output gave the total dollar value of non-wood manufacturing costs for each region. Given estimated relationships between output capacity and log size, as derived above for each region, we calculated the theoretical manufacturing costs for each log size at a constant log throughput volume as our first approximation of unit costs by log size, which exhibit a pronounced inverse relationship to log diameter (as shown by the "constant throughput" relationship in figure 2). However, again, it would be unrealistic to assume that lineal log throughput speed could remain constant with varying log diameter, so we applied again the log speed adjustment (table 2) to reflect accelerated throughput with smaller logs and slower throughput with larger logs. The result is the relationship shown as the "variable throughput" cost curve in figure 5, which we used to model lumber manufacturing costs by log diameter in FTM–West. Despite the log speed adjustment, there is a big cost difference between processing small logs and large logs.

Plywood manufacturing capacity, manufacturing costs, and product recovery are modeled in an identical manner, using the same V factors and replacing LRF by the plywood recovery factor, whose behavior is identical to the LRF for the same basic reasons (fig. 4).

Finally, as noted previously, regional production capacities in the FTM–West model will shift over the projection period from 2005 to 2020 in response to

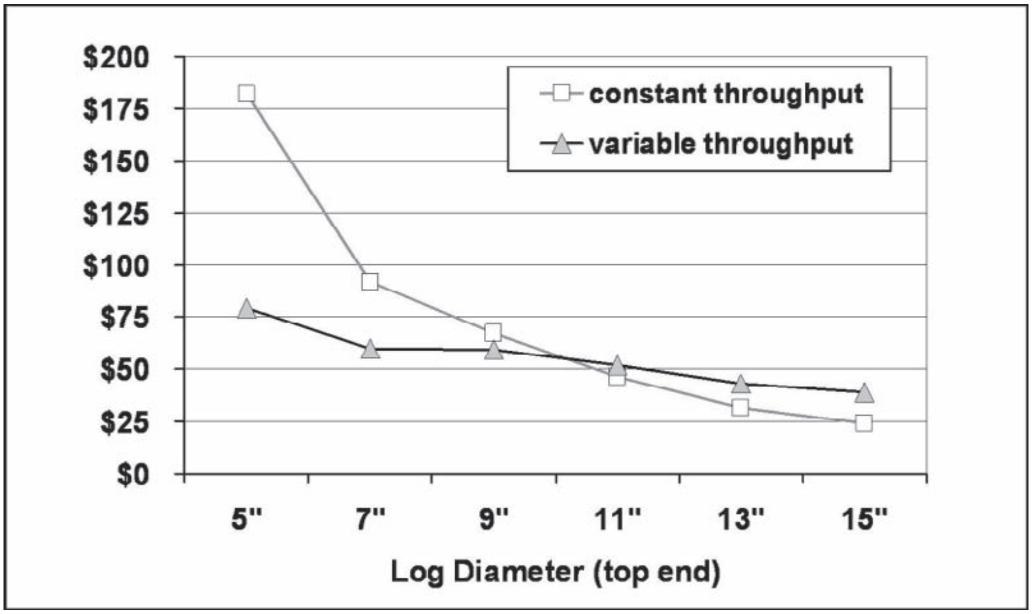

Figure 5—Non-wood lumber manufacturing costs ($/thousand board feet) with constant log throughput and variable-speed log throughput assumptions.

projected economic profitability of investments (Tobin's *q* ratio), simulating long-run capital investment responses to economic opportunities. In scenarios that introduce increased supply of wood from fuel treatment programs, we found that the model responds with capacity expansion, increased regional wood harvest, and displacement of conventional timber harvest by wood from fuel treatments. However, treatment regimes that introduce marginally higher proportions of small-diameter wood than conventional timber harvest will also marginally offset regional production capacities, reduce average product recovery, and increase manufacturing costs for lumber and plywood. Those impacts affect the producer surplus and consumer surplus consequences of fuel treatment programs. Net market welfare impacts of alternative treatment regimes are described in a companion paper in these proceedings (Kramp and Ince 2006).

Summary

The development of FTM–West provided a tool to evaluate future market scenarios for large-scale fuel treatment programs with various thinning regimes that may have varying costs and may yield wood with divergent size class distributions. It also provided a capability to analyze and project how much harvestable wood the markets can absorb from thinning programs over time and the regional timber price and timber harvest impacts of expanded thinning under various assumptions about fuel treatment program subsidy or administrative costs, variations in thinning regime, or alternative projections of future product demands across the spectrum of products ranging from wood fuel to lumber, plywood, and wood fiber products.

Acknowledgments

This study was funded in part by the Joint Fire Science Program (JFSP), a partnership of six federal agencies: USDA Forest Service, Bureau of Indian Affairs, Bureau of Land Management, National Park Service, U.S. Fish and Wildlife Service, and U.S. Geological Survey. Additional in-kind contributions were provided by researchers at the USDA Forest Service Forest Products Laboratory (FPL) and Pacific Northwest Research Station (PNW). Andi Kramp of FPL helped enter data input for the FTM–West market model and assisted in running the model and interpreting model results. Ken Skog of FPL assisted in developing treatment program scenarios for FTM–West using the Fuel Treatment Evaluator (FTE, version 3.0). Dennis Dykstra of PNW provided estimates of log and chip volume yields for each tree size class in each of the eight supply regions of FTM–West, based on data from regional wood utilization studies. The study was part of a larger JFSP-funded project, identified as JFSP project 01-1-2-09, "A national study of the economic impacts of biomass removals to mitigate wildfire damages on federal, state, and private lands," coordinated by Jeffrey Prestemon and Karen Lee Abt of Forest Service Southern Research Station (SRS). The authors sincerely appreciate the consultation provided by the project coordinators, as well as consultation on the PELPS modeling system from Patti Lebow of FPL, additional data input from Matt Alderman of FPL, and consultation or input from other members of the JFSP project, including Roger Fight and Jamie Barbour of the PNW and Bob Rummer and Robert Huggett, Jr., of SRS.

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FTM-West Model Results for Selected Fuel Treatment Scenarios

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***Abstract**—This paper evaluated potential forest product market impacts in the U.S. West of increases in the supply of wood from thinnings to reduce fire hazard. Evaluations are done using the Fuel Treatment Market–West model for a set of hypothetical fuel treatment scenarios, which include stand-density-index (SDI) and thin-from-below (TFB) treatment regimes at alternative levels of harvest administrative fees or subsidies. Results show that even with industry bearing the assumed administrative costs of thinning programs, substantial volumes of wood could be thinned, but more so in coastal regions than inland regions of the West. Also, replacing administrative fee assumptions with hypothetical removal subsidies increases the proportion of harvestable wood removed; a sensitivity observed primarily in the inland regions. Results show also that wood removals from fuel treatment programs could displace a large fraction of timber supply from conventional sources, reducing regional timber harvest and timber revenues that would otherwise be projected to increase for state and private timberland managers in the West. The SDI thinning regime can result in potential gains in forest product consumer surplus that more than offset losses in timber producer surplus, resulting in positive net market welfare, while the TFB regime can produce the opposite result (negative net market welfare).*

Introduction

The Fuel Treatment Market (FTM) model for the U.S. West, or FTM–West, is a dynamic partial equilibrium model of the markets for softwood timber and forest products produced in the western United States. The model projects the market for wood from fuel thinning treatments along with the market for timber from conventional sources in order to project the market impacts of fuel treatments (Ince and Spelter, this proceedings; Ince and others 2005). At the present time, only a small fraction of the fuel treatment acreage on federal lands in the U.S. West involves wood harvest (over 90% of the fuel treatment acreage involves prescribed burning or mechanical treatment without wood byproduct removal). This paper illustrates projected market impacts of hypothetical expanded fuel treatment programs involving thinning and wood removal on federal lands in the West.

Different scenarios can be run in the FTM-Westmodel with different hypothetical forest treatment programs or with no treatment program at all. The two hypothetical thinning regimes analyzed in this study were created using the Fuel Treatment Evaluator (FTE 3.0) model (Skog and others 2006) and the areas considered for treatment were NFS and other federal land (BLM, BIA, etc.). The thinning regimes were developed by a team of researchers whose objective was to identify places where the use of woody biomass from

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thinning can best help pay for hazardous fuel reduction treatments. The effort identified USDA Forest Service Forest Inventory and Analysis (FIA) plots on timberland in 12 western states—127 million acres—that passed screens excluding high severity fire regime forest types (where crown fires are normal), low fire hazard plots, plots in roadless areas, and plots in selected counties on Oregon and Washington where treatments would be done primarily for purposes other than fire hazard reduction. Twenty four million acres were identified as eligible for treatment, of which 14 million acres are on federal land. Eligible acres received simulated treatment by one of two silviculture treatment regimes to meet certain fire hazard reduction targets if the treatment would provide at least 300 ft^3/acre (~ 4 oven-dried tons/acre). The SDI treatment removed trees across all age classes to leave an uneven-aged stand. The TFB treatment removed trees beginning with the smallest to leave an uneven-aged stand. The paper by Skog and Barbour (this proceedings) explains the SDI treatment regime (a combination of treatments 2A and 4A) and the TFB treatment regime (a combination of treatments 3A and 4A).

Each regime was run with two different cost assumptions (making four total scenarios). In one scenario, administrative fees (stumpage fees) were levied on the wood available for treatment to pay for the estimated average cost per acre to the Forest Service to make the wood available ($500 per acre), whereas the other scenario eliminated the fee and instead offered a subsidy for the wood ($200 per MCF). The sensitivity of the volume of wood treated to the stumpage fee or subsidy was not intensely analyzed in this study, and therefore the cost assumptions are not assumed to maximize possible revenue to the Forest Service or the volume of wood treated under any constraints.

Scenario Inputs

Two different hypothetical forest treatment regimes were evaluated using the FTM-Westmodel, the inputs of which were obtained using the FTE model. In this paper they are referred to as SDI and TFB, respectively. The FTM-West required as input three different aspects of the scenarios: the volume distribution of available wood by d.b.h. class for each supply region (table 1), the volume of wood to be made available for treatment in each year for each supply region, and the weighted average cost of the wood from treatments, which includes harvest and transport costs and possibly an administrative cost or subsidy, also in each supply region. Most of the figures in this paper are aggregated for the whole U.S. West. As Skog and others (this proceedings) mention, the SDI scenarios consist of more (about twice as much) total wood

Table 1—Volume of wood by diameter at breast height class for two hypothetical thinning programs compared with 1997 estimates on conventionally harvested wood (Ward and others 2000; Larsen and others 2000). Rows might not add to 100% due to rounding.

	Wood by diameter at breast height class						
	<5	5 to 6.9	7 to 8.9	10 to 11.9	12 to 13.9	14 to 15.9	>15
	Inches						
TFB	9%	20%	15%	17%	12%	7%	20%
SDI	8%	10%	8%	10%	9%	6%	48%
Conventional (1997)	3%	8%	14%	18%	17%	14%	27%

and acres available than the TFB scenarios (figures 1 and 2). Also note that the FTE only gives the total amount of wood available for treatments in each region, so a logarithmic-growth function was used to smooth this amount over a 16-year period, 2005 to 2020. Each scenario was run once with an added $500 per acre administrative fee (equivalent to a stumpage fee) for wood available from forest treatments, which is estimated to cover the cost of making the wood available, and once with no fee and an unconstrained $200/MCF subsidy.

In all the effects discussed here (volume harvested, timber prices, producer and consumer surplus) except the change in net market welfare, the SDI scenarios had larger impacts compared with the TFB scenarios. Similarly, the scenarios where forest treatments were subsidized had larger effects when compared with the scenarios that required administrative fees.

Volume Harvested and Timber prices

In all four scenarios, more than half of the wood made available from forest treatments was utilized (table 2). Subsidizing the programs resulted in an additional 3.6 and 3 billion cubic feet representing 16% and 30% of the total FTE volume for the SDI and TFB programs, respectively. This additional wood treated was located exclusively in the interior region of the U.S. West because in every scenario 100% or nearly 100% of wood made available in the coastal region (Pacific Northwest and California coasts) was treated. For the

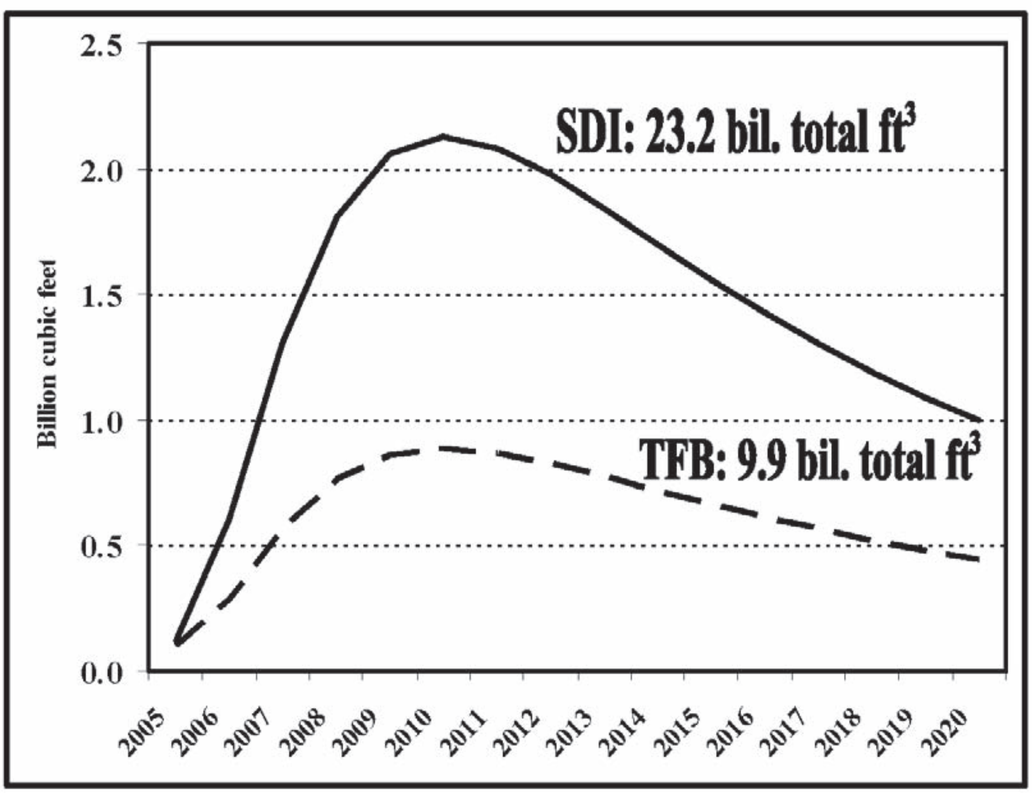

Figure 1—Maximum volume of wood made available annually. SDI, Stand Density Index; TFB, Thinning From Below.

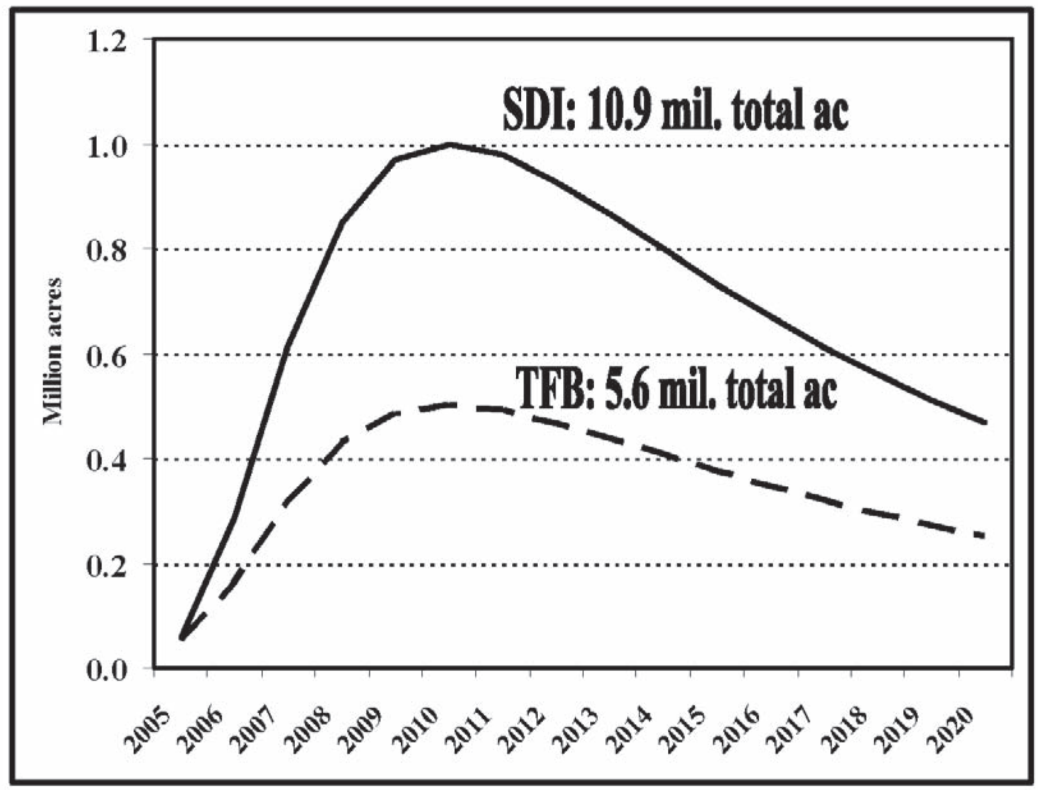

Figure 2—Acres made available annually assuming a constant average volume per acre.

Table 2—Billion cubic feet, million acres, and percentage of total wood available projected to be treated over the 16-year period, 2005 to 2020. SDI, Stand Density Index; TFB, Thinning From Below

Regime		$500/acre admin fee	$200/MCF subsidy
	Billion cubic feet	13.9	17.5
SDI	Million acres	4.7	7.3
	FTE volume (%)	60%	76%
	Billion cubic feet	5.3	8.2
TFB	Million acres	2.4	4.5
	FTE volume (%)	54%	84%

interior regions, this amounted to an increase from 5% to 42% of available wood treated and an average of 2.6 million acres for the SDI program, and 5% to 66% and an average of 2.1 million acres for the TFB program, as a result of dropping the administrative fee and adding the subsidy (figure 3).

In all four scenarios, the total harvest of wood increased when compared to a scenario with no wood available for treatment (figure 4). However, the additional utilization of wood from forest treatments displaced wood utilized from conventional sources (mostly state and private). This crowding out of conventional timber ranges from 5 to 12 billion ft^3 over the 16-year time period, depending on subsidy and thinning regime (figure 5). Over the time

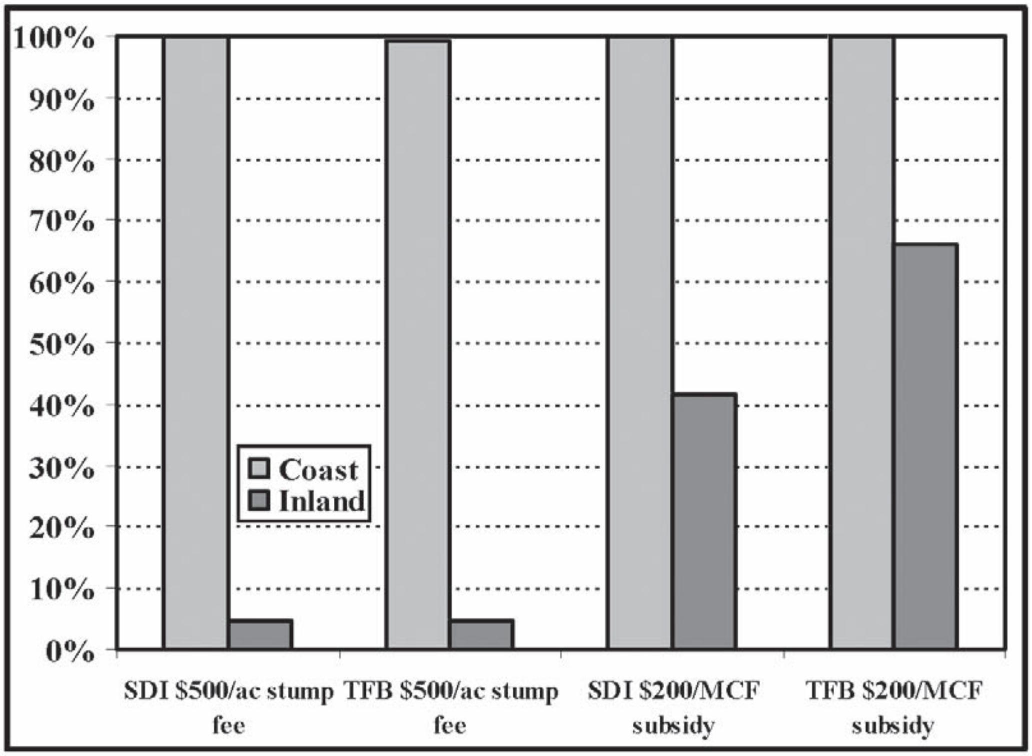

Figure 3—Percentage of available wood utilized. SDI, Stand Density Index; TFB, Thinning From Below.

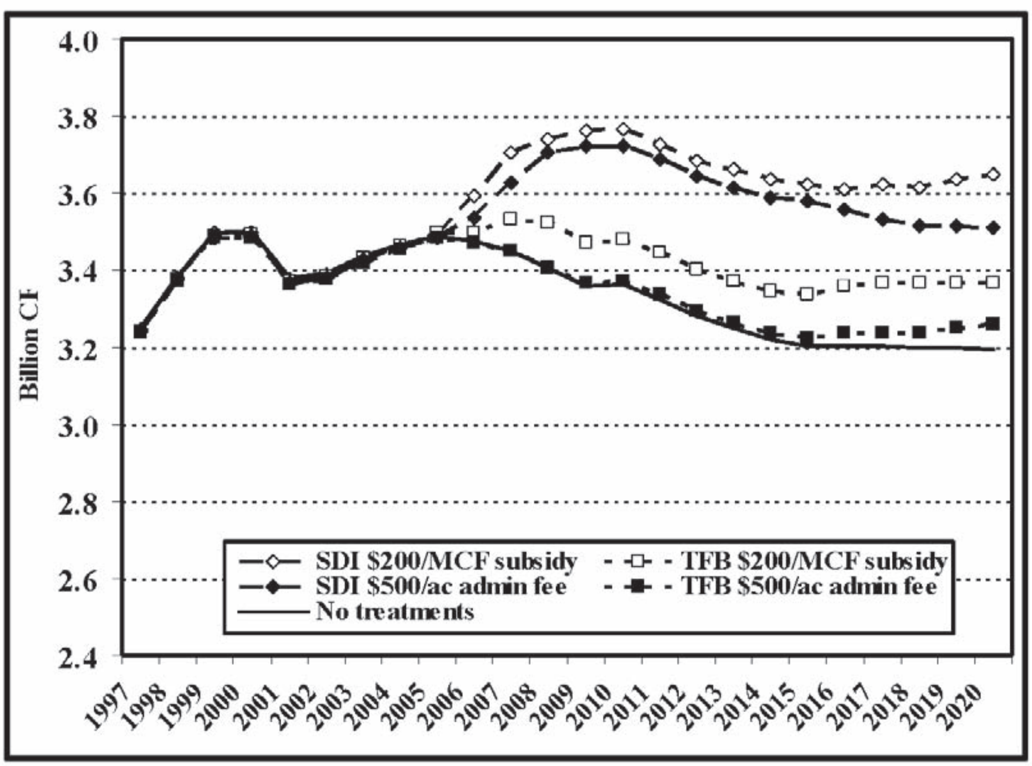

Figure 4—Total volume of wood harvested annually. SDI, Stand Density Index; MCF, per thousand cubic feet; ac, acre.

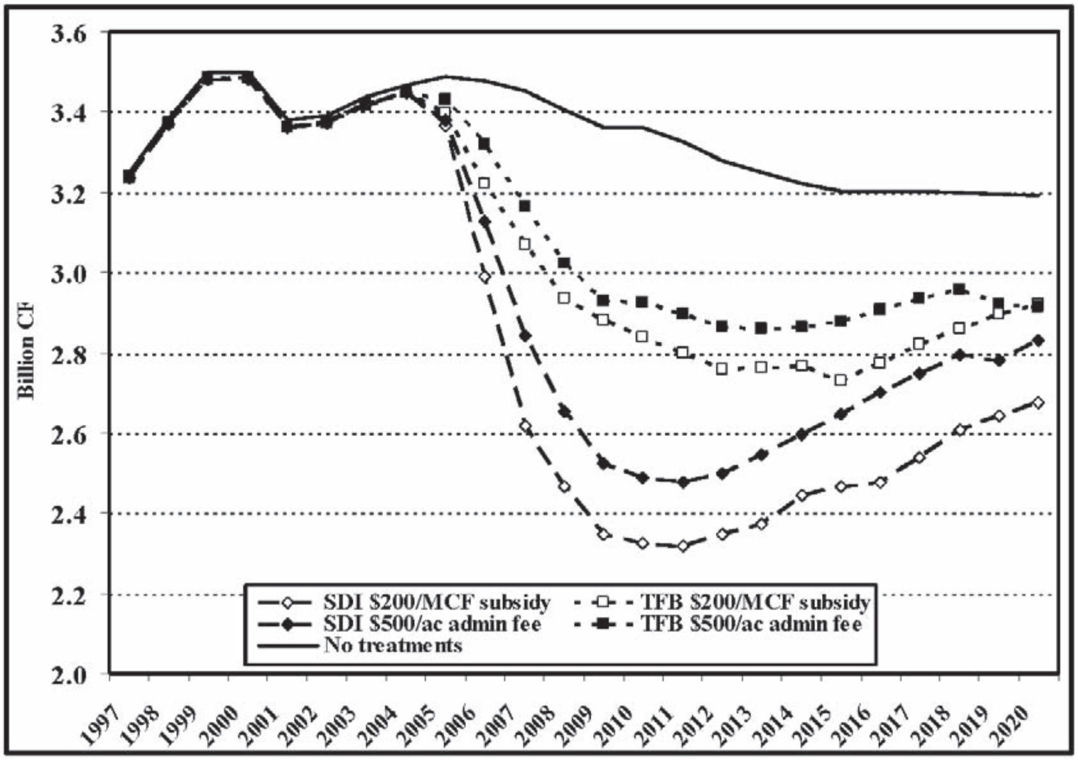

Figure 5—Volume of wood harvested from conventional sources. SDI, Stand Density Index; MCF, per thousand cubic feet; ac, acre.

period, the wood from treatments accounted for an average of 10% to 30% of the total volume of wood harvested, also depending on subsidy and thinning regime. Consequently, the boost in timber supply from thinning and reduction in harvest from conventional supply sources is projected to result in lower timber prices as well (figure 6).

Producer Surplus, Consumer Surplus and Net Welfare

All four scenarios project a decrease in potential revenue to conventional timber suppliers, a loss of producer surplus, which is a direct result of the decrease in regional timber prices and the volume of conventional timber harvested (as compared to a no-treatment scenario). The cumulative potential losses over the 16 year projection period (2005 to 2020) are quite significant, ranging from $34 billion to $70 billion (figure 7).

On the other hand, all four treatment scenarios projected lower wood product prices and increases in wood products consumption resulting in increases in forest product consumer surplus. Over the projection period the cumulative increases ranged from $26 billion to $74 billion (figure 8).

When we observe the changes in cumulative net welfare, defined as the change in producer surplus plus the change in consumer surplus, we see a deviation from the theme of the other results. Both TFB scenarios result in decreasing net welfare totaling as low as –$8.3 billion after 16 years with

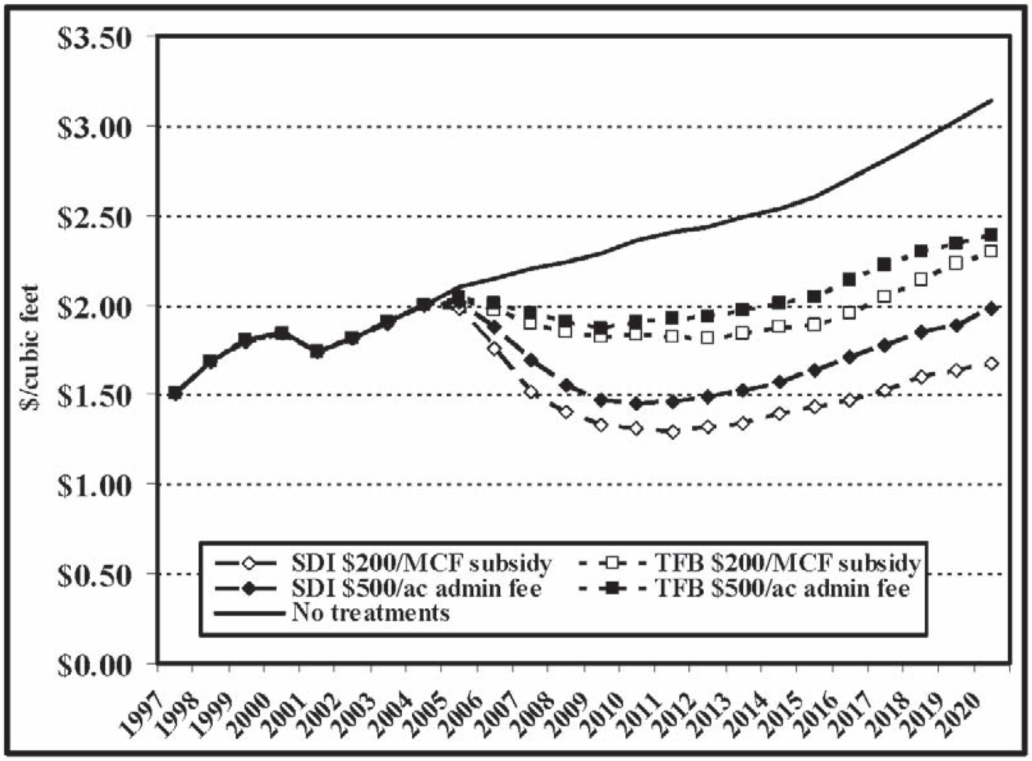

Figure 6—Weighted average softwood timber price in the U.S. West. SDI, Stand Density Index; MCF, per thousand cubic feet; ac, acre.

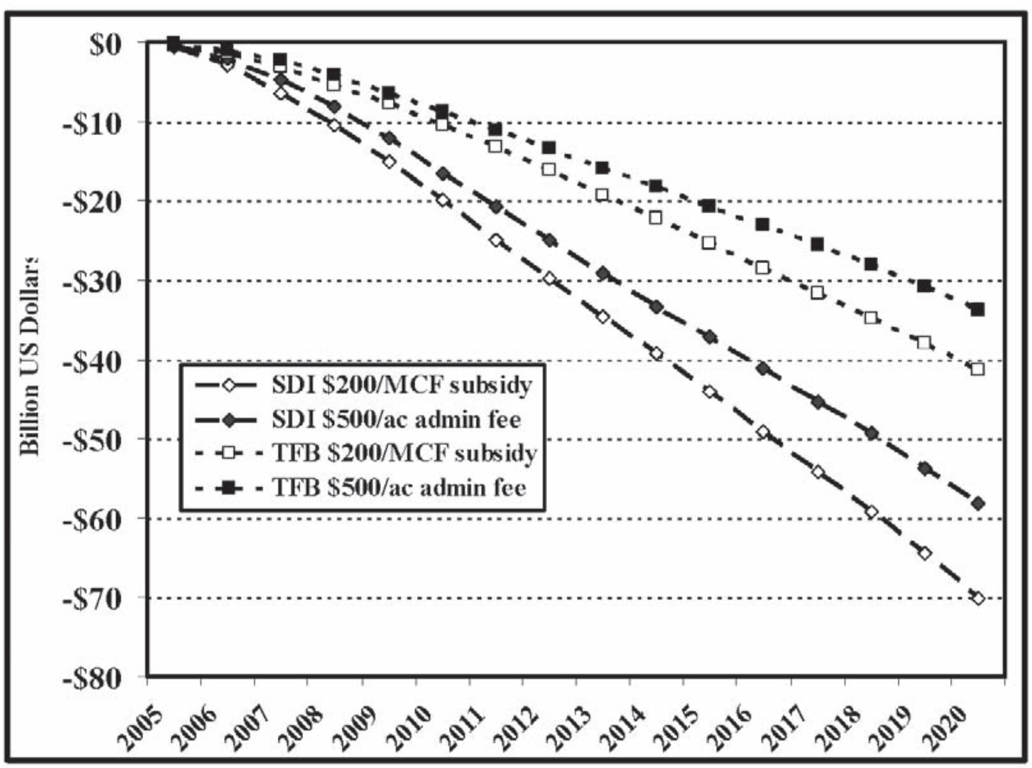

Figure 7—Cumulative change in producer surplus as compared to a no-treatment scenario. SDI, Stand Density Index; TFB, Thinning From Below.

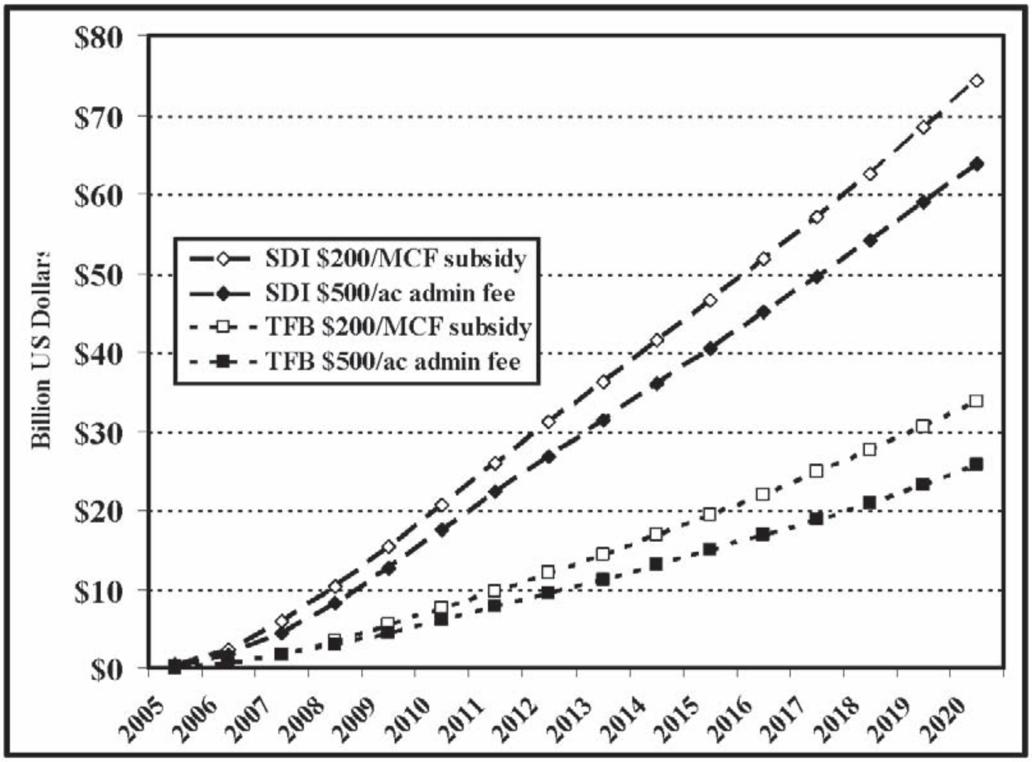

Figure 8—Cumulative change in consumer surplus as compared to a no-treatment scenario. SDI, Stand Density Index; MCF, per thousand cubic feet; TFB, Thinning From Below; ac, acre.

the subsidy making little difference. Conversely, the SDI scenarios show an increasing net welfare and, in fact, the unsubsidized program shows the largest increase in net welfare, $5.7 billion after 16 years (figure 9). This can be seen mainly as a result of the fact that the SDI treatment makes much more high value large timber available than the TFB. This large timber has lower harvest costs, higher product yields, higher output capacity, and lower manufacturing costs (all per volume), and only a model like the FTM-Westthat models these economic complexities of tree and log size class can observe such economic effects. Note that these figures for changes in net welfare do not include a quantification of the effects from reduced fire hazard; they represent only market welfare impacts. The social welfare benefits from reduction in fire hazard are difficult to assess. However, Lippke and others (2006), in their analysis, make a conservative estimate from $1,186/acre to $1,982/acre, increasing with initial fire risk.

Conclusions

We can draw several important conclusions from these results. First, markets would use a substantial volume of wood from fuel treatment programs, even if administrative fees are levied. Second, subsidies for wood from forest treatments seem unnecessary in the coastal region but are crucial to achieve forest treatment goals in the interior region. Third, expanded fuel treatments can have substantial positive impacts on forest product consumer surplus yet negative impacts on revenue to conventional timber sources. Finally, the SDI

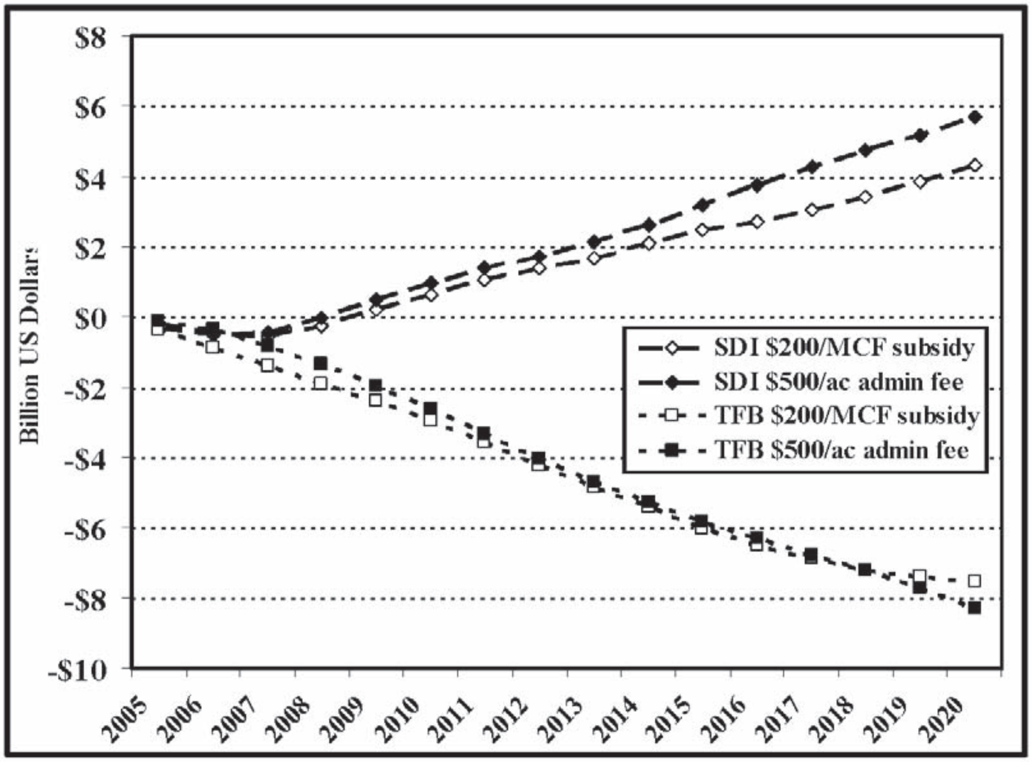

Figure 9—Cumulative change in net economic welfare as compared to a no-treatment scenario. SDI, Stand Density Index; MCF, per thousand cubic feet; TFB, Thinning From Below; ac, acre.

thinning regime can result in potential gains in forest product consumer surplus that more than offset losses in timber producer surplus, resulting in positive net market welfare, while the TFB regime can produce the opposite result (negative net market welfare).

In addition, since the SDI scenarios result in more acres treated and more wood per acre removed, logically they would also result in greater reductions in forest fuels and related fire hazard, producing consequently unambiguously higher net welfare than the TFB scenarios, taking into account both the market welfare and fuel reduction impacts. Other factors should also be considered in judging net welfare, including changes in suppression costs, environmental impacts, wildfire damages, and other less tangible costs and benefits of reduced fire hazard that are addressed, for example, by Lippke and others (2006). All these factors are important when considering policy toward use of thinning treatments that include biomass utilization. In this study, we have focused primarily on the market welfare and fuel reduction impacts.

Acknowledgments

This study was funded in part by the Joint Fire Science Program (JFSP), a partnership of six federal agencies: USDA Forest Service, Bureau of Indian Affairs, Bureau of Land Management, National Park Service, U.S. Fish and

Wildlife Service, and U.S. Geological Survey. Additional in-kind contributions were provided by researchers at the USDA Forest Products Laboratory (FPL) and Forest Service Pacific Northwest Research Station (PNW). Ken Skog of FPL assisted in developing treatment program scenarios for the FTM-Westusing the Fuel Treatment Evaluator (FTE, version 3.0). Henry Spelter of FPL helped estimate conventional stumpage prices, lumber production coefficients, and manufacturing costs. Dennis Dykstra of PNW provided estimates of log and chip volume yields for each tree size class in each of the eight supply regions of FTM–West, based on data from regional wood utilization studies. The study was part of a larger JFSP-funded project, identified as JFSP project 01-1-2-09, "A national study of the economic impacts of biomass removals to mitigate wildfire damages on federal, state, and private lands," coordinated by Jeffrey Prestemon and Karen Lee Abt (Forest Service Southern Research Station). The authors sincerely appreciate the consultation provided by the project coordinators, as well as consultation on the PELPS modeling system from Patti Lebow of the Forest Products Laboratory, additional data input from Matt Alderman of the Forest Products Laboratory, and consultation or input from other members of the JFSP project, including Roger Fight and Jamie Barbour of the Pacific Northwest Research Station and Bob Rummer and Robert Huggett, Jr., of the Southern Research Station.

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Estimating Woody Biomass Supply From Thinning Treatments to Reduce Fire Hazard in the U.S. West

Kenneth E. Skog[1] and R. James Barbour[2]

Abstract—*This paper identifies timberland areas in 12 western states where thinning treatments (1) are judged to be needed to reduce fire hazard and (2) may "pay for themselves" at a scale to make investment in forest product processing a realistic option. A web-based tool—Fuel Treatment Evaluator 3.0—is used to select high-fire-hazard timberland plots from the Forest Service Forest Inventory and Analysis Program (FIA) database and provide results of simulated thinning treatments. Areas were identified where either torching or crowning is likely during wildfires when wind speeds are below 25 mph. After additional screens are applied, 24 million acres are deemed eligible for treatment (14 million acres on federal lands). Uneven-aged and even-aged silvicultural treatments analyzed would treat 7.2 to 18.0 million of the 24 million acres, including 0.8 to 1.2 million acres of wildland–urban interface area, and provide 169 to 640 million ovendry tons of woody biomass. About 55 percent of biomass would be from main stem of trees ≥7 inches d.b.h. Sixty to seventy percent of the area to be treated is in California, Idaho, and Montana. Volumes and harvest costs from two treatments on the 14 million acres of eligible federal lands are used as inputs to the fuel treatment market model for U.S. West (FTM–West) discussed in these proceedings.*

Introduction

Fire hazard is unacceptably high on many acres of forest land in the U.S. West. For some of these acres, mechanical treatments are a way to reduce fire hazard. A cohesive strategy is needed for identifying the long-term options and related funding needed to reduce fuels (GAO 2005). Given limited government budgets, one approach is to identify places where the use of woody biomass from thinning can best help pay for hazardous fuel reduction treatments and to use this information to aid in allocating funds for all types of hazardous fuel reduction treatments.

We do not attempt to identify all acres in the U.S. West where removal of woody biomass would improve resilience to undesirable fire effects nor did we set out to demonstrate that if this were done enormous volumes of wood materials could be collected. We focus on areas in surface and mixed-severity fire regime forests, where treatments are needed to reduce fire hazard.

For 12 western states (table 1), we selected timberland acres (land capable of producing 20 ft^3/acre/year and not withdrawn from timber utilization) eligible for treatment (determined in part by fire hazard level), applied several alternative silvicultural treatments to reduce hazard while seeking to maintain ecosystem integrity, and evaluated to what extent revenues from the sale of biomass may offset harvest costs. Full results of our study were reported by

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Table 1—Area treated, by state and treatment scenario (million acres).

	Treatments for forest types other than spruce–fir and lodgepole						Treatments for spruce-fir and lodgepole, even-aged in WUI area only	
	Uneven-aged treatments				Even-aged treatments			
	High structural diversity		Limited structural diversity					
State	50% BA removal limit 1A	No BA removal limit 1B	50% BA removal limit 2A	No BA removal limit 2B	50% BA removal limit 3A	No BA removal limit 3B	25% BA removal limit 4A	50% BA removal limit 4B
AZ	0.5	0.5	0.4	0.4	0.1	0.1	0.0	0.0
CA	4.4	4.4	3.8	3.8	1.5	1.5	0.0	0.0
CO	1.2	1.3	1.1	1.1	0.4	0.5	0.1	0.1
ID	2.4	2.5	2.2	2.2	1.1	1.1	0.4	0.4
MT	2.9	3.0	2.5	2.6	1.5	1.6	0.0	0.0
NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NM	0.9	1.0	0.8	0.8	0.3	0.3	0.0	0.0
OR	2.2	2.2	1.8	1.8	0.9	0.9	0.0	0.0
SD	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
UT	0.4	0.4	0.4	0.4	0.2	0.2	0.0	0.0
WA	1.8	1.8	1.5	1.5	0.6	0.6	0.0	0.0
WY	0.3	0.4	0.3	0.3	0.2	0.2	0.0	0.0
Total	17.1	17.5	14.8	15.1	6.7	6.8	0.5	0.5

Skog and others (2006). Results are compared to those from a previous Forest Service assessment (Forest Service 2003).

This evaluation of potential acres to be treated and biomass to be removed is intended to be the first of several evaluation steps:

1. Identify locations across the West where hazardous fuel reduction treatments are needed and that would generate amounts of woody biomass for use that could offset treatment costs.
2. For selected localities in the West, evaluate both current market potential for using wood and prospects for expanding specific markets to use additional wood material.
3. Evaluate the social acceptability of establishing and supporting the infrastructure necessary to use sales of wood as a means for funding fire hazard reduction within the selected areas.

This paper also notes special estimates of biomass supply and treatment costs for two treatments on the 14 million acres of federal lands that are used as inputs to the fuel treatment market model for U.S. West (FTM–West) discussed by Ince and Spelter and by Kramp and Ince in these proceedings. The FTM–West model is used to evaluate the potential impact of increased biomass supply on projected conventional timber supply quantity and timber prices.

The 12 western states have 127 million acres of public and private timberland and 77 million acres of other forest land (Miles 2006a). Although other forest lands have hazardous fuels and wood from treatments that can provide higher value products, the volume and value per acre is very likely to be lower in relation to treatment costs than it is for timberland. Treatments of other forest land may provide an average 7 ovendry tons (odt) of woody biomass per acre (Perlack and others 2005) in the 12 states considered in our study compared with 24 to 34 odt/acre estimated for timberland thinning treatments.

The terms "woody biomass" and "biomass" refer to all wood in all trees—in the main stem, tops, and branches of all sizes of trees. "Merchantable wood" refers to the main stem of all live trees with a diameter at breast height (d.b.h.) ≥5 in., from 1 ft above ground to a minimum 4-inch top diameter outside the bark of the central stem, or to the point where the central stem breaks into limbs and does not include rotten, missing, and from cull.

Methods

Data used were plot-level data from the Forest Inventory and Analysis Program (FIA) of the USDA Forest Service (Smith and others 2004), with additional plot information from the National Forest System (about 37,000 plots in 12 states). The area to be treated and woody biomass to be removed were estimated as if the treatments were to be done within 1 year. In reality, the area treated and amounts removed would extend over many years. Methods were used to simulate treatments on all ownerships, and those results are explained in detail. Methods were also used to simulate treatments on federal land alone, and those results were used to provide biomass amounts and harvest costs to be used in the FTM–West market model.

Screens to Identify Area Eligible for Treatment

Of the 126.7 million acres of timberland in the 12 selected western states (Miles 2006a), 23.9 million acres passed an initial screen and were considered eligible for treatment. A second screen was applied when considering a specific silvicultural treatment, and less than 23.9 million acres actually receive simulated treatment.

Initial Screen—The initial screen was applied to two different groups of forest types: group 1, forest types with surface or mixed-severity fire regimes; and group 2, forest types with high-severity fire regimes. Group 2 includes lodgepole pine and spruce–fir forest types. Group 1 contains all other forest types.

Plots excluded from fire severity group 1 include (a) inventoried roadless areas, (b) counties west of Cascade Mountains in Oregon and Washington, where forests have a long fire return interval, (c) plots with lower fire hazard (both crowning index (CI) and torching index (TI) >25 mph, or CI alone >40 mph). For a map of inventoried roadless areas, see www.roadless.fs.fed.us/maps/usmap2.shtml

Plots excluded from group 2 include (a) all plots outside wildland–urban interface (WUI) areas, (b) inventoried roadless areas, (c) counties west of Cascade Mountains in Oregon and Washington, where forests have a long fire return interval, and (d) plots with lower fire hazard (CI and TI both >25 mph, or CI alone >40 mph).

Selected counties west of the Cascades were excluded because treatments in forests there would be designed to meet objectives other than fire hazard reduction.

Oregon counties excluded were Benton, Clackamas, Clatsop, Columbia, Coos, Curry, Lane, Lincoln, Linn, Marion, Multnomah, Polk, Tillamook, Washington, and Yamhill. Washington counties excluded were Clallam, Clark, Cowlitz, Gray's Harbor, Island, Jefferson, King, Kitsap, Lewis, Mason, Pacific, Peirce, San Juan, Skagit, Snohmish, Thurston, Wahkiakum, and Whatcom.

Of the 126.7 million acres of timberland, 67.5 million acres (53 percent) have lower fire hazard than our criteria. Of the remaining 59.2 million acres, 21.6 million acres (17 percent of all timberland) are in roadless areas or in excluded counties in Oregon and Washington. Of the remaining 37.6 million acres, 13.8 million acres (11 percent of all timberland) are in forest types with high-severity fire regimes, which leaves 23.9 million acres eligible for treatment. In total, our screens removed 81 percent of all timberland and 60 percent of acres with higher fire hazard.

Second Screen—When applying a specific silvicultural treatment, a second screen determined which eligible plots actually receive simulated treatment. Plots were not treated if they would not provide 300 ft^3 of merchantable wood per acre (about 4 odt/acre). Previous studies found that mechanical treatments that produce <300 ft^3 of merchantable wood are unlikely to cover costs of the treatment (Barbour and others 2004, Fight and others 2004).

Fire Hazard Reduction Objectives and Assumptions

Selection of Plots for Treatment—Each FIA plot was assessed for fire hazard by estimating CI and TI (Scott and Reinhardt 2001). Torching index is the 20-ft aboveground wind speed at which crown fire can begin in a specified fire environment; CI is the 20-ft wind speed at which active crown fire behavior is possible (can be sustained) in that environment. Plots were selected for treatment if CI < 25 mph alone or TI < 25 mph and CI < 40 mph (denoted hereafter as CI<25 and TI<25). The focus on crown fires is useful because, although all stands may burn under certain conditions, stands that are likely to burn in crown fires present particular suppression problems, and consequences of crown fires are more severe than those of surface fires. Plots with CI<25 or TI<25 were chosen for treatment because fires might commonly be expected to occur at wind speeds between 15 and 25 mph.

Assumptions for Calculating Torching and Crowning Indexes—Torching and crowning indexes were calculated for each plot based on (a) canopy fuel profile as computed from plot data, (b) slope steepness, (c) selected set of fuel moisture conditions corresponding to "summer drought" conditions (Rothermel 1991), and (d) use of fire behavior fuel model (FM) 9 to represent surface fuels (Anderson 1982).

Fuel model 9 is described as hardwood or long-needle pine litter. It was chosen not because we assume that all surface fuels are hardwood or long-needle pine litter, but because FM 9 results in surface fire behavior mid-range between FM 8 and 10 (other timber litter models) and FM 2 (timber grass model) (personal communication, Paul Langowski, Branch Chief, Fuels and Fire Ecology, USDA Forest Service, Rocky Mountain Region, 2004).

No single fuel model can be expected to adequately represent surface fuels in all timberlands. However, no plot data exist to characterize surface fuels. Assuming more extreme fire behavior, such as FM 10, might lead to recommending thinning where none is really needed, whereas a FM 8, which results in very low-intensity surface fires, may not identify stands at risk of crowning. Fuel model 9 was a compromise.

We also used FM 9 when computing TI and CI after thinning; that is, we assumed that the thinning treatment did not change the surface fuels enough to bump the fuel model into a higher fuel class.

Targets for Crowning and Torching Indexes after Treatment—The fuel hazard reduction objective for each plot was to increase TI and CI to >25 mph or to increase only CI to >40 mph. These objectives are intended either to keep a crown fire from starting or to prevent a crown fire from spreading if crowns are ignited.

Limits on Removal of Basal Area—In some treatment cases, we limited total basal area (BA) removal to keep canopy closure as high as practical. Opening the canopy, while reducing canopy fuels, can lead to different fuel hazard problems: (1) expose surface fuels to solar radiation and wind, which can alter surface fire behavior; (2) increase herbaceous and shrub growth, which may also change surface fire behavior; (3) enhance conifer regeneration, ultimately creating ladder fuels; and (4) increase the risk that remaining trees will be blown down by strong winds.

To the extent that additional objectives call for refinement of our treatments and more removals in local areas, we may be underestimating the amount of area that may be treated with positive average net revenue.

Long-Term Effect of Treatments on Fire Hazard—Forest stands are dynamic, as are forest fuels. The necessary frequency of treatments should be analyzed as part of a much more site-specific planning process, using tools such as FFE–FVS (Reinhardt and Crookston 2003) or fire history studies.

We acknowledge that the fuel hazard reduction treatments described here do not address constraints on land management activities specified in existing land and resource management plans and their potential effects on removals. Nor do these scenarios address the effect on importance of maintaining forest stocking, ground fuels, and other factors that may negatively contribute to CI and TI values on the ecologic health and productivity of forests.

Silvicultural Treatment Objectives and Assumptions—The thinning treatments to reduce fire hazard have an objective to move the stand toward either (1) an uneven-aged condition or (2) an even-aged condition. In addition, the objective of some treatments is to limit BA removed to limit change in stand structure.

Some authors (Graham and others 1999) have suggested that thinning uneven-aged stands in some cases does not reduce fire hazard. We address this concern by designing uneven-aged treatments that take enough trees to be effective in reducing TI, CI, and the risk of crown fire.

Timberland area was divided into forest types that tend to have (1) high-severity fire regimes (where severe fires are routine under natural conditions) and (2) surface or mixed-severity fire regimes. High-severity forest types are excluded from treatments except in WUI areas because severe fires (crown fires) are routine in these forest types under natural conditions, and thinning to avoid severe fire does not support normal fire ecology.

Treatments for Forests with Surface and Mixed-Severity Fire Regimes— Treatments 1A and 1B—uneven-aged, leaving high structural diversity—remove trees so the number of trees remaining in each d.b.h. class after treatment contribute equally toward the numerical value of residual stand density index (SDI) for the stand (Long and Daniel 1990). The final level of overall SDI is adjusted downward by simulated removal of trees across all d.b.h. classes until TI≥25 and CI≥25, or CI≥40. In scenario 1A, removals are limited to 50 percent of initial BA; in 1B, there is no limitation. This scenario results in forest structures that retain high structural diversity with intact understories of small trees.

Restricting removals to <50 percent of the original BA ensures that some semblance of an uneven-aged forest structure is maintained (Alexander and Edminster 1977, Burns 1983).

Treatments 2A and 2B—uneven-aged, limited structural diversity—attempt to achieve TI and CI goals by removing as many small trees as possible while still retaining smaller trees to ensure an uneven-aged structure. The remaining trees in a large d.b.h. class contribute more to the residual stand SDI than do trees in a smaller d.b.h. class.

The level of overall SDI is adjusted downward by simulated removal of trees until the target TI and CI values are reached (treatment 2B) or until 50 percent of the original BA has been removed (treatment 2A).

Treatments 3A and 3B—even-aged, thin from below—emulate intermediate thinning in an even-aged silviculture system where the intent is to ultimately harvest and replace the existing forest. Small trees are completely removed in successively larger d.b.h. classes until CI and TI goals are met (treatment 3B) or until 50 percent of the original BA has been removed (treatment 3A). Thinning more than 50-percent BA may fundamentally alter the character of the forest and should not be prescribed without careful consideration of all potential ecosystem effects.

Treatments for Forests with High Severity Fire Regimes—Treatments 4A and 4B—even-aged, thin from below (spruce–fir and lodgepole pine forest types)—are similar to treatments 3A and 3B, except BA removals are restricted to 25 percent of existing stocking (treatment 4A) or 50 percent of existing stocking (treatment 4B) and *are only in WUI areas.* The 25-percent removal restriction is based on published partial cutting guidelines and is necessary to avoid wind throw in shallow-rooted tree species such as spruce, fir, and lodgepole pine (Alexander 1986a,b).

Harvest Costs and Product Revenue Estimation

The cost to provide biomass ready for transport at the roadside was estimated for each plot using the Fuel Reduction Cost Simulator (FRCS) from My Fuel Treatment Planner (Biesecker and Fight 2006, Fight and others 2006). Cost estimates are made for up to eight harvesting systems, based on the number and average volume of trees in various size categories and the slope of the site. Ground-based harvesting systems include (a) manual-felling log-length system, (b) manual-felling whole-tree (WT) system, (c) mechanized-felling WT system, and (d) cut-to-length (CTL) system. Cable-yarding systems include (a) manual-felling log-length system, (b) manual-felling WT system, (c) manual WT/log-length system, and (d) CTL system.

The cost for the least expensive suitable system was assigned to each plot. We assumed that (1) harvest is only a partial cut, (2) tops and branches are collected for use when the low-cost system brings whole trees to the landing, (3) trees down to 1 inch d.b.h. are removed, (4) average distance that logs are moved from stump to landing is 1,000 ft, (5) average area treated is 100 acres, and (6) distance to move equipment between harvest sites is 30 miles. Costs might be reduced if small d.b.h. trees are not removed from the site and treated by another method (e.g., pile and burn).

We assume the product values and hauling costs used in the 2003 Assessment. Actual prices will vary by location and over time.

Delivered sawlogs (volume from main stem ≥7inches d.b.h.)	$290/10^3$ board feet
Delivered chips (volume from wood and bark <7 inches d.b.h., tops and branches of larger trees)	$30/odt
Haul distance	100 miles
Haul cost (for both sawlogs and chips)	$0.35/odt/mile

The Fuel Treatment Evaluator 3.0 (FTE), a web-based tool available for general use, was used to select areas for treatment, apply treatments to FIA plot data, and generate removal information and maps (Miles 2006b).

Findings

Area Treated and Biomass Removed

The 2003 Assessment identified 96.9 million acres of timberland for possible thinning in fire regime condition classes (FRCCs) 1, 2, and 3, with 28.5 million acres in FRCC 3. The 2003 Assessment selected plots for treatment if timber density, as measured by SDI, was greater than 30 percent of the maximum SDI for the plot forest type.

FRCC refers to the degree to which the current fire regime (including fire recurrence, intensity, severity) is different from the historical pattern, with FRCC 3 having the most divergence (see definitions at http://ncrs2.fs.fed.us/4801/fiadb/fire_tabler_us/rpa_fuel_reduction_treatment_opp.htm).

In contrast, our treatments 3A (all group 1 forest types) and 4A (group 2 forest types in WUI areas) together would treat 7.2 million acres, and treatments 1B and 4B together would treat 18.0 million acres, with 85 percent of acres in FRCCs 2 and 3.

Of the 21.2 million WUI acres identified in 12 western states (Stewart and others 2003), an estimated 4.1 million acres are in timberland. For the high-severity types, 0.5 million acres of WUI were included in treatments 4A or 4B (table 1). For all other forest types, 0.3 to 0.7 million acres of WUI were included in treatments 1A to 3B. So the total WUI area to be treated could be 0.8 to 1.2 million acres, or 20 to 30 percent of the timberland WUI acres. We could be underestimating area to the extent that communities decide to treat larger WUI areas.

Treatment 1B would thin the largest area—17.5 million acres, or about 14 percent of all timberland in the 12 western states. The highest percentage of timberland to be treated would be in California (33 percent), followed by New Mexico (24 percent), Idaho (21 percent), Montana (21 percent), and Arizona (16 percent).

The 2003 Assessment identified total possible removal of 2.1 billion (10^9) odt biomass with treatment of all 94.5 million acres of treatable timberland. Removal from 66.3 million FRCC 2 and FRCC 3 acres could provide 1.5 billion odt of biomass. If only 60 percent of FRCC 3 acres are treated (17.1 million acres), the yield would be 346 million odt of biomass.

In our assessment, we identified 7.2 to 18.0 million acres for treatment that would yield 169 million odt (smallest amount) from treatments 3A and 4A and 640 million odt (largest amount) from treatments 1B and 4B (tables 1 and 2).

The distribution of biomass removed by tree size differs greatly between the uneven-aged and even-aged treatments (table 3). In addition, the distribution for the uneven-aged treatments differs substantially from the results of the uneven-aged treatment used in the 2003 Assessment. The 2003 Assessment showed the most biomass removed from the 10-inch d.b.h. class. In contrast, our uneven-aged treatments provide most biomass in the ≥21-inch d.b.h. classes. Our uneven-aged treatments remove more because residual SDI for our treated stands is <20 percent of maximum SDI, compared with 30 percent of maximum in the 2003 Assessment. Thinning to an average 20 percent of maximum SDI is needed in our assessment to thin to achieve CI>40 when we cannot attain TI>25. We could help attain TI>25 rather than having to reach CI>40 by pruning branches to raise canopy base height and by decreasing surface fuels.

In our assessment, the proportion of all acres treated and biomass removed that comes from National Forest or all Federal land is about 55 or 60 percent, respectively, for both even-aged and uneven-aged treatments.

Fire Hazard Reduction Outcomes

Four possible fire hazard reduction outcomes were identified for the 23.9 million acres eligible for treatment:

1. Treatment is applied; both CI>25 and TI>25.
2. Treatment is applied; CI>40.
3. Treatment is applied; 50-percent BA removal limit is achieved before achieving either (1) or (2).
4. No treatment is applied; <300 ft^3 of merchantable wood could be removed.

Uneven-aged treatments with the 50-percent BA removal limit (1A and 2A) treat 71 and 61 percent of eligible acres, respectively. These treatments reach the medium or high hazard reduction goal for 44 and 30 percent of eligible

Table 2—Initial standing biomass and biomass removals from this assessment (million ovendry tons).

		Treatments for forest types other than spruce–fir and lodgepole						Treatments for spruce-fir and lodgepole, even-aged in WUI area only	
		Uneven-aged treatments				Even-aged treatments			
		High structural diversity		Limited structural diversity					
State	Initial volume on treatable timberland	50% BA removal limit 1A	No BA removal limit 1B	50% BA removal limit 2A	No BA removal limit 2B	50% BA removal limit 3A	No BA removal limit 3B	25% BA removal limit 4A	50% BA removal limit 4B
	million acres								
AZ	29.5	11.0	13.1	8.9	9.9	2.3	2.6	0.1	0.1
CA	419.2	219.5	222.4	144.8	145.2	37.4	40.1	0.2	0.3
CO	49.3	20.6	28.4	17.4	21.8	6.0	7.5	0.8	1.4
ID	171.4	68.1	83.1	57.7	63.4	26.6	29.4	6.4	10.5
MT	166.7	66.8	84.4	58.9	69.2	36.5	41.9	0.1	0.2
NV	0.9	0.3	0.3	0.2	0.2	0.1	0.1	0.0	0.0
NM	41.9	18.3	24.1	15.0	18.4	5.5	6.3	0.0	0.0
OR	210.4	76.8	88.7	53.9	56.2	25.5	26.3	0.0	0.0
SD	3.9	1.3	1.4	1.1	1.1	0.3	0.3	0.0	0.0
UT	18.2	7.5	9.8	6.9	8.0	2.9	3.2	0.0	0.1
WA	128.7	50.0	60.9	38.8	42.4	14.9	15.4	0.0	0.0
WY	17.7	7.5	10.3	7.3	8.9	3.6	4.5	0.1	0.2
Total	1,257.7	547.8	626.8	410.8	444.7	161.6	177.5	7.6	12.8

Table 3—Biomass removal by treatment and tree d.b.h. class (tons per acre).

	Treatments for forest types other than spruce–fir and lodgepole						Treatments for spruce-fir and lodgepole, even-aged in WUI area only	
	Uneven-aged treatments							
	High structural diversity		Limited structural diversity		Even-aged treatments			
d.b.h. class	50% BA removal limit 1A	No BA removal limit 1B	50% BA removal limit 2A	No BA removal limit 2B	50% BA removal limit 3A	No BA removal limit 3B	25% BA removal limit 4A	50% BA removal limit 4B
(in.)								
2.0	0.4	0.5	0.5	0.6	0.8	0.9	0.4	0.5
4.0	1.2	1.5	1.5	1.7	2.2	2.4	1.5	2.2
6.0	2.1	2.4	2.8	3.0	4.9	5.1	4.9	5.4
8.0	2.9	3.3	3.6	3.8	6.2	6.5	4.8	6.6
10.0	3.1	3.6	3.6		2.5	2.8	0.7	2.1
14.0	2.5	2.8	2.2	2.4	1.2	1.4	0.4	0.9
16.0	1.9	2.2	1.5	1.6	0.6	0.8	0.4	0.8
18.0	1.4	1.7	0.9	1.0	0.4	0.5	0.0	0.2
20.0	1.0	1.2	0.4	0.5	0.3	0.3	0.0	0.0
22+	12.5	13.2	7.6	7.7	0.7	0.6	0.0	0.0
Total	32.0	35.8	27.7	29.5	24.2	26.0	16.6	24.5

acres, respectively (table 4). When the BA limit is removed (1B and 2B), a slightly greater percentage of acres is treated (72 and 62 percent, respecively), all reach a hazard reduction target, and biomass removal increases 14 percent (548 to 627 million odt) and 8 percent, respectively.

The even-aged treatment with the 50-percent BA removal limit (3A) treats 28 percent of all eligible acres but reaches the medium or high hazard reduction goal for only 7 percent of the eligible acres (table 4). When the 50-percent limit is removed (3B), 28 percent of acres are treated and all these treated acres reach the medium or high hazard reduction goal. Moving from treatment 3A to 3B requires a 10-percent increase in biomass removals, which includes the biomass from the additional 1 percent of acres treated.

In general terms, for forest area where there is the need to obtain a minimum level of merchantable wood to yield positive average net revenue and a restriction on BA removal, our results suggest that the uneven-aged treatment would more likely achieve one of the hazard reduction targets than would an even-aged treatment—in our example, 44 percent or 30 percent, compared with 7 percent.

If raising TI is a priority, then even-aged treatments are more effective than uneven-aged treatments. However, even-aged treatments are less likely to produce 300 ft^3 of merchantable wood and provide positive net revenue from sale of products.

Treatment Costs, Product Revenues, Net Revenues

Average treatment costs per acre for even-aged treatments are about the same as for uneven-aged treatments for the acres selected for each treatment, though fewer acres are selected for even-aged treatments because fewer acres are able to provide 300 ft^3/acre.

Table 4—Fire Hazard outcomes (percentage of treatable acres).

	Goal attainment						
Treatment	Low (50% BA limit is reached) (treatment is made but BA limit is reached)	Medium CI>40 only	High CCI&TI >25	Total achieving a medium or high target	Total receiving some treatment	Not treated (provides less than 300 ft^3 merchantable wood/acre)	Total
1A	28	21	22	44	71	29	100
2A	31	18	12	30	61	39	100
3A	21	4	3	7	28	72	100
1B	0	23	49	72	72	28	100
2B	0	14	48	62	62	38	100
3B	0	6	22	28	28	72	100

Average net revenues per acre are positive without subsidy for all treatments on gentle slopes and for uneven-aged treatments 1A, 1B, and 2B on steep slopes (table 5). With a $20/green ton subsidy for chips, average net revenues per acre are also positive for uneven-aged treatments 2A and for even-aged treatment 3B on steep slopes. Even with a subsidy, even-aged treatment 3A on steep slopes incurs a net cost per acre. With the subsidy, we could relax the 300-ft^3 merchantable wood requirement for all treatments on gentle slopes and still attain positive average net revenue.

Treatment Costs—The estimated cost to harvest and move biomass to the roadside is less than $1,000/acre for about 50 percent of acres treated for all treatments except treatment 4A, for which estimated costs are lower. Acres on gentle slopes (≤40 percent) tend to cost less, and acres on steep slopes (>40 percent) cost more.

Even though the even-aged treatments call for more trees to be harvested per acre on average, harvesting cost per acre is lower than or about the same as for uneven-aged treatments, which harvest fewer trees. This may be explained in part by the fact that we selected the lowest cost harvesting system for each plot analyzed. Costs for even-aged treatments would also be kept low by the requirement to provide a certain volume in larger trees to provide 300 ft^3/acre.

Biomass Revenues—The estimated delivered value of biomass per acre varies from $1,600 to $,2600, excluding treatments 4A and 4B, if the main stem volume of trees ≥7 in. d.b.h. goes to higher value products and the remainder is delivered as fuel chips. If all volume goes for chips, the delivered value varies from $430 to $640/acre.

For uneven-aged treatments 1A and 1B, about 67 percent of biomass is merchantable wood from trees ≥7 in. d.b.h. For even-aged treatments 3A and 3B, about 50 percent of biomass is merchantable wood from trees ≥7 in. d.b.h. Also, biomass removed per acre is greater for treatments 1A and 1B than for treatments 3A and 3B. As a result, if merchantable wood goes to higher value products, the revenue from the uneven-aged treatments 1A and 1B is $800 to $1,200/acre more than for even-aged treatments 3A and 3B. If all wood goes for chips, treatments 1A and 1B provide only $50 to $100 more per acre than do treatments 3A and 3B.

Table 5—Estimated treatment costs, and revenuesa minus fuel treatment costs when larger diameter logs are sold for higher value products or for chips.

	Average treatment cost ($/acre)		Net revenue (cost) with merchantable wood used for higher value products ($/acre)		Net revenue (cost) with merchantable wood used for chips ($/acre)		Net revenue (cost) with merchantable wood used for higher value products and chips given a subsidy of $20 per green ton ($/acre)	
Treatment	Slope ≤40%	Slope >40%	Slope ≤40%	Slope >40%	Slope ≤40%	Slope >40%	Slope ≤40%	Slope >40%
1A	903	1,774	619	(256)	(1,064)	(1,933)	1,039	163
2A	844	1,831	343	(453)	(978)	(1,867)	757	(32)
3A	854	1,966	(112)	(833)	(973)	(1,882)	391	(368)
4A	692	1,811	(144)	(726)	(766)	(1,550)	202	(478)
1B	986	1,839	686	(9)	(1,161)	(1,917)	1,159	479
2B	882	1864	356	(120)	(1,023)	(1,909)	798	114
3B	902	1975	(86)	(762)	(1,024)	(1,892)	441	(255)
4B	952	1,822	(18)	(266)	(1,073)	(1,615)	421	36

[a] Product value assumptions: delivered sawlog value, $290/mbf; delivered chip value, $30/od ton; transport cost, $0.35/od ton; haul distance, 100 miles.

Net Revenue (Costs) from Treatments—Average net revenue from uneven-aged treatments is positive for gentle slopes ($340 to $690/acre) and negative for steep slopes (–$9 to –$450/acre). Average net revenue for even-aged treatments is $400 to $700 less than that for uneven-aged treatments in the same slope category (table 5). Net revenues for treatments on steep slopes are least negative for uneven-aged treatments 1B and 2B (–$9 and –$120/acre, respectively).

In comparison to the uneven-aged treatment analyzed in the 2003 Assessment, our uneven-aged treatments (1A, 1B, 2A, 2B) provide about the same net revenue per acre for sites with gentle slopes ($350 to $700/acre). For steep slopes, however, our net revenue per acre is about $700 less and negative, whereas the estimates from the 2003 Assessment are positive. This difference could be due to the difference in plots selected.

If a subsidy of $20/green ton is provided for chips delivered to a mill, then the net revenue is positive for all treatments on gentle slopes and uneven-aged treatments 1A, 1B, and 2B (table 5). For these treatments and revenues, we could relax the requirement for 300 ft^3/acre and treat more acres.

Biomass Removal Maps—Areas where biomass removal from thinning on timberland is most likely to provide net revenues per acre include northern California, northern and central Idaho, western Montana, central and northern Oregon, and Washington. Smaller acreages include central to southern Colorado, central/east Arizona, and northern New Mexico. The timberland in WUI areas receiving simulated treatment is found primarily in northern California, northern Idaho, western Montana, western Washington, and central Colorado (figs. 1 and 2).

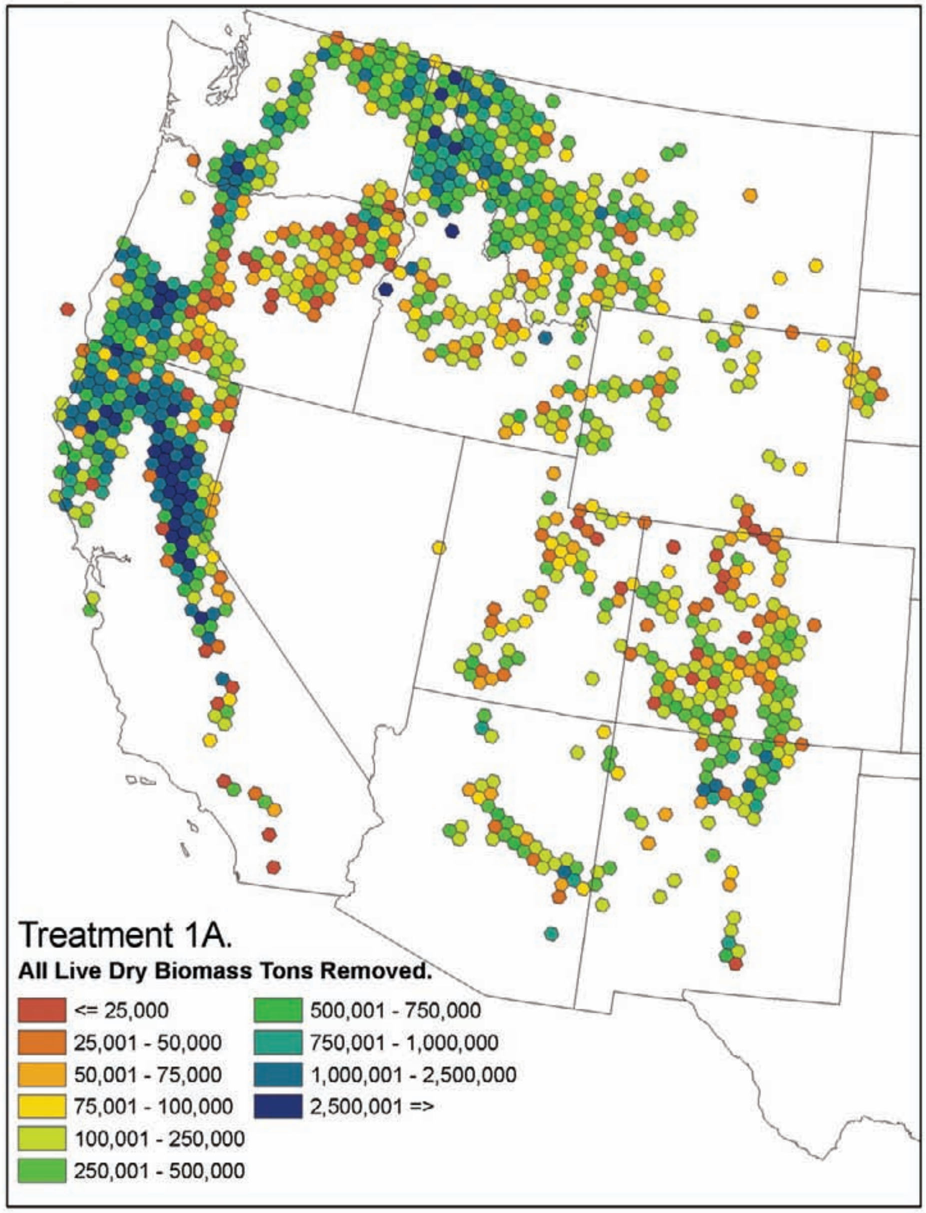

Figure 1—Total biomass removed per 160,000-acre area for uneven-aged treatment 1A (tons).

Estimates of Biomass Removed and Harvest Costs Used in the FTM–West Model

Two sets of treatments were applied to the 14 million acres of federal timberland judged eligible for treatment. These are treatments 1A and 4A and treatments 3A and 4A. Volumes and harvest costs from these treatments are used as inputs to the FTM–West market model described by Ince and Spelter and by Kramp and Ince in these proceedings. Unevenaged treatments 1A and 4A combined (SDI treatment) treat 10.9 million acres and provide 347 million tons (23.2 billion ft^3) at an average cost of $1,531/acre ($0.719/ft^3). Even-aged treatments 3A and 4A combined (TFB treatment) treat 5.6 million acres and provide 148 million tons (9.9 billion ft^3) at an average cost of $1,420/acre ($0.807/ft^3).

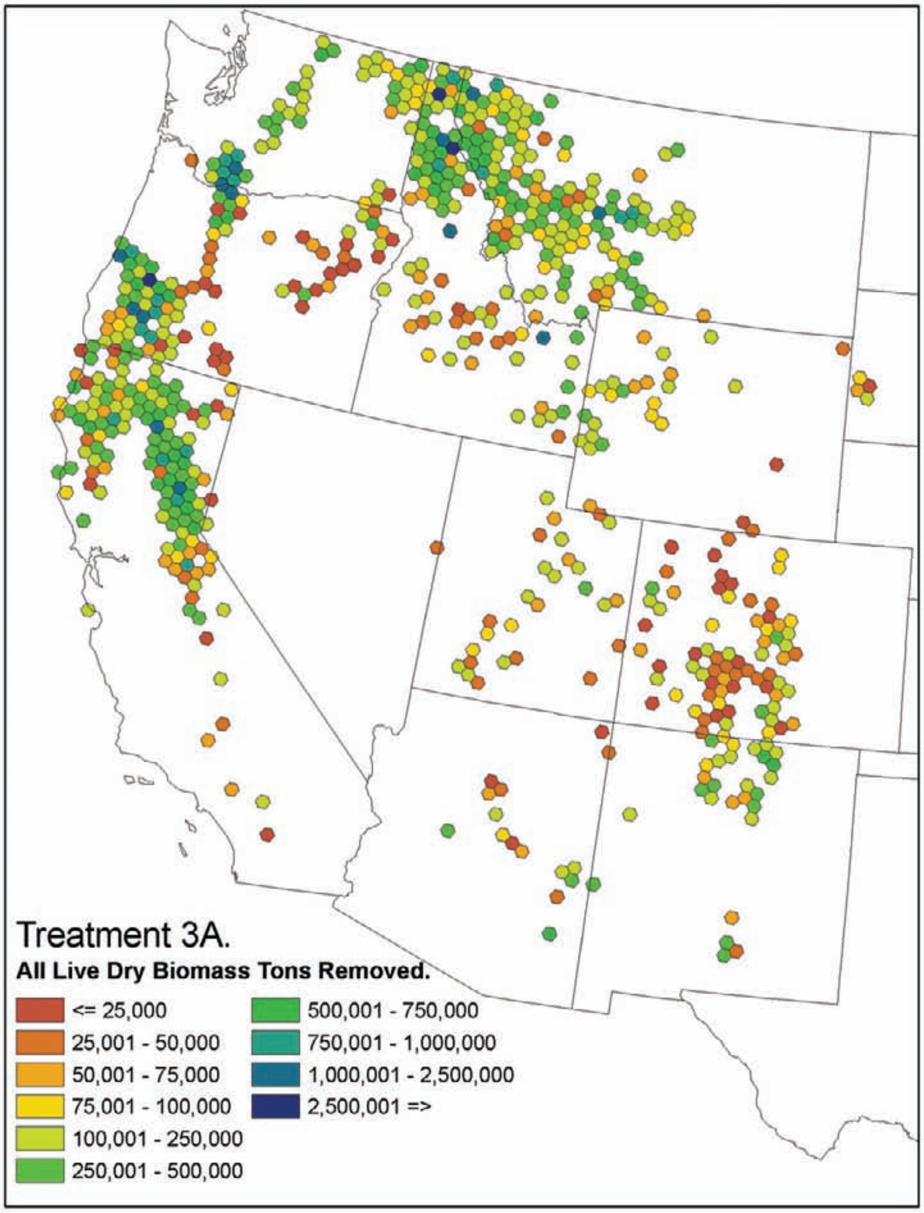

Figure 2—Total biomass removed per 160,000-acre area for even-aged treatment 3A (tons).

Summary

The proportion of the 23.9 million eligible acres that can be thinned and provide positive net revenue from the sale of biomass products varies substantially, depending on whether an even- or uneven-aged silvicultural treatment is used and whether removals are limited or not limited to taking 50 percent of initial BA.

Under our assumptions, uneven-aged treatments will be able to treat a higher proportion of acres with resulting positive net revenue than will even-aged treatments. Moreover, for treated acres, if BA removal is limited to 50 percent limit, then uneven-aged treatments are more likely to attain one of our hazard reduction targets (CI>25 and TI>25, or TI>40) than are the even-aged treatments.

Both uneven-aged and even-aged treatments are able to meet hazard reduction targets on all acres if we remove the BA removal limits and the requirement to provide 300 ft^3/acre of merchantable wood. But the hazard reduction benefit of removing the BA limit may be limited or offset by the effect of a more open canopy and more greatly altered stand structure. The data on costs and revenues suggest that if uneven-aged treatments were used everywhere, revenues could cover a notably higher proportion of costs than if even-aged treatments were used everywhere.

If we assume a $20/green ton subsidy for chips, average revenue is positive for all treatments on gentle slopes and increases the most for even-aged treatments (about $500/acre) because they provide the most chips. Revenue for uneven-aged treatments increases about $410/acre.

The eligible acres and treated acres are predominately in California, Idaho, and Montana, which include 65 to 70 percent of the treated acres for both uneven-aged and even-aged treatments. There are an estimated 21.2 million acres of WUI area in the 12 western states studied, of which an estimated 4.1 million acres is timberland. Treatments would cover 20 to 30 percent of this timberland

Given the concern about removing large trees by uneven-aged thinning, it may be possible to reduce large tree harvest by pruning or reducing surface fuels to increase torching index rather than thinning to reach a high crowning index. Supplementary treatments are likely to increase harvest costs and decrease net revenue per acre.

Acknowledgments

This paper is an outcome of the Wood Utilization Opportunity Areas (WUOA) Project that was funded in part by the National Fire Plan Research Program (Project 02.FPL.C.1). The project is a collaborative effort of USDA Forest Service researchers and managers including Ken Skog, Forest Products Laboratory, and Jamie Barbour, Pacific Northwest Research Station, co-team leaders; Roger Fight, research forest economist (retired), Pacific Northwest Research Station; Karen Abt and Bobby Hugget, research economists, Southern Research Station; Frank Burch, silviculturist, Washington, DC; Pat Miles, research forester, North Central Research Station; Elizabeth Reinhardt, project leader, Rocky Mountain Research Station; and Wayne Sheppard, research silviculturist, Rocky Mountain Research Station.

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Biomass Utilization Modeling on the Bitterroot National Forest

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***Abstract**—Utilization of small-sized wood (biomass) from forests as a potential source of renewable energy is an increasingly important aspect of fuels management on public lands as an alternative to traditional disposal methods (open burning). The potential for biomass utilization to enhance the economics of treating hazardous forest fuels was examined on the Bitterroot National Forest and surrounding areas. Initial forest stand conditions were identified from Forest Inventory and Analysis (FIA) data. The Forest Vegetation Simulator (FVS) was used to simulate stand growth and development and estimate removed volumes. Harvest and haul cost models were used to estimate stump to mill costs and these were integrated into MAGIS, a natural resources decision-support system. Temporal and spatial implications of utilization were examined through optimization modeling with MAGIS to identify sustainable quantities and associated costs based on accessibility, haul distance, flow, and quantity of small-diameter material. This study enables land managers, investors, and policy-makers to make informed economic and environmental decisions regarding biomass as a renewable energy source in the Bitterroot National Forest area and will serve as a model for biomass utilization in other areas.*

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Introduction

In the western U.S. there are approximately 15.8 million acres of accessible forestland that could benefit from mechanical fuel treatments to reduce hazardous fuels and disastrous effects of severe wildfires (USFS 2003). Mechanical treatments will produce significant quantities of currently sub- and non-merchantable biomass material not suitable for lumber or pulp production that must be disposed to avoid leaving hazardous fuels in the forest. Traditionally, this biomass has been disposed onsite by burning, which has drawbacks such as potential escape, air quality issues and limited burning windows.

Research has indicated that fuel treatments on public lands have the potential to produce an abundance of biomass (Barbour and others 2004, USDOI Unpublished, USFS 2003), but competitive markets for this material are generally lacking. However, gaining popularity, momentum, and financial feasibility is utilization of this traditional waste material for renewable energy production, specifically, thermal energy production at relatively small scales in rural areas throughout the Western U.S. With the establishment of the Fuels for Schools Program, a collaboration of federal and state agencies providing financial subsidies and incentives, small scale thermal energy production facilities are now being constructed (www.schoolsforfuels.org). Other potential uses of biomass are also being investigated (LeVan-Green and Livingston 2003). Thus, outlets for biomass are forming, providing an alternative to onsite burning.

This paper compares the economic tradeoffs between biomass recovery from fuel treatment for renewable energy production and biomass disposal by open burning in Ravalli County, Montana. We have integrated fuel treatments devised with Bitterroot National Forest personnel with several independent and exogenous models to develop a set of biomass disposal alternatives. These alternatives reflect realistic choices managers must make when determining if biomass utilization for renewable energy production is economically justified or if onsite burning may be the best option. From this notion of alternative disposal options, we have devised a spatial and temporal model of biomass utilization economics based on site distance from a utilization center.

Methods

Study Area

The location specified for this analysis – the Bitterroot National Forest in western Montana – was chosen due to a number of economic and environmental factors it has in common with other communities in the inland western U.S. The area has an abundance of National Forest land, a growing population particularly in the Wildland Urban Interface (WUI), and contains a significant amount of forestland categorized as moderately to highly removed from historical wildfire regimes (USFS 2003b). Furthermore, this area is within proximal distance of a modest amount of existing wood products infrastructure with biomass utilization capacity. These include two recently established, small-scale facilities within the study area capable of utilizing biomass for thermal energy, and in adjacent Missoula county to the North, a sawmill and a pulpmill that utilizes biomass as hogfuel.

Silvicultural Treatments Selected for the Bitterroot National Forest

A wide variety of silvicultural treatments are available to land managers to achieve differing fuel treatment objectives. In this analysis we focused on mechanical treatments designed to reduce wildfire effects and restore forests to sustainable and historical conditions, where prescribed burning would not be feasible under present conditions. Discussions with Bitterroot National Forest (BNF) silvicultural and fire management personnel yielded the following three prescriptions:

1) **Thin from below (TB9)** – cut and remove all trees up to a 9 inches diameter breast height (d.b.h.); apply this prescription only to stands having 1) basal area (BA) greater than 50 ft^2/ac for trees greater than 9 inches d.b.h., or 2) BA greater than 20 ft^2/ac for trees 9 inches d.b.h. or greater where there are at least 109 trees per acre that are 9 inches d.b.h. or less. This prescription may be applied in all stands excluding lodgepole, white pine, grand fir and sub alpine fir.

2) **Moderate density (Moderate)** – cut and remove all trees up to 7 inches d.b.h., plus some larger diameter trees with a target residual stand having 100 ft^2/ac BA in the largest and healthiest trees; apply this prescription

only to stands having a BA greater than 100 ft^2/ac for trees 7 inches d.b.h. or greater. Grand fir and sub alpine fir are removed first, and then the smallest Douglas fir, ponderosa pine and western larch are cut equally until the desired BA is achieved. This prescription may be applied in all stands excluding lodgepole and white pine.

3) **Comprehensive restoration (Comprehensive)** – cut and remove all trees up to 7 inches d.b.h., plus some larger diameter trees with a target residual stand having 50 ft^2/ac in fire resistant tree species such as ponderosa pine, western larch, and large Douglas fir. Remaining tree sizes, numbers, and their locations will restore the stand to a sustainable structure given current conditions. Apply this prescription only to stands having a BA greater than 50 ft^2/ac for trees 7 inches d.b.h. or greater. This prescription was designed for application in ponderosa pine habitat types only.

Timber Volume Estimation

Forest Inventory and Analysis (FIA, http://www.fia.fs.fed.us/) data were used to estimate the volume of merchantable logs (7+ inches d.b.h. to a 4.5 inch top) and sub-merchantable biomass (whole trees less than 7 inches d.b.h. and tops and limbs of harvested trees 7+ inches d.b.h.) that would be removed by the three mechanical fuel reduction prescriptions. A whole tree harvest system was assumed. To obtain an adequate amount of stand data, FIA plots were selected from six western Montana counties having forest conditions similar to those found in Ravalli County, yielding a total of 912 FIA plots.

These data were imported into the Northern Idaho/Inland Empire variant of the Forest Vegetation Simulator (FVS, http://www.fs.fed.us/fmsc/fvs/) to predict merchantable timber volumes and biomass harvested from applying each of the three fuel treatment prescriptions described earlier. We assumed that no cut stems, tops, or branchwood were left in the stand, in other words everything cut was removed.

To capture the dynamic aspect of timber stand composition over time, as well as to allow stands to move between vegetation states, the FIA plot growth was simulated using FVS for up to five decades from 1997, the most recent inventory year, to 2007,..., 2047. Each plot was grown from its inventory condition to each of these decadal time periods and then the fuel treatment prescriptions were applied. Based on the forest conditions for applying each of the three treatments, the Comprehensive prescription set consisted of 2,703 plots, the Moderate prescription set had 1,346 plots and the TB9 prescription set had 2,267 plots. Many plots qualified for more than one prescription.

Weights for all merchantable logs that would be removed from the FIA plots by the prescriptions were computed through a combination of the FVS Database Extension, tree component ratio equations from Jenkins and others (2003), and dry cubic foot weights obtained from Reinhardt and Crookston (2004). Quadratic mean diameter (QMD) and trees per acre cut were tallied for both the merchantable and non-merchantable categories. The Fire and Fuels Extension was utilized to estimate the weight of the total biomass removed. Subtracting the removed merchantable log weight from the weight of the total biomass removed yielded weight of the sub- or non-merchantable biomass. We assumed that all cut stems and branchwood were removed from the stand (FVS YARDLOSS keyword). Statistics are displayed in tables 1 through 3.

Table 1—Summary statistics of quadratic mean diameter (QMD), cubic feet, trees per acre cut, biomass, and harvest costs for trees removed using the Comprehensive prescription (n=2,703).

Statistics	QMD >7" DBH	QMD <=7" DBH	Cubic Ft >7" DBH	Cubic Ft <=7" DBH	Trees per Acre Cut >7" DBH	Trees per Acre Cut <=7" DBH	Total Removed (dry tons)	Biomass (dry tons)	Harvest Cost per Acre: With Biomass Chipping	Harvest Cost per Acre: Without Biomass Chipping
Mean	11.93	3.53	1,740.77	269.07	97.69	215.31	39.22	13.09	$1,595	$1,458
Std. Error of Mean	0.06	0.04	25.06	6.47	1.20	6.59	0.45	0.15	$19	$17
Std. Deviation	3.13	1.98	1,302.63	336.38	62.57	342.62	23.63	7.97	$980	$897
Median	11.27	3.84	1,471.76	148.41	87.64	95.81	36.00	11.81	$1,468	$1,335

Table 2—Summary statistics of quadratic mean diameter (QMD), cubic feet, trees per acre cut, biomass, and harvest costs for trees removed using the Moderate prescription (n=1,346).

Statistics	QMD >7" DBH	QMD <=7" DBH	Cubic Ft >7" DBH	Cubic Ft <=7" DBH	Trees per Acre Cut >7" DBH	Trees per Acre Cut <=7" DBH	Total Removed (dry tons)	Biomass (dry tons)	Harvest Cost per Acre: With Biomass Chipping	Harvest Cost per Acre: Without Biomass Chipping
Mean	10.29	3.71	1,126.87	250.82	80.21	201.11	27.09	10.37	$1,223	$1,117
Std. Error of Mean	0.07	0.05	28.17	7.91	1.51	8.79	0.51	0.18	$22	$20
Std. Deviation	2.40	1.89	1,033.35	290.18	55.42	322.38	18.68	6.78	$804	$736
Median	9.83	4.01	834.83	155.24	70.38	94.53	23.00	8.95	$1,067	$968

Table 3—Summary statistics of quadratic mean diameter (QMD), cubic feet, trees per acre cut, biomass, and harvest costs for trees removed using the TB9 prescription (n=2,267).

Statistics	QMD >7" DBH	QMD <=7" DBH	Cubic Ft >7" DBH	Cubic Ft <=7" DBH	Trees per Acre Cut >7" DBH	Trees per Acre Cut <=7" DBH	Total Removed (dry tons)	Biomass (dry tons)	Harvest Cost per Acre: With Biomass Chipping	Harvest Cost per Acre: Without Biomass Chipping
Mean	6.93	3.93	261.98	304.70	42.21	250.10	12.30	8.26	$763	$693
Std. Error of Mean	0.06	0.04	5.38	7.02	0.82	7.55	0.22	0.16	$16	$14
Std. Deviation	2.77	1.74	255.92	334.10	39.15	359.57	10.36	7.61	$738	$673
Median	7.93	4.12	187.99	192.20	32.13	131.55	10.00	6.00	$562	$517

Modeling Treatment Costs

Treatment costs (excluding administrative and planning) were modeled for each application of the three treatments applied to the FIA plots summarized in tables 1 to 3 using the Fuel Reduction Cost Simulator (FRCS, Fight and others 2006). Required FRCS input variables include trees per acre removed, QMD, average tree volume, green wood weight, and residue weight to bole weight fractions. These were calculated from the cut tree lists (tables 1 to 3), regression equations from Jenkins and others (2003) and dry wood weights from Reinhardt and Crookston (2004) adjusted to 50 percent wood fiber moisture content. We used the average slope of 22 percent for lands identified through GIS analysis. We specified a whole tree system with an average skidding distance of 800 feet. The model was calibrated to reflect western Montana wage rates – $24.60/hour for fallers and/or buckers and $16.13/hour for all others (2002 dollars, ACINET 2003). The model's default labor benefit rate of 35 percent was retained, and move-in costs were not included. Tables 1 to 3 display summary statistics from the harvest cost modeling.

Haul Cost Estimation

Material delivery costs from the logging unit to an end use facility can often determine the financial success of mechanical treatment operations. Western Montana is home to several locations that utilize biomass as thermal-energy fuel, and therefore, haul distances are not as great as many other locations. For our analysis we specified two end use locations as destinations for the biomass and one end use facility for merchantable logs that resulted from implementing the three fuel reduction prescriptions. These are respectively the towns of Darby in the southern portion of Ravalli County, Frenchtown in western Missoula County and Milltown in southern Missoula County (fig. 1).

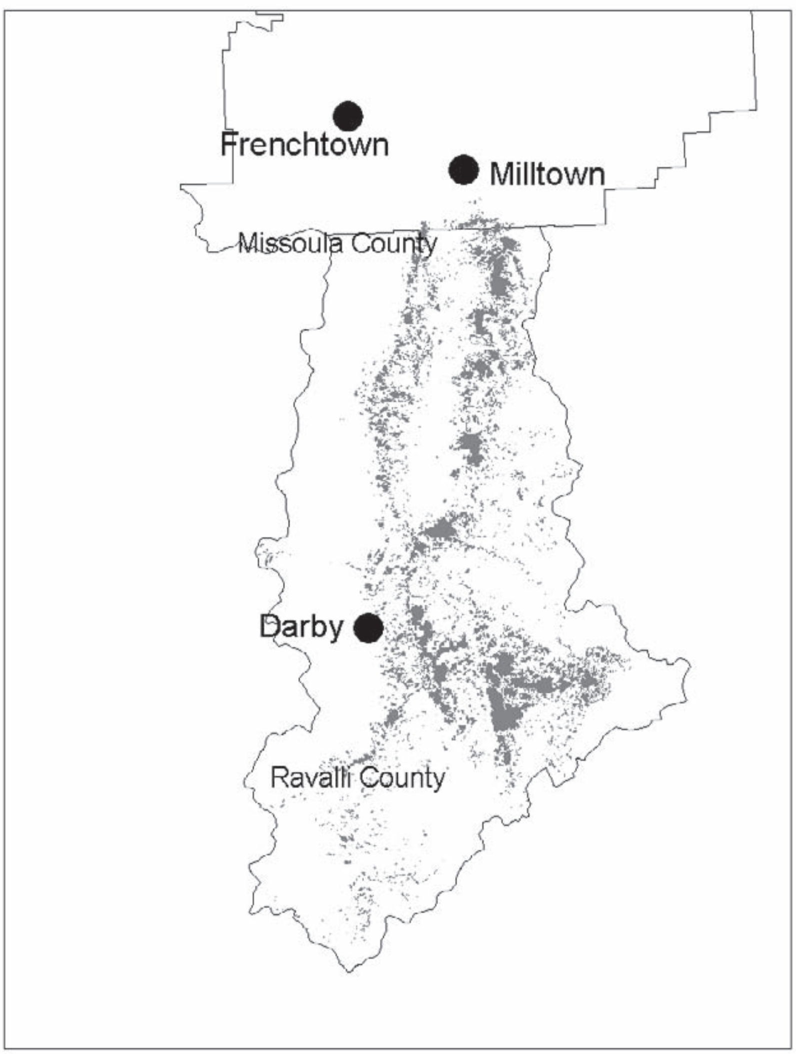

Figure 1—Location of delivery points. Darby and Frenchtown for biomass. Milltown for timber products. Gray shaded area is the study area polygons.

Haul costs were estimated on a per mile basis for each of two types of roads, paved and non-paved, using the Forest Residue Trucking Model (FoRTS; http://www.srs.fs.usda.gov/forestops/) and a GIS road coverage for the study area (Loeffler and others 2006). We further verified our results from FoRTS with the Log Truck Haul Cost Appraisal model (http://www.fs.fed.us/r6/nr/fp/FPWebPage/FP70104A/Programs.htm). Chip truck haul costs were based upon hourly roll-off container truck operating costs and average miles per hour speed, and log truck haul costs were based upon the hourly costs of operating a tractor trailer. We calibrated the haul cost model to reflect local wages and conditions using an average driver wage of $16/hour with 35 percent benefit rate. We assumed the chip truck would haul 16 green tons of chips and the log truck 28 tons, diesel fuel costs $2.50/gallon and oil costs $9/gallon.

We estimated haul costs for log trucks delivering merchantable logs to Milltown (where a mill exists that purchases logs) and roll-off container trucks hauling biomass to both Frenchtown and Darby. Distances in both paved and non-paved miles (total miles is the sum of paved and non-paved) were tallied from the polygons identified in the GIS portion of this analysis to Darby, Frenchtown, and Milltown. Average speeds were estimated at 15 miles per hour on non-paved roads and 45 miles per hour on paved roads. Using these estimates, costs per mile for each road surface type were estimated using the FoRTS model as the quotient of operating costs per driving hour and average miles per hour speed (table 4). Differences in the costs per mile are attributable to changes in variable truck operating costs when combinations of road types change. These average costs per mile were then multiplied by the actual paved and unpaved distances for each polygon to compute unique haul costs for each polygon.

Selection of Analysis Area

GIS data were used to identify the stands in the frequent fire regime class where mechanical treatment is appropriate and feasible. The current vegetation was represented by the vegetation states assigned to the stand polygons by Chew and others (2004). Based on fuel management objectives, only those vegetation states having the dominant tree species displayed in table 5 were considered for treatment. Additional characteristics of vegetation states included size class (QMD of SS = <5", Pole = 5" to 8.9", Medium = 9" to 14.9", Large = 15" to 20.9", and Very large = 21"+) and density (crown canopy cover of 1 = 0 to 15%, 2 = 15 to 39%, 3 = 40 to 69%, 4 = 70 to 100%). The FIA plots were categorized into these pre-treatment vegetation states. Since FIA data did not exist for certain vegetation states (21 percent by area), missing data was interpolated through a method of substituting

Table 4—Round trip distances and haul cost to the three end use locations.

End Use Locations - Montana towns	Average Round Trip Miles: Paved Roads	Average Round Trip Miles: Non-paved Roads	Cost per Mile: Paved Roads	Cost per Mile: Non-paved Roads
Darby (chip truck)	38	13	$1.26	$3.78
Frenchtown (chip truck)	134	16	$1.37	$4.10
Milltown (log truck)	124	16	$1.36	$4.08

Table 5—Tree species combinations selected for analysis.

Dominant species	Descriptions
DF	Douglas-fir (*Pseudotsuga menziesii*)
DF-GF	Douglas-fir - Grand fir (*Abies grandis*)
DF-LP	Douglas-fir - Lodgepole pine (*Pinus contorta*)
DF-LP-AF	Douglas-fir - Lodgepole pine - Subalpine fir (*Abies lasiocarpa*)
L-DF-LP	Western larch (*Laryx occidentalis*) - Douglas-fir - Lodgepole pine
L-DF-PP	Western larch - Douglas-fir - Ponderosa pine (*Pinus ponderosa*)
PP	Ponderosa pine
PP-DF	Ponderosa pine - Douglas-fir

based on proportional data from other vegetation states. From the GIS data we restricted analysis to non-wilderness areas, with slopes less than or equal to 35 percent (based on the requirements of the whole tree ground-based harvest system), only lands categorized as FRCC 2 or 3 (USFS 2003b) and polygons that fell within a 1500 foot buffer of existing roads. The resulting polygons are included in figure 1.

MAGIS Modeling Parameters

MAGIS (Multi-resource Analysis and Geographic Information System) is an optimization model designed to solve complex spatial and temporal scheduling problems in natural resource management (Zuuring and others 1995). MAGIS is based on a mixed-integer mathematical programming formulation that includes vegetation management options for treatment unit polygons and an optional network component for analyzing road access and associated costs and resource impacts (Weintraub and others 1994). Decision variables for each treatment unit polygon include "no action" and treatment options comprised of alternative management regimes that vary by the treatment(s) they prescribe over time, and the period when the management regime is implemented.

The objective of this study was to analyze the quantities of biomass that could be made available by treating hazardous fuels accessible from existing roads. Haul distances and costs were incorporated into the vegetation management alternatives along with costs of burning biomass on site. Separate decision variables were created for each combination of vegetation management treatment option (TB9, Moderate, and Comprehensive) and the three options for biomass disposal from the treatments: Burning (pile burning at logging site), biomass hauled to Darby, and biomass hauled to Frenchtown. This resulted in up to nine possible treatment choices for the optimization solver to choose from for each treatment unit polygon.

Vegetation Succession—Successional pathways were used to determine changes in vegetation states in 5 decadal time steps (50 year planning horizon) if no hazardous fuel treatment is undertaken. These predicted states describe the vegetation that would exist when the future treatment options would occur. The most important successional pathways in terms of acres are listed in table 6.

Table 6—Pathways for the major vegetation states in the study area.

Habitat group[a]	Initial dominant species, size class, density	Acres (1000)	Successional changes: resulting dominant species, size class, density
B2	PP, SS, 2	76	4th decade goes to PP, Pole, 2 5th decade goes to PP-DF, Pole, 2
A2	PP, SS, 2	16	3rd decade goes to PP, Pole, 2 5th decade goes to PP, Medium, 2
B2	L-DF-PP, Large, 3	13	no changes
B2	L-DF-PP, Medium, 3	12	2nd decade goes to L-DF-PP, Medium, 4 5th decade goes to L-DF-PP, Large, 4
B2	DF, Large, 3	7	no changes
B2	DF, Medium, 3	5	2nd decade goes to DF, Large, 3

[a] Habitat group descriptions: A2 is warm and dry, and B2 is moderately warm and dry.

Effects Functions—Functions that were used as constraints or objectives by period within the model consisted of the following:

1) Total acreage functions: total acres: treated, treated with TB9, treated with Comprehensive, treated with Moderate, with biomass removal, with pile burning, of FRCC treated (class 2 and 3, tabulated separately), and of WUI treated
2) Cost functions: total costs, cost of biomass removal (stump-to-truck and chipping), site costs (merchantable (stump to truck) and any biomass removal or preparation for pile burning), haul costs of biomass (to Darby or Frenchtown, tabulated separately), haul costs of merchantable (to Milltown), and costs of pile burning
3) Revenue functions: biomass revenue, merchantable revenue, and total revenue
4) Net value functions: total net value (total revenues minus total costs), biomass net value (biomass revenue minus biomass removal and haul costs)
5) Volume/weight functions: merchantable volume and biomass weight

These functions incorporate the volume and cost computations described earlier. The value of delivered merchantable material was set at $2 per cubic foot, and the value of delivered biomass was set at $13 per green ton. Both values were based on current local markets. The cost of pile burning was estimated at $100 per acre.

Results

MAGIS can be used to develop many types of spatial and temporal analyses. We present five analyses that capture the economic aspects of utilizing biomass produced by mechanical hazardous fuel treatments. For each, we describe the question, the MAGIS set up and runs made to address the question, then present the results.

Maximum Net Value by Treatment Prescription

This section investigates the extent to which each of the three mechanical fuel treatment prescriptions result in a positive net return, and the number of treatment acres expected to result in a positive net return. Three scenarios were run that constrained treatment prescription to biomass utilization first to only the Comprehensive prescription, next to only the Moderate prescription, and last to only the TB9 prescription. Each scenario optimized on the objective function of maximum net value in period one. The results showed that acres that could be treated with a positive return were 20,984, 56,421, and 60,689 for TB9, Moderate, and Comprehensive, respectively, from 160,954 treatable acres in the study area. The costs, revenues, and net values per acre for these prescriptions are displayed in figure 2. The vast majority of the total revenue predicted for these treatments comes from the commercial component that would be removed. The Comprehensive prescription had an understandably higher net value than the TB9, with the Moderate prescription falling in between, as was expected from the level of commercial products each prescription produces. The net values per acre treated for positive valued units for TB9, Moderate, and Comprehensive were $83, $1,632, and $2,939, respectively, which support the basic findings Fiedler and others (1999) with regard to the economic value of the Comprehensive prescription.

A Spatial View of Economic Importance of Biomass Mill Location

Haul costs are known to be an important economic component in the feasibility of off-site biomass utilization. As such, the location of biomass markets affects the economics of biomass utilization. In this section we compare the economics of biomass utilization with on-site burning for three biomass market scenarios: 1) markets at both Darby and Frenchtown, 2) market only at Darby, and 3) market only at Frenchtown. In each scenario we assume the markets can utilize all the biomass these scenarios would deliver. All three scenarios maximized net value in period one as the objective function and

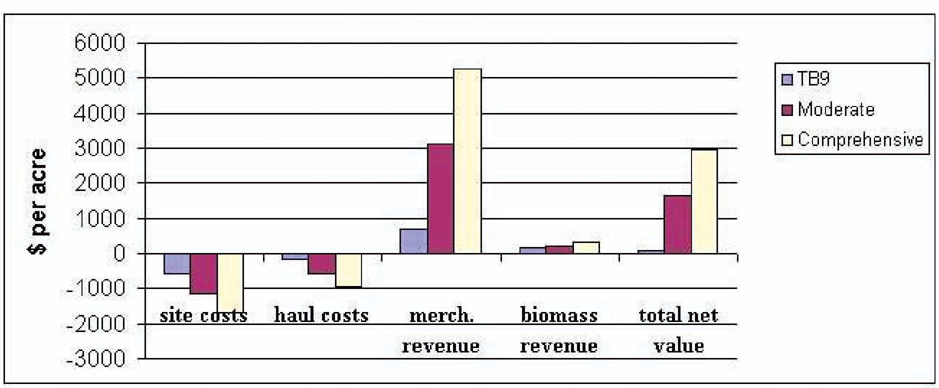

Figure 2—Costs, revenues and resulting net value for the three mechanical fuel treatment prescriptions applied where they result in positive returns. Site costs include merchantable (stump-to-truck) and any biomass removal (stump-to-truck and chipping) or preparation for pile burning. Haul costs include hauling merchantable material and biomass for biomass scenario. Merch revenue is the revenue for merchantable material.

constrained acres treated to include all that were treatable. The first scenario (markets at both Darby and Frenchtown) had no other constraints. The second scenario constrained biomass delivery to Darby only. The third scenario constrained delivery to Frenchtown only.

Results mapped in figure 3, panels a to c, show the most economical disposal of biomass for each polygon. When delivery was allowed to both Darby and Frenchtown, it was most economical to deliver 82 percent (by area treated) of the biomass to centrally located Darby, while the northern 16 percent of biomass went to Frenchtown, north of the study area, and only 2 percent was burned on the peripheral units (fig. 3, panel a). When Darby was the only location, biomass delivery (97 percent) was more economic than burning (3 percent) (fig. 3, panel b). Finally, when Frenchtown was the only location, biomass delivery fell to 57 percent and burning increased to 43 percent (fig. 3, panel c). In this scenario, burning was more cost effective in the southern area away from the northern mill site and the paved delivery routes that run down the center of the study area. This result clearly shows the importance of biomass markets nearer to the forest resources, whereby Darby, with an average haul distance of 25 miles one-way, showed biomass utilization to be profitable in 97 percent of the area, whereas Frenchtown, with an average haul distance of 75 miles one-way, showed biomass utilization to be profitable in only 57 percent of the area.

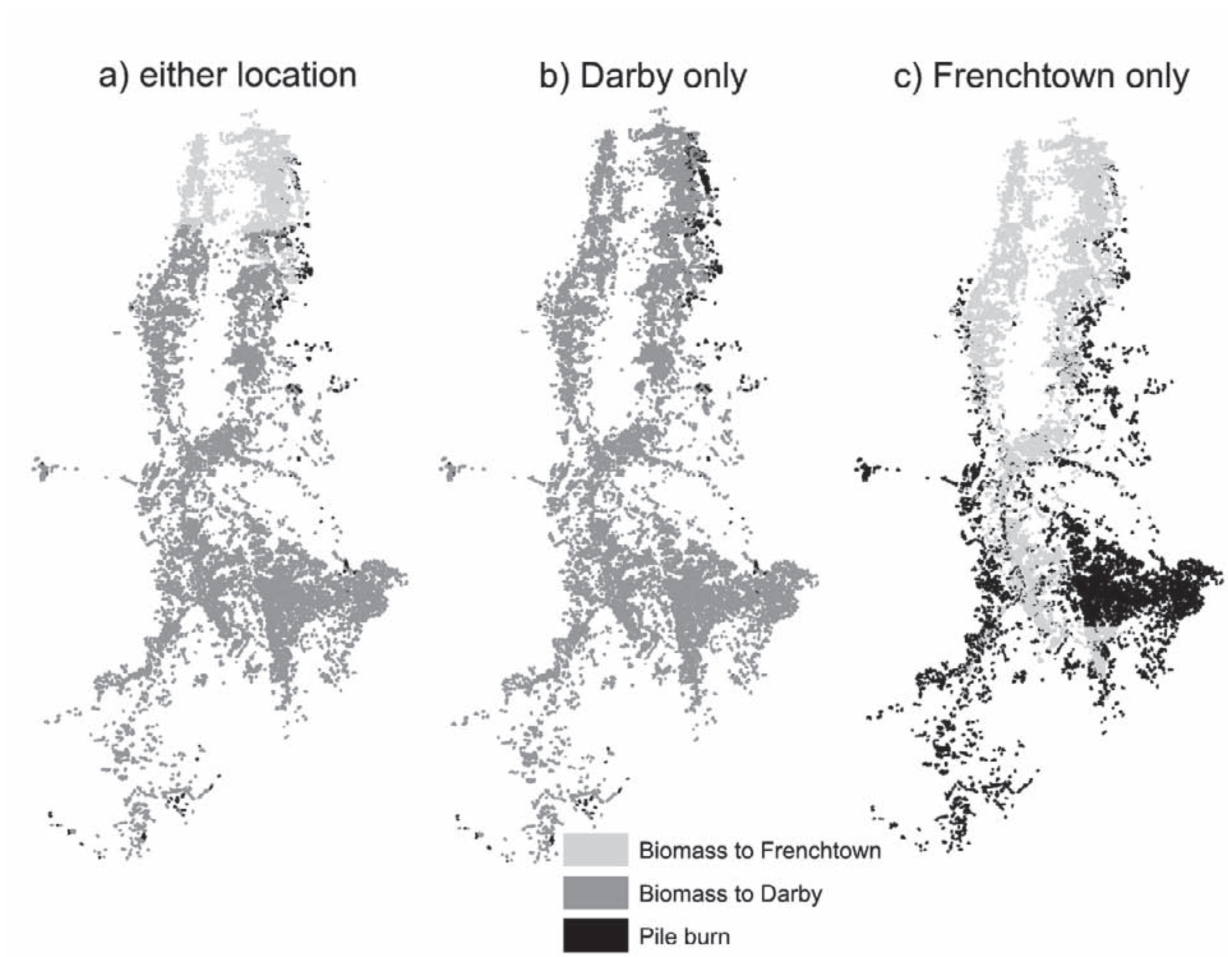

Figure 3—Spatial view of use of small diameter materials to maximize net value for all treatable acres for three biomass market scenarios: a) markets at both Darby and Frenchtown; b) market at Darby only; and c) market at Frenchtown only. See figure 1 for mill locations.

Biomass Utilization versus Burning for Selected Zones

We also compared the economics of utilizing biomass created by mechanical fuel treatments with pile burning within specific zones, first all acres in FRCC class 3, and next in WUI acres. For this comparison, net value was maximized for scenarios that treated all 71,984 acres of FRCC class 3 and all 119,126 acres of WUI with either solely biomass utilization or solely pile burning in period one. Utilizing biomass while treating all FRCC class 3 acres resulted in a positive average net value for applying mechanical fuel reduction treatments, whereas pile burning resulted in a negative average net value. As can be seen in figure 4, the additional revenue came primarily from biomass, which offset increased haul costs enough to show the positive return. The biomass revenue is understandably high in FRCC 3 areas as this indicates a fire regime condition class that has grown with thicker forests which would provide more biomass in these mechanical fuel treatments. Treating WUI acres showed positive net values for biomass utilization and burning, with modest increases from biomass revenue offsetting haul costs (fig. 5). The WUI zone generated higher merchantable revenue than the FRCC 3 zone because of a higher percentage of area in size classes over 9" d.b.h. (27 percent for WUI versus 11 percent for FRCC 3).

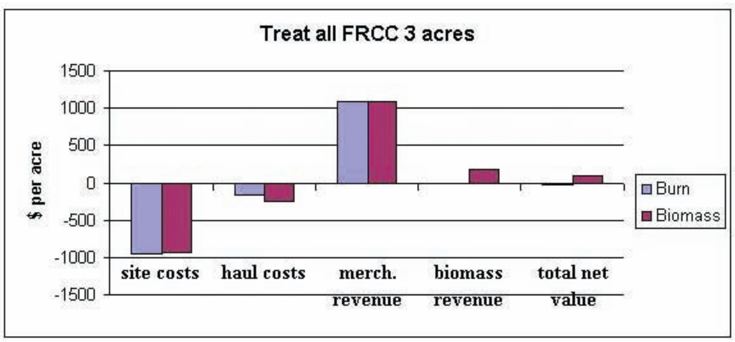

Figure 4—Costs, revenues and resulting net value for treatment of all FRCC 3 acres exclusively using biomass utilization or burning. Site costs include merchantable (stump to truck) and any biomass removal (stump to truck and chipping) or preparation for pile burning. Haul costs include hauling merchantable material and biomass for biomass scenario. Merch. revenue is the revenue from merchantable material.

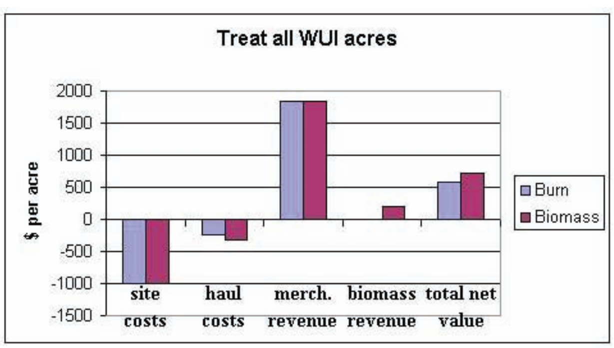

Figure 5—Costs, revenues and resulting net value for treatment of all WUI acres exclusively using biomass utilization or burning. Categories as defined in figure 4.

Comparing Biomass Utilization with Pile Burning for TB9 on Lands Classified as FRCC 3

Brown (2000) cautioned land management agencies regarding public perception of the removal of large merchantable trees during fuel treatment projects. Some public factions prefer fuel treatments that remove only understory ladder fuels and no larger trees. Results presented earlier show that this approach represented by TB9 in this study is more economically challenging than the other two prescriptions which do remove some larger trees having a commercial value. Here we investigate what effects biomass utilization has on the ability to accomplish TB9 treatments for specific budget levels. We focus attention on the FRCC class 3 acres, those presumably most in need of mechanical fuel treatments. Although treating all FRCC class 3 stands resulted in a positive net value with biomass utilization when all treatment prescriptions were available (fig. 4), limiting the options to only TB9 yields a negative net value, requiring a net cost outlay to perform treatments. This analysis was accomplished by running scenarios with five different budget levels for treatments in period one. Budget levels were set at $0, 10, 20, 30, and 35 million dollars, by constraining net value to be greater than the negative of these values. One scenario with only burning and one with only biomass utilization were run for each budget level. The objective function in each scenario was to maximize total acres treated.

The resulting graphs, comparing with and without biomass utilization, suggest that biomass utilization can make a large difference in making limited budgets go further in treating the landscape (fig. 6). For example, at the $20 million level, utilizing biomass increases acres treated from 60 percent with only burning to 76 percent. Similarly, treating 60,000 acres would cost approximately $22 million with biomass and $29 million without biomass.

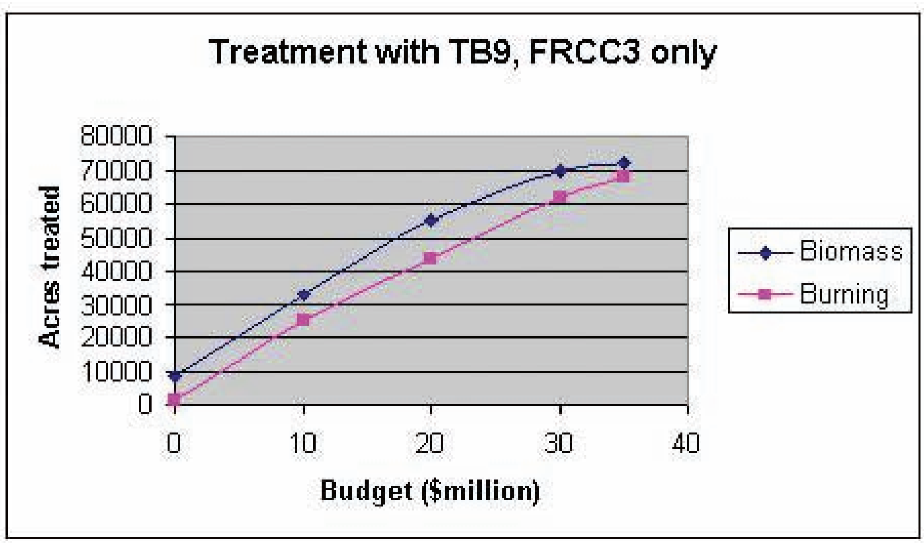

Figure 6—Period one treatment with TB9 in the FRCC3 zone only, constrained by different budget levels.

Even Flow of Biomass Utilization Across Five Decades

Is biomass produced by mechanical fuel treatments sustainable over time? This is an important question for potential investors in new biomass processing facilities. To address this question multiple scenarios were run to identify the maximum sustainable biomass quantity per decade from mechanical fuel treatments over five decades. This was accomplished by constraining the periods 2 through 5 biomass volumes to identical minimum levels and then using the biomass volume in period 1 as the objective function in successive solutions until the resulting period one biomass volume equaled the constrained level for the other periods. This occurred at 758,800 tons of biomass volume per decade.

Next we looked at the amount of biomass that would be produced at different levels of acres treated per decade. These scenarios set constraints at intervals of 5,000 acres treated per decade and used an even-flow of net value as the objective function. The outcome provides economically efficient biomass volumes per decade at different treatment levels (fig. 7). After 15,000 acres per decade, the rate of increase in additional biomass volume with additional acres treated drops as a point of maximum efficiency is reached.

Discussion

Our findings demonstrate that utilizing small diameter wood can enhance the economics of performing fuel treatments to reduce the risk of wildfire and restore forests to natural conditions. By applying a common mechanical fuel treatment prescription, in many instances it is more efficient to extract and utilize the biomass than it is to pile and burn it on site. The breakeven

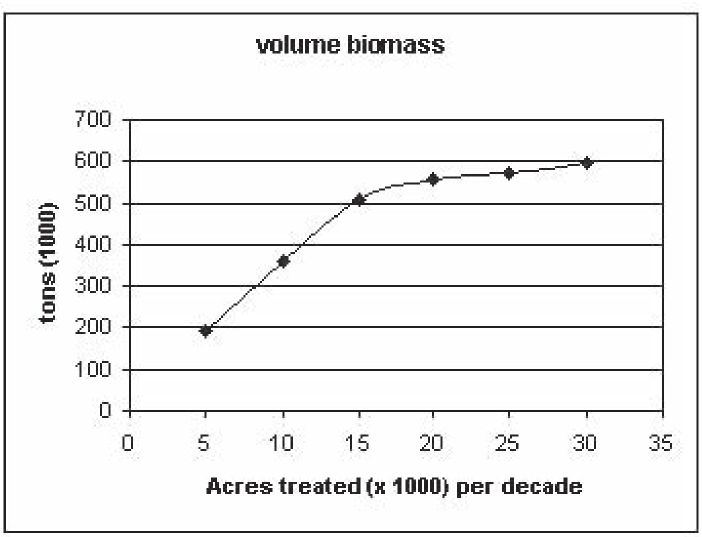

Figure 7—The volume of biomass per decade obtainable with treatments that maximized even-flow net value at different levels.

point between biomass utilization and pile and burning is dependent on haul distances and costs to biomass markets as shown in the maps presented in figure 3. The advantage of biomass utilization is also present in the thin from below prescription, TB9, which removes very little commercial product. These analyses show that the acres that can be treated by TB9 within a fixed budget can be increased by utilizing the biomass created by the treatment rather than pile and burning it on site.

For this paper we analyzed the economics of biomass utilization when conducting fuel treatments focusing on maximizing net value for the majority of the spatial and temporal modeling. However, the principles and the modeling techniques developed here could easily be adopted by managers and planners with different objectives. For example, considerable effort has been invested into determining where best to place fuel treatments to reduce the risk of wildfire (Weise and others 1999, Agee and others 2000, Hof and Omi 2003, Jones and others 2003). Treatment locations can be based on predictions of fire behavior models that do not consider economics (Finney 2001). However, the modeling system presented here is flexible and indices such as crown fire reduction or fire spread rates (Finney 2003) could also be used as the driver to guide treatment placement. With this approach, analysis can be conducted that considers both fire behavior (through use of the crown fire reduction or fire spread indexes) and economics in locating places to apply treatments.

For businesses to establish small diameter wood processing facilities, a guaranteed, long term supply is necessary (Stewart and others 2004; Keegan and others 2005). The analysis presented in this paper indicates that with the current fuels conditions and expected growth of forest fuels in the future as quantified in the successional pathways, significant sustainable volumes of biomass could be made available from applying mechanical fuel treatments to acres in need of fuel reduction treatments over the next five decades. The aspect of this question we have not been able to analyze is whether these mechanical treatments will actually occur on the ground, which on public land is dependent largely on local as well as national political and legal processes.

There are understandable environmental concerns when proposing the removal of vast quantities of woody material from a national forest. Our analysis found the Comprehensive prescription to be the most economically efficient method of treating the landscape and utilizing biomass in the process. Although this was designed as a prescription for ecological restoration (Fiedler and others 1999), the present political climate which influences management decisions indicates extraction of this much material would likely be controversial, whether or not environmentally sound. The TB9 prescription, on the other hand, has the potential to address the fire danger problem with less controversy, though at higher net costs, as shown here, and perhaps less effectively (Fiedler and others 2003). Furthermore, establishing markets for biomass utilization to face the immediate problem of overstocked forests has the potential to create a future demand for forest products that can not be met in an ecologically sound way once the ecosystems are truly restored. The even-flow analysis indicated this is not an immediate concern in the study area, but ecological restoration may occur much sooner in other locations. Thus, the question of sustainability is important for environmental as well as economic reasons, and would be an important direction for further research to expand on what we have begun here.

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Communication and Collaboration

A Collaborative Approach to Community Wildfire Hazard Reduction

Marc Titus[1] and Jennifer Hinderman[2]

Abstract—*This paper highlights the very successful collaborative approach to community wildfire hazard reduction being used in the 5 county NW Region of the Washington State Department of Natural Resources. NW Region cooperators have created a successful model to help affected communities reduce their risks to wildland fire. Identified high risk communities have been approached by a multi-agency team with Firewise education and hazard assessment methodology. Participating communities have received mini-Firewise workshops, community hazard assessments and hazard mitigation planning assistance. By working collaboratively with communities, local fire districts, County Conservation Districts, County Fire Marshal's Offices and Departments of Emergency Management, as well as other State and Federal fire managers, dramatic results in the Region have been achieved. The Firewise Communities/USA model has been used to guide communities through a nationally recognized process of risk assessment, mitigation planning and community specific outcome based solutions. Community fuels reduction efforts have focused on the creation of defensible space and shaded fuel breaks, reducing structural ignitability, as well as implementation of forest stewardship and greenbelt plans. Community recognition by the Firewise Communities/USA program is the measure of success.*

Introduction

The Washington State Department of Natural Resources (WADNR) is responsible for wildfire protection on 12.7 million acres of private and state forest land. While fire can play a beneficial role in the forest ecosystem, it can also be a destructive force that endangers our natural resources, our property, and even our lives.

In today's firefighting in rural and forested areas of the state, traditional boundaries between those fighting wildfires and those battling structural fires overlap giving way to the common need to help one another. The Wildland Urban Interface (WUI), where "the trees meet the eaves," is an area of great concern to the wildland fire fighting community. It is in this area, the WUI, that fire prevention and education activities can have a great positive impact.

By educating property owners and community groups on loss mitigation strategies in the WUI, fire managers from all agencies can influence positive changes in a very hazardous element of the fire ground (the WUI). It is this social change, the change from passive to active behaviors, that can create home sites and communities that are more resistant to loss or damage caused by wildfires. In addition, as property owners and communities become more educated, the dangers associated with firefighting in the WUI can be greatly

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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diminished. Toward these efforts, the NW Region of the Washington Department of Natural Resources has embarked on a WUI wildfire education campaign that has been very successful.

The Northwest region of Washington Department of Natural Resources is located in northwest Washington State, west of the Cascade Crest and just south of the Canadian Border (Figure 1). It covers a 5 county area north of Seattle that includes Whatcom, Skagit, San Juan, Island and Snohomish counties. Puget Sound and the San Juan Islands add considerably to this region's diversity.

Risk Assessment

Using the Wildland Urban Interface Fire Hazard Assessment Methodology and risk assessment components from NFPA 299 (now NFPA 1144), the WADNR, NW Region conducted a systematic wildfire risk assessment. Recent census data was queried to identify potential WUI areas. These landscape areas were assessed for risk using a representative sample scored against NFPA 299 criteria. Hazard levels were identified and subsequently mapped using census polygons. The rating scale as defined by NFPA 299 was utilized resulting in hazard ranking from Low to Extreme (Figure 2).

Figure 1—Washington State Department of Natural Resources Regions

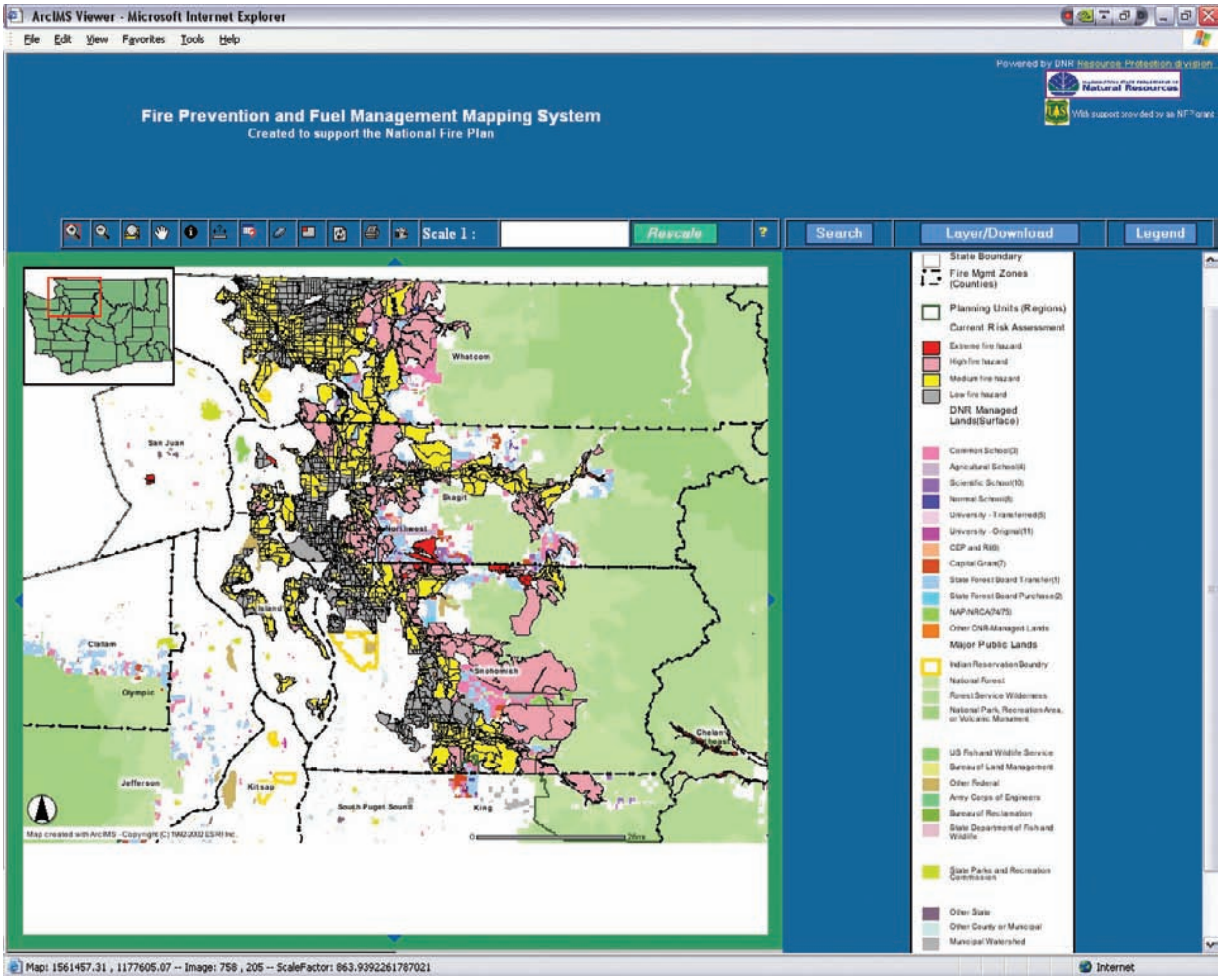

Figure 2—Risk Assessment. The first phase to identifying Landscapes of Similar Risk

Landscapes of Similar Risk

Under the Healthy Forests Initiative and the Healthy Forests Restoration Act (HFRA), the requirement to identify at-risk communities and conduct Community Wildfire Protection Planning (CWPP) was defined. Using guidance provided by the National Association of State Foresters, WADNR used its most recent Wildfire Risk Assessment to identify Landscapes of Similar Risk. Members of local fire management agencies assisted with this effort along with County Departments of Emergency Management, Fire Marshal's Offices and other local state and federal fire managers in the spring of 2004. They took the current regional risk assessment and consolidated risk assessment boundaries down to the landscape level. Landscapes risks were not restricted by county borders, therefore a true landscape was considered. These landscapes were named and digitized to create a GIS map layer (Figure 3).

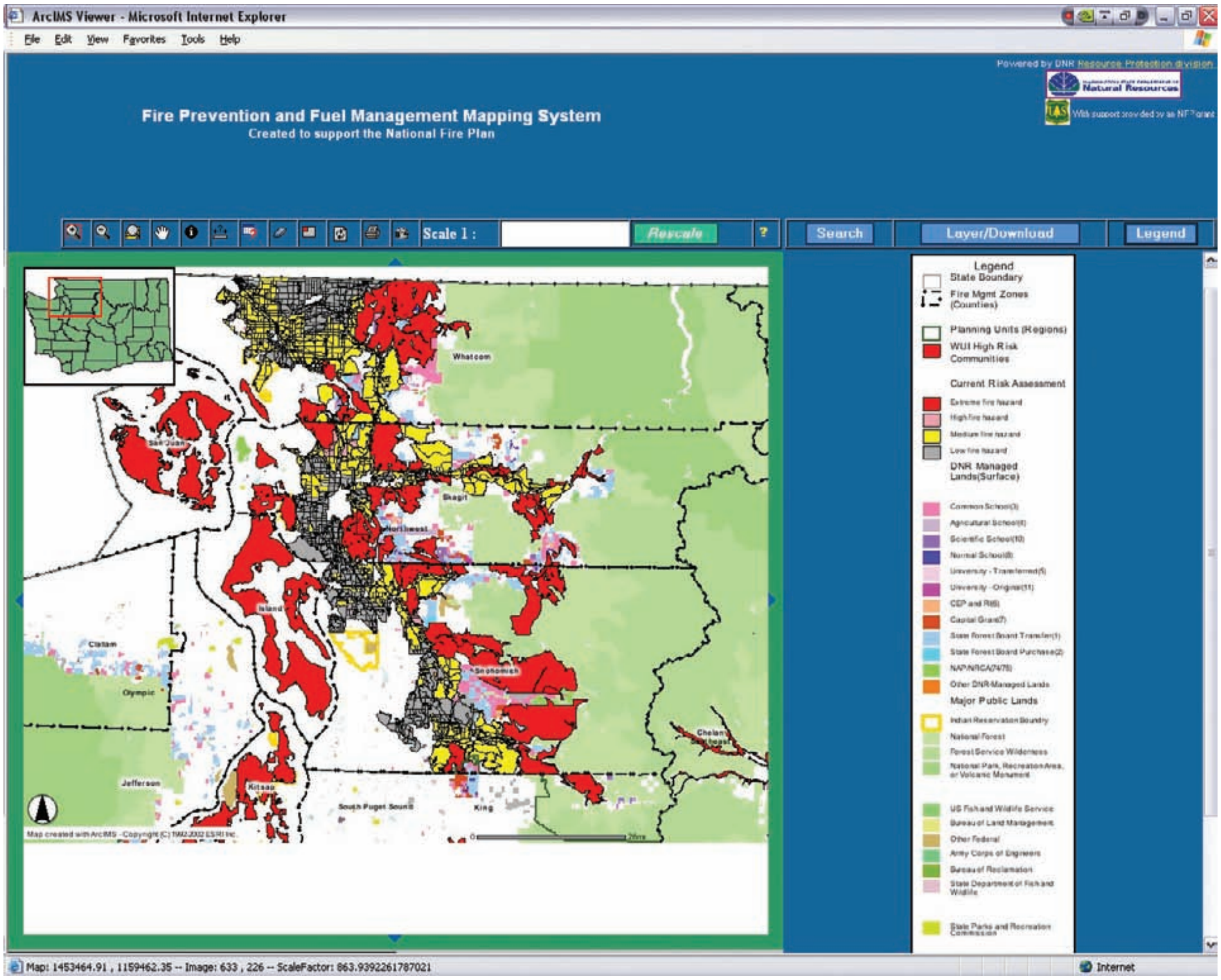

Figure 3—Landscapes of Similar Risk. Identified by regional fire managers through a collaborative process.

Prioritize With RAMS (Risk Assessment & Mitigation Strategies)

RAMS is a computer software program designed to systematically perform landscape level risk assessments (RA), prioritize landscapes and plan mitigation strategies (MS). Federal agencies, as well as WADNR, have adopted RAMS to prioritize, plan and track fire prevention activities. A component of RAMS is the communities' module. This module allowed us to perform a systematic assessment of our landscapes of similar risk using the following standard criteria:

- Fuels Hazard
- Ignition Risk
- Historical Fire Ignition
- Fire Return Interval
- Values, and
- Protection Capability

Inter-Agency Collaboration

A critical component of the National Fire Plan, as well as HFRA, is inter-agency cooperation. This component was also critical to the success of our WUI prevention & education program. Generally speaking, in Western Washington where catastrophic wildland fire incidents are not an every day occurrence, it is difficult to convince WUI residents that they have a fire problem. Residents have been more receptive to Firewise education when addressed by a multi-agency team of fire and education professionals.

In the WADNR NW Region, strong inter-agency relationships were created to facilitate the WUI Prevention & Education program. Partner agencies were identified based on concurrent agency missions. For example, the mission of the Skagit Conservation District is *to provide voluntary, incentive based options that support working landscapes while protecting and enhancing our natural resource land base*. This mission, along with the Skagit Conservation District's experience in community education and outreach make them an ideal collaborator. Funding and support from the local Skagit County government and Title III funds make it possible for the Conservation District to play a vital role in WUI prevention and education.

County Fire Marshal's Offices and Departments of Emergency Management are examples of other agencies whose missions align with the DNR in Community Wildfire Prevention efforts. Partnering with other Federal and State fire managers is important as well. The local fire department is the final key to a successful community wildfire prevention program.

With this multi-agency team, a strong, coordinated message can be delivered to WUI residents. It becomes very apparent to residents, when speaking with one voice, that there really is a fire problem. As understanding comes, residents are more receptive to mitigation strategies and an effective education campaign can begin.

Working With At-Risk Communities

Once the team is assembled and roles and responsibilities have been decided, steps to initiate contact with targeted at-risk communities can begin. There are two ways that contact is initiated between a community at risk and an agency representative. The agency can target a community they have determined is a priority for outreach efforts. In this situation the first and most important step is to get the community to recognize that there is an ignition risk and then take ownership for that risk. This is often the most difficult part of the education process, but is much easier with a multi-agency team. Another way is when the community initiates contact with the agency, seeking guidance in dealing with their fire problem. This situation circumvents the hurdle of getting the community to recognize and take ownership of their fire problem because at that point they have already done so. In either scenario, developing a relationship with, and an understanding of, the community is crucial to determining how to move forward in the process.

Initial stages of developing a relationship with a target community require an effort on the agency's part to understand the demographics of that community. This includes such factors as community size, community governance, resident lifestyles and any other characteristics of the community that play into its' abilities to respond to a wildfire issue. For example, a community that has well established governance may be able to enforce a covenant that requires fire resistant roofing materials on new construction or any other Firewise type of practice; whereas a community without well established governance may not be able to enforce such a rule, they may only be able to suggest it. In cases like this, the agency representative would want to tailor outreach approaches in the community to reflect these concerns. Understanding the community and making the approach specific to that community will allow for a more successful result.

Community Leadership

Another important aspect of developing a relationship with a community is to identify a "community spark plug." This term refers to a member, or members, of the community who has taken on a leadership role or has the most interest and/or concern for the matter. The role the community spark plug fills is crucial to the dissemination of information in the community. This person is the front line contact for agency representatives to communicate with a community. They are an integral component of all WUI prevention programs. They could, for example, be the person who gets permission from the community board for the wildfire experts to do a presentation for the community. Having a member of the community take personal responsibility to bring forward the message and draw in other community members opens the door for further outreach opportunities. In a successful model, there will always be an individual or group of people who will emerge to fill this role.

The Workshop

In order to reach the community as a whole and disseminate information, it is best to host some sort of informational meeting or workshop (Figure 4). Whether the community solicits an agency for a presentation or vice versa, it is most effective to bring the presentation to the audience. Including the presentation as part of some other event that's already scheduled will be more effective because the audience is already there. For example, scheduling a presentation as part of a regularly attended board meeting won't require any extra time of the community members.

No matter what you call your meeting or workshop, there are some important aspects to consider. First, the community should be approached by a team of experts which should include but aren't limited to the local fire district, any wildfire and/or forestry experts that have jurisdiction in the area, and a county fire marshal or warden. A team of experts can provide informational presentations of all aspects of wildfire and can deliver a more powerful message than just one person representing one agency. This also allows for shared responsibility in communicating information to the community and allows for use of a wider range of resources. Even though the experts hosting the meeting may be federal or state representatives, the focus of the presentation should be local.

Using materials available at the Firewise website, a tailor-made presentation can be easily created. At a minimum, the workshop should address the community fire problem, information on what makes homes burn (structural ignitability) and information on mitigation strategies in the Home Ignition

Sixty-five Shelter Bay residents gathered at the Clubhouse for a Firewise presentation on ways homeowners can lower the risk of wildfire damage to their properties. The Skagit Conservation District and the Washington State Department of Natural Resources provided the presentation.

Figure 4—Mini-Firewise Workshop.

Zone (the home and it's immediate surroundings). With this basic toolbox, property owners can, if they choose, begin to make an impact where the impact is needed, at the home. If the workshop can convince property owners that they can greatly reduce their homes potential ignitability, then we have begun the necessary paradigm shift. If property owners in the community begin to manage their home ignition zones and reduce structural ignitability then the community is well on its way to a better outcome when a wildfire does occur.

A good way to get the community to respond to a presentation and initiate follow-up contact is to offer free technical assistance. One way to do this is to offer home assessments where all homeowners that are interested receive individual attention and expert advice on their home ignition risk. Making it easy for the community to access these resources will result in a more positive and successful response. After the workshop, an introduction to the Firewise Communities/USA program can provide the process and motivation for a community to become firewise.

A Collaborative Approach to Community Wildfire Hazard Reduction: Shelter Bay Community Case Study

The community of Shelter Bay is located in western Washington, on Fidalgo Island in western Skagit County, just outside the small town of La Conner (Figure 5). Fidalgo Island was identified by the Washington State Department of Natural Resources as a high-risk area for wildfire due to various physical characteristics of the landscape and the proximity of homes to the wildlands. The community consists of just over 900 lots, as well as greenbelt tracts, community beaches, and recreational areas (Figures 6 & 7). Shelter Bay homes

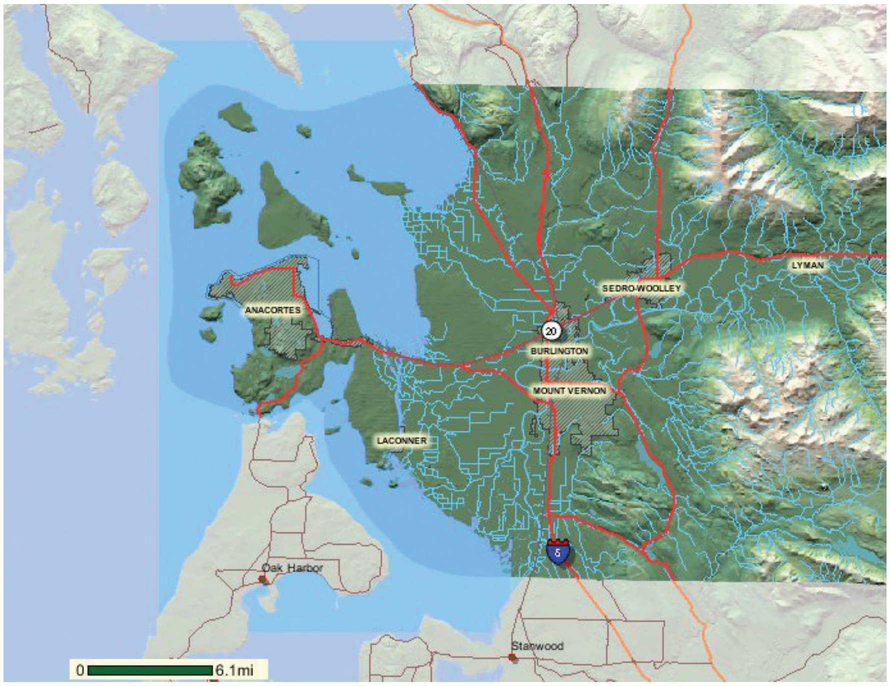

Figure 5—Shelter Bay is located just outside La Conner, WA.

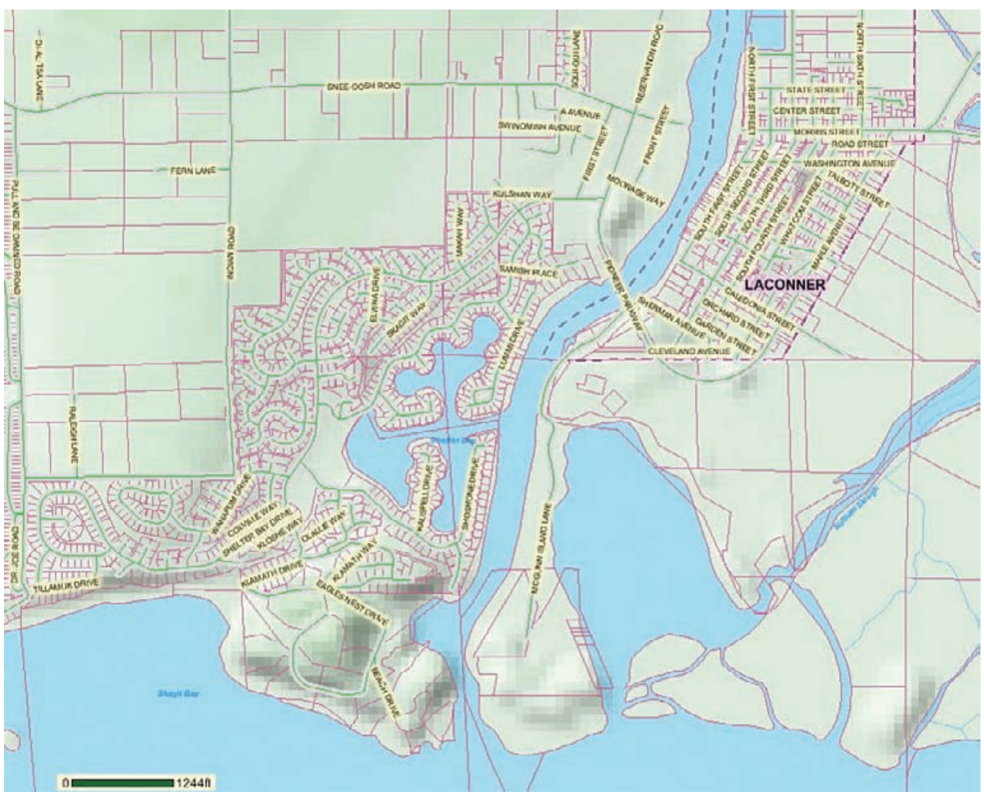

Figure 6—Shelter Bay Parcels.

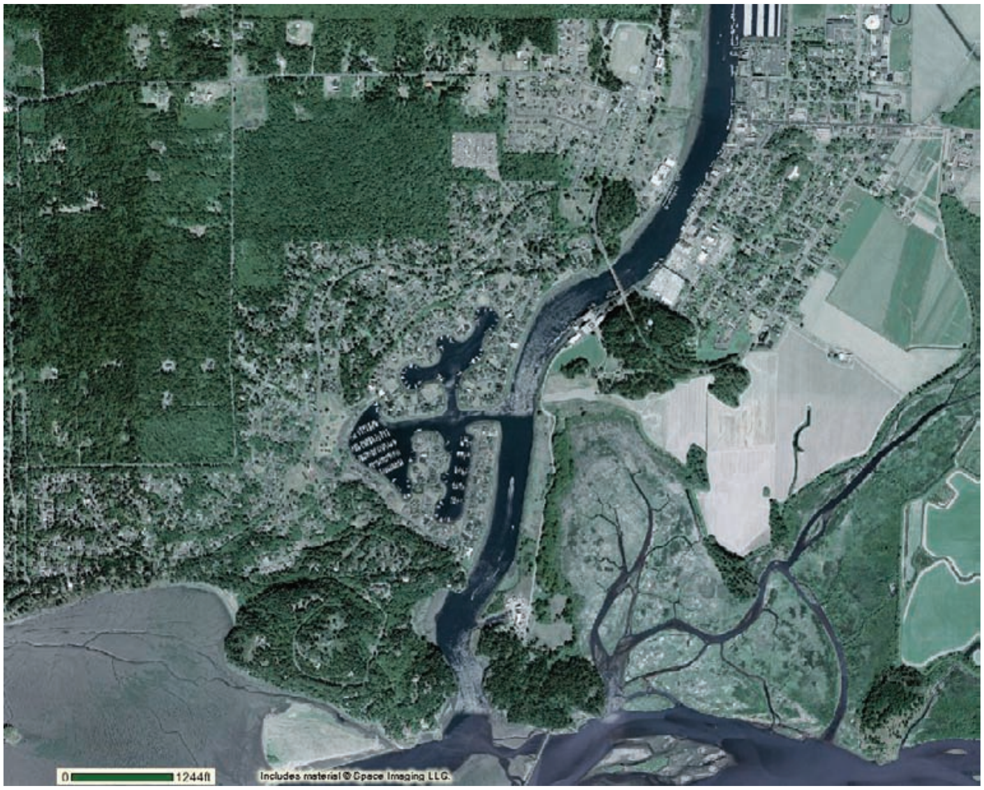

Figure 7—Shelter Bay Aerial Photo.

and streets wind through a maze of steep and hilly topography. Interspersed throughout the homesites are varying acreages of designated greenbelt. These greenbelts make up approximately ¼ of the community's acreage. The greenbelts vary in their fuel models and range from grass and dense brush to heavy timber. Enough ladder fuels are present in the greenbelts to cause single-tree and group-tree torching that could result in ember showers on adjacent homes. Shelter Bay Community has well established governance that allows the management of community issues through the use of standing committees. For example, the greenbelt committee deals with management issues in the greenbelt such as views, pruning, thinning and tree topping. There are building and lot committees that handle issues with building and construction covenants, rights, and restrictions. When the Firewise committee was approved, it was appropriate that it become an ad hoc committee to provide advice to and interface with other committees in the community. The Firewise Committee is dedicated to reducing the ignition potential and increasing awareness of WUI issues in the community.

They contacted the wildfire experts in the region, including the Skagit Conservation District (SCD), the Washington State Department of Natural Resources (WADNR), and the Skagit County Department of Emergency Management/Fire Marshal's Office (DEM, FMO). Together these agencies are responsible for promoting the Firewise program throughout the county and the region. The stakeholders also included the Shelter Bay Community at large, the local fire chief and a Skagit County Commissioner. Once the community made contacts, the multi-agency team was able to guide the community in their actions.

It started with a Firewise presentation in conjunction with an already scheduled information session to answer questions about the ongoing use of the goats for greenbelt cleanup. The purpose of the presentation was to educate the community on the wildfire hazard and emphasize personal responsibility and defensible space regarding protection of private property. This presentation was developed and lead by SCD and DNR. Also present were the Skagit County Fire Marshal, the district fire chief, and one of the Skagit County Commissioners.

Each representative had a specific role and perspective to offer the community as well as specific resources for wildfire safety. The SCD was able to effectively communicate the idea of personal responsibility and mitigation strategies for around the home. The SCD took on the responsibility of being the direct line of communication to the community as a whole, as well as individual landowners in offering them technical assistance and free home assessments. The DNR was able to offer expertise in fire behavior and communicating the risk situation. The fire chief provided perspective on local fire fighting resources and current fire fighter capabilities. The fire marshal was able to provide a regulatory perspective, building code information and discuss outdoor burning regulations. The County Commissioner was there to offer support of the program, recognizing the importance of our/their efforts and provide encouragement. This approach not only allowed for all aspects of fire safety to be addressed in an initial presentation, but also as the community moves forward with their Firewise mitigation measures, this multi-agency team can offer a comprehensive set of resources to aid the community. Sixty-five community members attended the presentation. This collaboration continued and will continue to be an effective way of guiding the Shelter Bay Community through the Firewise process.

Once the relationships between agency representatives and the community were established, the multi-agency team was able to assist the community with moving forward in their pursuit of Firewise actions. This began with a Community Hazard Assessment for the Shelter Bay Community. The hazard assessment addressed the various aspects of wildfire hazards throughout the community on a community-wide scale. These hazards were analyzed and addressed with a final recommendation of creating an action plan to establish mitigation measures.

From here, the residents that had become active and interested in the Firewise process formed an ad-hoc Firewise Committee of 11 members in order to follow through with an action plan and pursue projects, as well as national recognition through the Firewise Communities/USA program. As the community had already completed a major project in reducing the fuels in their greenbelts, they were already well on their way to meeting the requirements of becoming a recognized Firewise Community. Their second project (currently under way) is a Firewise demonstration landscape. The community picked one highly visible area of greenbelt as their project site. Between the Conservation District and the WADNR, the site was evaluated and a planting design was created that met the objectives of the community: Firewise, wildlife habitat enhancement. Currently a final plan is being developed that addresses these goals and objectives as well as the planting design and plant list, and provides resources on such aspects of the project as proper planting methods and proper pruning techniques etc. Once this project is established, the community hopes to use it as an education tool. They also hope to pursue further Firewise planting projects within the other greenbelt areas.

As these ideas developed, so did the need for additional community organization. With the guidance of the Conservation District and the WADNR, the Firewise Committee is currently working on developing a comprehensive five-year action plan for their community. This action plan will be included as part of the community's comprehensive emergency management plan. Also, as part of the requirements of being a Firewise Community, they are planning a Firewise education event at the end of April where they will showcase their Firewise demonstration planting area and invite the community to celebrate their Firewise Communities/USA recognition status.

As the Shelter Bay community continues to build upon their first years' accomplishments, momentum continues to build as well. Their most recent accomplishment was a covenant change to prohibit the use of cedar shake roofs on all new construction (& re-roofing projects where greater than 50% of the roof is replaced), opting to support more fire resistant roofing materials to be used. This represents a major accomplishment and a significant understanding of the wildland fire problem in the community. As the committee finalizes the 5-year action plan, it is assured that their success will continue.

Shelter Bay Community was recognized as a Firewise Community/USA for the year 2005. Requirements of 2006 recognition will be met by May 2006.

Firewise Communities/USA

The Firewise Communities/USA is a recognition program designed and maintained to give communities the maximum flexibility in creating outcome based site specific solutions to identified wildfire hazards. Briefly the program involves:

- Enlist a wildland/urban interface specialist to complete a community assessment and assist with the creation of a plan that identifies achievable solutions to be implemented by the community.
- Form a Firewise Committee which promotes and maintains the FWC/USA program and monitors and reports progress.
- Observe a Firewise Day annually that is dedicated to a community Firewise project or education event.
- Invest a minimum of $2.00 per capita on community Firewise Projects
- Submit an application that documents compliance with recognition requirements and renew annually to maintain status.

It provides community members with the knowledge necessary to maintain an acceptable level of fire readiness, while ensuring firefighter safety during a wildland fire emergency. The program draws on a community's spirit, its resolve, and its willingness to take responsibility for its ignition potential.

By implementing the FWC/USA as described, it truly becomes a self-perpetuating program. All of the training, education and tools for a community to take action are provided. Ongoing support by the multi-agency team is needed, but becomes less and less time consuming the more a community learns. Support activities will always be necessary, but the community leadership is always at the forefront. The local fire department needs to stay engaged as the resident expert on emergency management, but this is a good relationship to foster as it provides a solid link between the community and Emergency Management Services.

Conclusion

Wildfire incidents do not have to be large, nor span many days to be catastrophic. Losing just one home in the Wildland Urban Interface becomes a significant, life changing problem for those involved. It has been shown that with proper preparation, a home does not have to become fuel for a wildland fire. Reducing structural ignitability by focusing on the home ignition zone is the easiest way for homeowners to mitigate wildfire hazards in their community. Every home that has been prepared in this way has a much greater chance of surviving a wildland fire incident. After all, a home that doesn't ignite is a home that doesn't burn.

The NW Region of Washington State Department of Natural Resources, in keeping with our agency mission and mandate, embarked on a collaborative WUI wildfire education campaign that has been very successful. After using national standards to identify at-risk communities, the FWC/USA program was utilized to engage community groups. It is a model that allows agency interaction with the greatest number of communities at a time. With proper preparation and a collaborative environment, fire management agencies can greatly impact communities in the WUI, thereby creating behavioral changes designed to mitigate losses in communites due to a catastrophic wildland fire event. NW Region has been a leader in implementation of FWC/USA in Washington state and has contributed to Washington's 2005 #2 ranking in the nation of recognized communities (Figure 8).

Success has been largely due to excellent inter-governmental and inter-agency relationships, a shared vision and the desire to succeed. The collaborative environment has been achieved through hard work and committment of all parties and continues to be a model that other areas of the state and the nation are striving to emulate.

Figure 8—Firewise Communities/USA Sites.

Organizational Characteristics that Contribute to Success in Engaging the Public to Accomplish Fuels Management at the Wilderness/Non-Wilderness Interface

Katie Knotek[1] and Alan E. Watson[2]

Abstract—*In the fall of 2003, the Rocky Mountain Ranger District of the Lewis and Clark National Forest initiated a multi-year, large-scale prescribed burn in the Scapegoat Wilderness. The objectives of this burn were to make the non-wilderness side of the wilderness boundary more defensible from wildfire and to establish conditions that will allow fire to play a more natural role within the wilderness in the future. Using this prescribed burn as a case study, qualitative research was conducted in 2005 to understand the local ranger district's public outreach efforts and its subsequent influence on public attitudes towards the burn. A series of in-depth interviews with agency personnel involved in the burn, and representatives from local communities who were aware of and/or participated in public outreach efforts for the burn, were the primary sources of data for this research. A framework of mindfulness processes exhibited by high reliability organizations was used in analysis for identification and understanding of organizational characteristics that contribute to success in engaging the public in Forest Service efforts to treat hazardous fuels and manage risk from wildfire. As a case study, the methods and results provide a means of comparison to additional cases on other management units.*

Introduction

Fire suppression policy on public lands over the past century has resulted in hazardous accumulations of fuel in forest and grass lands. In many places, fire is a naturally occurring process, and fire exclusion has spurred greater incidents of large-scale, uncharacteristic wildfire impacting both ecological and social values across the wilderness/non-wilderness interface. The urgency, complexity, and oftentimes contentious nature of fire and fuels management operations have signaled the need for increased public outreach (public information and involvement efforts) by wildland fire management organizations. The public must be informed about and engaged in decisions concerning appropriate fuels management techniques to reduce the risk of catastrophic fire and restore the health of our wild lands (HFI 2002; USDA/USDI 2000).

Along the Rocky Mountain Front in northwestern Montana, public land protected under federal designation as the Bob Marshall Wilderness Complex (includes the Bob Marshall, Scapegoat, and Great Bear Wilderness areas) interfaces with public and private lands comprising roadless areas, ranches, outfitter/guide operations, recreational residences and other human uses. There is a rich history of naturally occurring fires in the Bob Marshall Wilderness Complex, although years of fire suppression has reduced the number of acres burned by these fires and created conditions for uncharacteristic fire behavior. In an effort to allow fire to play a more natural role within the

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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wilderness and to make the non-wilderness side of the wilderness boundary more defensible from wildfire, the Rocky Mountain Ranger District of the Lewis and Clark National Forest initiated, in the fall of 2003, the first phase of a multi-year prescribed burn inside and along the boundary of the Scapegoat Wilderness. The complex ownership and human uses surrounding this area exemplifies the importance and need for mindful management of public outreach concerning such a large-scale fuels management project.

In their book, *Managing the Unexpected: Assuring High Performance in an Age of Complexity*, Weick and Sutcliffe (2001) outline a theory of managing high-risk operations with mindfulness. Their research on managing mindfully draws upon the concept of high reliability organizations (HROs). They suggest businesses or other organizations "benchmark on the experts in reliability" in managing for unexpected events, offering "techniques that are worth copying because they ensure faster learning, more alert sensing, and better relationships with customers" (p. xv).

It may be appropriate to apply concepts of high reliability to an organization's management of public outreach, because managing the interaction between an organization and the public also involves managing the unexpected. Many unexpected events can occur when managing public outreach: contentious public meetings; withdrawal of key publics from participation; harassment of personnel within the organization; negative editorial or opinion pieces in reference to the organization; and litigation. To reduce the likelihood of such events occurring, an organization needs some framework to guide their management of public outreach.

Using the South Fork of the Sun River Prescribed Burn as a case study, we applied Weick and Sutcliffe's theory on managing with mindfulness to the USDA Forest Service's (USFS) management of public outreach for the prescribed burn. A framework of mindfulness processes was used as a guide to document and analyze the organization's public outreach during the planning and implementation stages of the prescribed burn and how it influenced local community attitudes. This research can increase understanding of organizational characteristics that contribute to success or failure in engaging the public to accomplish fuels management at the wilderness/non-wilderness interface.

Research Framework

Research on high reliability indicates there are five central processes that produce mindful behavior within high-risk organizations, including: 1) recognizing potential barriers to accomplishment of management objectives (preoccupation with failure), 2) resisting simplification of information or interpretations (reluctance to simplify interpretations), 3) ensuring situational awareness of events as they occur (sensitivity to operations), 4) being prepared to respond to and recover from unexpected events (commitment to resilience), and 5) calling upon appropriate expertise in decision-making and management efforts (deference to expertise) (adapted from Weick and Sutcliffe 2001). These five attributes are believed to be the hallmarks of HROs and managing with mindfulness.

Research on managing with mindfulness has typically focused on interaction within an organization (i.e., wildland firefighting, nuclear aircraft carriers, air traffic control systems, and emergency medical treatment) without necessarily considering interaction that occurs external to an organization such as public outreach. It is important to understand how mindfulness can be applied to the management of external, as well as internal interaction, because it is often this interaction that people use to evaluate and respond to a particular organization and their management capabilities. Using a framework of mindfulness processes to analyze the USFS's management of external interaction (public outreach) should provide new insight into the value of managing with mindfulness.

Methods

A case study research design and qualitative methods (in-depth interviews) were used to facilitate the research and provide a deeper understanding of the contribution of the USFS's mindfulness in managing public outreach for the South Fork of the Sun River Prescribed Burn. Interviews were conducted with a sample of agency representatives on the Lewis and Clark National Forest and non-agency public representatives from local communities surrounding the Rocky Mountain Ranger District.

Interviews were guided by a pre-arranged set of themes and suggested lead-in questions, using a semi-structured interview guide, but they did not follow a fixed question format (Patterson and Williams 2002). All interviews were tape-recorded in their entirety, transcribed verbatim, and kept anonymous. Analysis began, following completion of the transcriptions. Each transcript was edited by simultaneously listening to the associated tape-recording and reading the text. The final edited transcripts were the empirical data that were analyzed using a qualitative data analysis software program, QSR Nvivo version 2.0.

In a case study research design, a previously developed theory is used as a template for analysis of the study findings (Yin 1989). A framework of mindfulness processes was used to guide analysis of agency and public representatives' perceptions of public outreach for the prescribed burn. Analysis emphasized objective description and personal interpretation by the researcher with a focus on organizing data to best document the phenomenon of interest within the specific case (Denzin and Lincoln 1998).

Results

A total of 14 agency representatives (both past and present) from the Lewis and Clark National Forest were individually interviewed. Interviews were conducted with personnel who had, in some way, been involved with the planning and implementation (including public outreach) of the South Fork of the Sun River Prescribed Burn. In order to get a diversity of perspectives, the intent was to conduct interviews with personnel representing different functional positions within the agency. Thus, interviews were conducted with personnel in the following positions: decision-making (line officers); planning; public affairs; information; fire; recreation; and wilderness.

A total of 24 non-agency public representatives from local communities surrounding the Rocky Mountain Ranger District were interviewed. Interviews were conducted with people who were aware of and/or participated in public outreach activities (i.e., attended public meetings, submitted public comment, read newspaper articles, received informational mailings, etc.) for the prescribed burn. To obtain a diversity of perspectives, interviews were conducted with people with varied social resources and interests. Thus, interviews were conducted with private landowners, outfitter/guides, representatives from cooperating city, county and state organizations, representatives from non-governmental organizations, media personnel, local recreationists, and recreation residence owners.

The database of interview transcripts serves as empirical evidence for claims or conclusions drawn in this Results section, which contains excerpts of raw text from interviews that correspond to specific subject headings. Detailed below are a select set of these interview excerpts, which serve as examples of public outreach efforts by the agency that seemed to be indicative of the five central processes of mindfulness.

Recognizing Barriers to Accomplishment of Management Objectives

Being consistently mindful of potential barriers to accomplishing management objectives, although suggestive of a negative mindset, is actually a positive behavior that can benefit an organization. Being mindful of potential operational failures or mistakes makes it possible for an organization to identify and mitigate small barriers that, if ignored, could complicate or jeopardize their objectives (adapted from Weick and Sutcliffe 2001). Perceptions of both agency and public representatives indicated personnel on the Lewis and Clark National Forest demonstrated this mindfulness process in managing public outreach during the planning and implementation stages of the prescribed burn.

Agency representatives felt that agency personnel made personal one-on-one contacts with landowners who had the greatest potential to be impacted by the prescribed burn should it escape. These landowners happened to also be outfitters in the local area preparing their camps for the upcoming hunting season. The agency's decision to contact these members of the public was symbolic of its ability to manage mindfully, for the agency saw the potential for damage to private property and human resources, and the possible barrier it could create to accomplishment of management objectives before an escaped burn occurred:

> **Interviewer**: *And how come it was those two resorts that you went to?*
>
> **Agency Representative**: *Because they are the ones in the vicinity that would be the ones that would be the most rapidly impacted if something went wrong with that fire … it was in the early fall, and so both of those resorts have backcountry camps and they were going in and out of their camps at that time, getting them ready for the hunting season. So they had even more stake in the whole scenario, because they had people actually in the backcountry hauling hay or doing that kind of thing, and so we needed to coordinate with them on those types of things so that we made sure that if their packers were on their way out we weren't going to have a problem.*

There was also evidence from perceptions of public representatives that agency personnel demonstrated an awareness of potential barriers to its management objectives by engaging the public early on in the planning of the prescribed burn. This early outreach, which included contact with the local media, allowed the public to be informed about project details from the very beginning and reduced the likelihood of them being "blindsided" by the agency's intentions:

> **Public Representative**: *But from my perspective, I thought what they did worked well, partly because they did it in advance. A lot of times people say, and this was a big criticism during the Canyon Creek Fire, we just didn't know what was coming. We just didn't really, we underestimated. We didn't know. You didn't tell us, etc. … I don't think anybody could fault them. Like you said, this started in '97. It happened in 2003. That's a long time and a lot of comment before the actual trees started to burn. So I think they did a good job … I don't know what else they could have done to get information out to people. And I think Augusta's a relatively small community, I think they probably had close to saturation knowledge of what was going on.*

Resisting Simplification of Information or Interpretations

In the modern world, success is often achieved when a person simplifies work by focusing on key issues or problems; in contrast, managing with mindfulness means resisting simplification of information or interpretations. When practicing this tenet of mindfulness, organizations intentionally simplify less and seek ways to perceive and discern more about their management situation, creating a more holistic, detailed understanding of the context they are working within (adapted from Weick and Sutcliffe 2001). It was evident from perceptions of both agency and public representatives that, during the planning and implementation stages of the prescribed burn, personnel on the Lewis and Clark National Forest demonstrated this mindfulness process in managing public outreach.

There was a perception among agency representatives that agency personnel made an effort to talk about the known risks of the project rather than glaze over them or hide their significance when interacting with the public. This effort to communicate directly with the public about the risks associated with the prescribed burn seemed to be an indicator of the agency's resistance to simplify information or interpretations related to public outreach. Here's what one agency representative said he or she would do in the future when dealing with similar fuels management projects and outreach to local communities:

> **Agency Representative**: *I'd follow the same model, and I would also be, and I believe we did this this time, I would also be frank about the risks … and by that I mean we have all these checks in process to be as safe as possible. And sometimes things are going to go south on us. And that happens. The fire could get out of our control, and we know that. And put that on the table early on in the process, not in terms of sugar coating. And (the District Ranger) did a good job of that. (The District Ranger) was very real. So, actually that's a good take-home message for other people, other units, other agencies. Sometimes we're not very good about talking about the real risks.*

Perceptions of public representatives indicated the agency resisted simplification of information or interpretations in managing public outreach, also, by addressing public concerns about the Canyon Creek Fire of 1988 (a wildland fire that escaped the Scapegoat Wilderness boundary) and how it related to the prescribed burn. As suggested in the excerpt below, it would have been easy for agency personnel to avoid this issue in order to simplify their communication with the public, but they chose to speak to the issue and to communicate their plans to prevent a similar occurrence:

> **Public Representative**: *… I keep coming back to '88 … clearly an event happened there that the Augusta community got exposed to. And, again, superficially that was something that it would have been easy to shy away from, and (the Fire Management Officer) didn't do that. (The Fire Management Officer) says we want to avoid that. And that's to say (the Fire Management Officer) took that experience, took that event, and presented it to the community saying we're with you, we recognize this is something that's not very fun to go through. It can be devastating to go through. And we think we have an idea to, if not prevent it, then potentially minimize it at the very least. And so with using that circumstance, it would have been easy just to stay away from, just to put a big veneer lacquer around it and just say, uh, that was a bad deal and just never go there again. But they didn't do that. They said let's take that and run with it or let's respond to that. And so bringing in that history, I think, was a good part of it.*

Ensuring Situational Awareness of Events as They Occur

There is a tendency for people to be forward thinking, but mindfulness requires personnel within an organization to display intense focus on what is happening in the present. Organizations that manage with mindfulness focus their attention on the front line of an operation, ensuring situational awareness of events (both planned and unexpected) as they occur. By paying attention to events as they unfold, these organizations are more able to reduce uncertainty and make operational adjustments as needed (adapted from Weick and Sutcliffe 2001). Again, there were perceptions of both agency and public representatives that indicated personnel on the Lewis and Clark National Forest demonstrated this mindfulness process in managing public outreach during the planning and implementation stages of the prescribed burn.

Agency representatives perceived that a big part of the USFS's engagement with the public prior to implementation of the burn was through briefings with key segments of the public, such as county commissioners, the governor's staff, and the media. Sensitivity to the information needs of these publics during the planning process and a willingness to engage in public dialogue about the project are an example of organizational efforts to ensure situational awareness in managing public outreach:

> **Agency Representative**: *The District Ranger was very proactive. I must compliment him on that, because he was very proactive in getting community involvement … he developed a PowerPoint and he went around to various organizations. He talked to his county commissioners. We set up a series of briefings for him. He briefed the governor's staff. He talked to the county commissioners from Lewis and Clark County, which is where Augusta is. He also talked to Teton County commissioners, which is where Choteau is … He talked to TV stations. He did radio call-in interviews with KGPR and the local station that's in Augusta, KMON. That's the station that most people could hear … We've only briefed the governor on two or three issues the whole time that I've been here, and this is one that we thought would be critical in case we did lose it.*

Public representatives perceived several other examples, which suggest agency personnel maintained situational awareness in managing public outreach. The agency's use of press releases and newspaper articles, making documents available for public review, providing informational handouts, and holding public meetings, all seemed to have helped keep the public informed and involved in the planning process and the agency aware of public interest and concern related to the project:

> **Public Representative**: *They were putting out press releases. They had obviously done studies, and they had those documents out for public review. And they had, I want to say that they had information available in the Augusta Information Station if people wanted to come in and get fact sheets on it. They had their personnel available at any time for people to call … They weren't just touching the Choteau Acantha as media, they were also, there were stories being published in the Great Falls Tribune, and I am almost certain that there were stories published in the Helena newspaper, although I didn't ever read any of those. But I think they were trying to reach as many people as they could. Particularly with this project, it seemed to me that they made a really big effort to do a really good job in informing people about what was going on.*

Being Prepared to Respond to and Recover from Unexpected Events

The fourth mindfulness process can be described as being prepared to respond to and recover from unexpected events that occur. Managing with mindfulness means moving beyond a simple anticipation of unexpected events to a greater focus on how, once an unexpected event occurs, an organization and its employees can respond to and/or recover from the event. This resiliency enables organizations to function responsively and facilitate management even when faced with operational obstacles (adapted from Weick and Sutcliffe 2001). In interviews with agency representatives, several examples were identified where it seemed as though personnel on the Lewis and Clark National Forest were prepared to respond to and recover from unexpected events when managing public outreach during the planning and implementation stages of the burn. These examples were easily identifiable in the analysis of the data because agency representatives were giving firsthand accounts of being prepared to respond to and recover from unexpected events that occurred.

For example, when the agency decided it was time to implement the prescribed burn, they realized that the Public Affairs Officer for the Forest was scheduled to be on a business trip to Washington, DC. As perceived by agency representatives, knowing that this position was crucial to public outreach during the burn, the agency seemed prepared to respond to this unexpected event by finding a qualified replacement to fill this position, an employee within the region with experience in both public relations and fire:

> **Agency Representative**: *And then when it came actually time to burn it, it was so frustrating because we didn't think we were going to have a window in the fall. And when the burning window opened up it was the same week we had scheduled, they were going to burn on whatever day they ignited the burn, I don't remember if it was Monday or Tuesday, but the Forest*

> *Supervisor and the Forest Planner and (the Forest Public Affairs Officer) were flying out to Washington, DC, because we had briefings with our senators and congressmen … so we had to call in other people. And (an employee) from the Regional Office came over and actually took the media out, because we had planned field trips for the media to be on a lookout to see the actual ignition of the burn and to watch the progress of it the first day.*

In the analysis of data from interviews with public representatives, examples in which the agency appeared prepared to respond to and recover from unexpected events were not as easily identifiable. Thus, there were no obvious interview excerpts from public representatives that can be used to demonstrate that the agency was prepared to respond to and recover from unexpected events when managing public outreach during the planning and implementation of the burn. There are a couple of possible explanations for this occurrence.

First, it might be possible that the public didn't perceive the unexpected events the agency was challenged with during planning and implementation and their resiliency in responding to them. This may be especially true in this case where several unexpected events occurred and were dealt with internally rather than publicly (i.e., having to fill in for the Public Affairs Officer while in Washington, DC). Also, the fact that agency personnel *were* resilient in responding to these unexpected events, may itself have made it more difficult for the public to perceive such behavior.

Calling Upon Expertise in Decision-Making and Management Efforts

The final mindfulness process is calling upon appropriate expertise in decision-making and management efforts. Unlike a rigid hierarchy where decisions are imposed from the top down, when incorporating mindfulness into decisions and operations, personnel with the most expertise, regardless of their position within the organization, are utilized. This does not preclude the fact that certain decisions must be made and operations led by personnel in specific positions (adapted from Weick and Sutcliffe 2001). As indicated from perceptions of both agency and public representatives, it seemed evident that personnel on the Lewis and Clark National Forest often called upon appropriate expertise in decision-making and management efforts related to public outreach for the prescribed burn.

One key indicator that the agency called upon appropriate expertise in decision-making and management efforts was the fact that local agency personnel were charged with the planning and implementation of the burn, including public outreach. Even though an Incident Management Team was brought in to assist in burn operations, agency representatives perceived that local personnel on the District were largely in charge of leading the multi-faceted operation:

> **Agency Representative**: … *we identified that at the beginning that we're going to help reduce risk by having a (Incident Management) team involved. But one of the major points, debates about that with the public was that we want you guys involved. You're not going to hand this over to a team, right? Oh, no, no. You know, our Burn Boss was still (a District employee), who's right here out of Choteau. Our ignition specialist in the air was*

> *(a District employee), our FMO (Fire Management Officer). Our ground ignition specialist was (a District employee), our AFMO (Assistant Fire Management Officer). And then (the District Ranger would) be there as the line officer making the calls for the Forest Supervisor in terms of whether we would ignite that day or not. And (he'd) be the one dealing with the people, heading up public meetings, talking to the media …*

It was also evident from public representatives that the agency called upon appropriate expertise (in this case local expertise) in their management efforts, including the Fire Management Officer, District Ranger, and Burn Boss, who are all employees of the Rocky Mountain Ranger District and members of the local communities, Augusta and Choteau. Public representatives, similar to agency representatives, talked about the importance of the agency utilizing the local expertise of these individuals, people well known in the local communities, in planning and implementing this specific project:

> **Public Representative**: *I think that they demonstrated to people that the local Forest Service personnel, like (the Fire Management Officer), (the Burn Boss), (the District Ranger), that they were local faces that were well-known that were going to be connected to this burn and that they were very credible and responsible and accountable. And I think people sensed that, that there was going to be an enormous amount of local accountability for this burn. And I think because of that some people probably felt that their concerns were expressed or reduced because it wasn't going to be some nameless face for a federal project. It was going to be the responsibility of people that you could look in the eye and talk with … You're my neighbor and I know you.*

Perceptions of Changes in Community Attitudes Towards the Burn

Through analysis, agency and public perceptions of changes in local community attitudes towards the burn were identified, as well as perceptions about whether the agency's management of public outreach had influenced these attitudes. Public representatives had mixed thoughts on whether or not local community attitudes had changed during the project. Some thought negative attitudes among local community members hadn't changed and never would change. There was also a perception that, for the most part, community members had become ambivalent towards the burn, knowing the agency was actively moving forward with the project. There was however, some evidence from public representatives that attitudes *were* influenced during project planning and implementation, in particular becoming more positive or accepting and supportive of the burn.

Agency representatives also had mixed thoughts on whether or not community attitudes had changed. Similar to public representatives, some agency representatives thought community attitudes toward the burn had become more positive, while others thought there had been no change. For those who thought community attitudes had changed, there was some indication that the agency's evident mindfulness in managing public outreach had influenced these attitudes. For example, there was some belief that the agency's openness in public meetings and one-on-one contacts, demonstrating situational awareness in managing public outreach, had an influence on community attitudes towards the burn. Thus, agency representatives provided additional evidence of some attitude change during the project that can be attributed, in part, to the agency's mindful management of public outreach.

Conclusions

This research offers an example of how a framework of mindfulness processes can be appropriately used to describe an organization's management of public outreach. The use of qualitative methods (in-depth interviews) allowed both agency and public representatives to openly talk about the agency's public outreach during the planning and implementation stages of the prescribed burn. Agency and public representatives discussed at length such things as public meetings, newspaper articles, one-on-one contacts with private landowners, briefing to key publics (county commissioners, governor's staff, media), and other such efforts detailed in the Results section, utilized by the agency in public outreach. Through analysis of the interview transcripts it was possible to not only identify but to also categorize and describe these outreach efforts by the agency as being indicative of the five central mindfulness processes (i.e., recognizing potential barriers to accomplishment of management objectives, resisting simplification of information or interpretations, ensuring situational awareness of events as they occur, responding to and recovering from unexpected events, and calling upon appropriate expertise in decision-making and management efforts). There was only one instance (public perceptions of the agency's ability to respond to and recover from unexpected events) where this was not possible.

Because use of the framework made it possible to analyze agency and public perceptions concerning the USFS's management of public outreach for the South Fork of the Sun River Prescribed Burn, this application of Weick and Sutcliffe's management theory seems to be effective at least to guide analysis. The USFS itself will have to determine the usefulness and effectiveness of this theoretical application as a management tool.

It is possible that the USFS and other wildland fire management organizations could use this framework of mindfulness processes as sort of a "checklist" before, during, and following public outreach to evaluate their management efforts. They could use the framework as a brainstorming tool when planning public outreach efforts. For example, they might individually, or as a group, proactively think about how they might be mindful of potential barriers to accomplishment of their management objectives, or how they might help to ensure situational awareness in managing public outreach. They could use the framework while they are actively conducting public outreach activities to incrementally evaluate individual and group behavior as it relates to the management of public outreach. For example, they might critique their efforts to resist simplification of information or interpretations related to public outreach, or their ability to respond to and recover from unexpected events that have or might occur. They could also use the framework following public outreach efforts to evaluate and learn from their efforts in a fashion similar to an After-Action Review. For example, they might discuss examples of where it seemed they had been exhibiting mindfulness processes, or examples of where it seemed they hadn't exhibited mindfulness processes and could improve upon their efforts in the future.

Finally, in using the framework of mindfulness processes to facilitate group discussion about public outreach efforts, it might be possible to identify where contrasting perceptions about individual or group behavior exist among personnel within a wildland fire management organization. Such uses of this framework of mindfulness processes would likely help to improve understanding and practice of organizational characteristics that contribute to success in engaging the public to accomplish fuels management at the wilderness/non-wilderness interface.

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Communicating the Wildland Fire Message: Influences on Knowledge and Attitude Change in Two Case Studies

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***Abstract**—Current wildland fire policy calls for citizen involvement in planning and management. To be effective in their efforts to engage outside stakeholders, resource professionals need to understand citizens' understanding and attitudes toward current practices as well as how to best communicate about proposed actions. A variety of outreach methods have been used to communicate the rationale behind fuel reduction techniques. Limited evaluation of these efforts has occurred resulting in a lack of information available to guide the outreach decisions of agency personnel. This paper evaluates the effects of two basic communication strategies—unidirectional information exchange and interactive approaches—on participant understanding and attitudes. Data was collected in two phases; first, citizens completed a survey on-site prior to outreach participation, then, a follow-up questionnaire was mailed to each participant two weeks following initial contact. Resulting data enable assessment of the influence of outreach activities on participant understanding and attitudes and evaluation of factors that contributed to program success. Findings suggest interactive outreach methods may be more effective at influencing knowledge. However, unidirectional and interactive approaches influenced participants with low initial understanding of fire management or less supportive attitudes toward fuel practices. Results also showed a strong association between knowledge and attitude change suggesting fire professionals have a real opportunity to help shape public perceptions about appropriate management actions.*

Introduction

Recent federal initiatives such as the National Fire Plan and Healthy Forests Restoration Act require a new approach to fire management. These policies emphasize two primary themes. First, there is an increased focus on using fuel reduction activities (such as prescribed fire or mechanized thinning) prior to a fire event to decrease the vegetation available to burn as fuel if a fire occurs. Second, both initiatives call for, and in some cases require, collaboration with stakeholders (including local citizens) in planning and prioritizing fire and fuel management activities. Natural resource communicators, including federal and state agency personnel, county extension agents, and interpretive staff, play an essential role in accomplishing these objectives.

Substantial research over the last several years has indicated the necessary role of social acceptability in resource management activities (see review in Shindler and others 2002) and specifically in fuel reduction efforts (Shindler and Toman 2003, Winter and others 2002). Accordingly, many management units are moving towards greater citizen involvement in the development and implementation of fire and fuel management strategies. To be successful,

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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resource professionals need to understand citizens' knowledge of and attitudes toward current practices as well as how to best communicate with local communities about proposed actions. Outreach activities, as the primary interface between resource agencies and citizens, play an essential role in these efforts (Bright and Manfredo 1997).

In recent years, resource agencies have used a variety of methods to communicate the rationale behind fuel reduction techniques. Approaches have ranged from traditional text and graphic displays, such as brochures and exhibits, to more targeted activities, including demonstration areas and guided field tours. To date, limited evaluation of these efforts has occurred resulting in a lack of available information to guide the outreach decisions of resource professionals. The purpose of this paper is to fill this research gap by exploring the influence of two basic communication strategies—unidirectional information exchange and interactive approaches—on participant understanding and attitudes.

Related Research

Research on the social aspects of fire management has increased steadily in recent years. A review of the literature suggests a number of findings relevant to this study. First, research over nearly three decades has identified a positive association between fire-related knowledge and treatment support among citizens (e.g., Stankey 1976, Carpenter and others 1986, Shindler and Toman 2003). This finding has prompted researchers to call for increasing fire-related outreach activities to raise public awareness and support (e.g., McCool and Stankey 1986, Carpenter and others 1986). However, public acceptance is a complex issue and is not based solely upon technical understanding. Support for fire management is particularly influenced by the interactions between citizens and resource managers over time and reflects citizen confidence in agencies to effectively manage risk as well as provide an adequate planning process that includes a role for the public (Winter and others 2002, Shindler and Toman 2003). Ultimately, understanding is a strong precursor to support, but not sufficient on its own.

Second, public understanding and acceptance of fuel treatments have increased over time. Early research found that participants generally overestimated the negative impacts of fire while underestimating fire's beneficial effects (Stankey 1976). Not surprisingly, a majority preferred complete fire suppression. Subsequent research has consistently identified an upward trend in citizen understanding of key fire management principles and acceptance of manager-ignited prescribed fire (e.g., Carpenter and others 1986) as well as thinning for fuel reduction (Loomis and others 2001, Shindler and Toman 2003). However, Manfredo and others (1990) cautioned that the identified increases may only be occurring in particular geographic regions, specifically those areas most affected by fire, and may not be representative of general attitudes. Brunson and Shindler (2004) also found variations in understanding and support among locations and cautioned against implementing "one-size-fits-all" management or communication approaches.

Third, and particularly relevant to our study, fire-related outreach activities can positively influence participant knowledge and, in some cases, attitudes. Prior studies have evaluated response change following exposure to various communication activities (brochures, slide shows, workshops, etc.). Such activities can be classified as interactive or unidirectional based on the type of outreach experience they provide. Interactive activities (including guided visits to demonstration sites and agency workshops) allow for two-way communication with resource professionals while unidirectional methods (such as brochures, public service announcements, and static displays) consist of a one-way flow of information. Toman and others (2006) suggest that interactive programs may be more consistent with principles of adult learning by relating information to the local context, incorporating citizen experiences and concerns, and providing greater opportunities to develop personal relationships between citizens and agency personnel. This project provides an opportunity to further test these ideas.

A review of prior research suggests that both unidirectional and interactive activities have achieved some success. For example, brochures have been effective at increasing knowledge (Taylor and Daniel 1984) and leading to more supportive attitudes (Loomis and others 2001). Nielsen and Buchanan (1986) evaluated a unidirectional (slide show) and an interactive activity (interpreter guided walk); both of which resulted in higher knowledge and attitude scores among participants. Marynowski and Jacobson (1999) report outcomes for an ecosystem management education program that targeted fire ecology as one of four content areas. The program consisted of various unidirectional communication methods including posters, brochures, youth activity booklets, and multiple news releases. These educational materials significantly increased knowledge of fire ecology, but did not result in a corresponding increase in support for fire management activities.

Recent research has increasingly emphasized interactive activities. For example, Parkinson and others (2003) evaluated the influence of workshops on attitudes and knowledge. The workshops consisted of hands-on activities adapted from FireWorks, an education program originally developed by the USDA Rocky Mountain Research Station to target middle school students. Following the workshop, participants experienced an increase in knowledge and more supportive attitudes toward fire management. Another study evaluated the influence of visits to sites treated by prescribed fire (Toman and others 2004). In a self-assessment, a majority indicated that prescribed fire was more acceptable to them as a result of having observed treated sites.

Finally, in a recent evaluation of a multi-faceted information program that used both unidirectional (brochures, mass media) and interactive methods (personal contact, group presentations, neighborhood meetings), McCaffrey (2004) found that personal contact contributed substantially to communication success. Indeed, educational materials, including unidirectional items, were more effective if delivered via personal contact. Findings suggest workshops, site visits, and other interactive activities may not only offer a means for information provision but also provide an opportunity for meaningful interaction with citizens.

Methods

Two study sites were selected; Sequoia and King's Canyon National Parks (SEKI) and the World Forestry Center (WFC). SEKI is comprised of adjacent parks located in the Sierra Nevada Mountains in central California. The parks have an active fuel management program that emphasizes management-ignited prescribed fires and managing naturally ignited fires to achieve resource objectives. Thinning, though less prevalent, is also used near structures to reduce fuel levels.

A broad range of outreach activities are represented at SEKI, including both unidirectional and interactive methods. Upon entering the park, all visitors receive a multi-page newsletter with details about park resources and facilities as well as general interpretive information. Within SEKI there are five visitor centers, each containing various interpretive activities including brochures, film strips, and static displays. Among these, the Giant Forest Museum offers a different, more sophisticated visitor experience than the other centers. Following recent renovation the Museum now provides a broad range of interactive and unidirectional activities, many of which emphasize the role of fire in the Sequoia lifecycle. National Park Service interpretive personnel are highly visible at the Museum and frequently engage visitors. Other outreach activities within SEKI include interpreter and self-guided walks and evening "naturalist talks" at the primary park campgrounds.

Given that visitors to SEKI were potentially exposed to both unidirectional and interactive communication methods, their responses provide an opportunity to assess the influence of communication type. In the follow-up questionnaire, respondents from SEKI indicated the specific programs they participated in while at the parks. Each activity was classified as interactive or unidirectional. Interactive programs included conversations with agency personnel, guided interpretive walks, evening naturalist programs, and visits to the Giant Forest Museum; all others were unidirectional.

The WFC is located in Portland, Oregon. From May through December 2003 the center presented "Fire: Forces of Nature." Each aspect of the exhibit was unidirectional and included photographs and text descriptions, examples of fire suppression equipment, videos on home protection and Smokey Bear, as well as an abridged version of the Nova film "Fire Wars" in the center's theater. The displays provided information about the use of prescribed fire and thinning to reduce fire risk. Overall, the exhibit represented a series of traditional formats that resource agency personnel could use to provide interpretive information at visitor kiosks, information centers, or state and county fairs. Although these formats are still largely unidirectional, recent technological advances have substantially increased the ability of outreach personnel to create high quality, visually appealing displays.

Data Collection

Data were collected in two phases. In the first phase, visitors were contacted and completed a brief questionnaire on-site before exposure to outreach activities. The on-site questionnaire included measures of citizen awareness and attitudes toward fuel treatments before soliciting respondents' contact information and agreement to participate in the follow-up survey. The follow-up was mailed to respondents two weeks following their initial contact. The delayed test was used to assess the enduring effects of exposure to outreach activities and control for experimenter expectancy effects (Leeming and others 1993). A primary benefit of the pre-test/post-test design is the collection of panel data, responses by the same individuals to the same measures at different points in time. Responses from individual participants can be "paired," or linked, over the separate data collection points to identify shifts in individual attitudes and beliefs.

Questionnaire design was informed by semi-structured interviews with agency personnel and project partners. Two questionnaires were developed, one for the on-site survey and another for the follow-up phase. The follow-up questionnaires replicated on-site questions while soliciting further information on awareness, attitudes, and understanding of fuel treatments, evaluations of the outreach activities, and demographic information. Resulting data enable assessment of *between* and *within*-site differences as well as contributory factors. Follow-up mailings were conducted using a modified version of the "total design method" (Dillman 1978); surveys were sent in three waves beginning approximately two weeks following on-site contact.

Sample sizes and response rates are displayed in Table 1. As might be expected, overall visitation levels differ greatly between SEKI and the WFC. These differences are reflected in substantially different sample sizes between the two sites. Where comparisons are made between locations, chi-square tests are used. Because the test is based on the proportion rather than the number of responses, the chi-square statistic is robust to differences in sample size (Cohen and Lea 2004). The remainder of the comparative analysis is based on responses from participants within each location. Thus, the differing sample sizes have little influence on findings reported here.

Results

Respondents were similar demographically (age, education, gender, urban-rural residence) between locations. Overall, respondents had a mean age of 49 and were well educated; two-thirds (66%) had a bachelor's degree or higher. Just under half (44%) were women. Two-thirds (66%) lived in an urban area, while 34% came from a rural community.

Geographic Variation

Knowledge—To gauge citizen knowledge specific to fire and fuel management, respondents completed a five-item true/false quiz about treatment objectives and potential effects. Item development was based upon prior studies (Stankey 1976, Cortner and others 1984, Loomis and others 2001, Shindler and Toman 2003). Respondents appeared relatively knowledgeable with a majority answering each question correctly (Table 2). Indeed, participants' average initial score was 76% at SEKI and 82% at the WFC.

Chi-square tests indicate a few differences in responses between study locations. Specifically, in the on-site surveys, fewer SEKI respondents understood the role of fires in shaping natural forests or the impact of fires on wildlife. Interestingly, in the follow-up survey significantly more SEKI respondents correctly indicated that prescribed fires effectively reduce the amount of fuel in forests.

Table 1—Sample sizes and response rate.

	On-site sample size*	Post-surveys received	Response rate
World Forestry Center (WFC)	92	68	74%
Sequoia and King's Canyon National Parks (SEKI)	395	269	68%
Total	653	459	70%

* Represents number who completed the on-site questionnaire and provided valid mailing addresses.

Table 2—*Between*-site differences in response to quiz questions measuring knowledge about fire management issues.

	Location	Percent of respondents: Generally true	Generally false	Not sure	X^2	Significance
Wildfires have played a significant role in shaping natural forests in the western United States.						
On-site	SEKI	*87*[a]	3	10	7.9	.019
	WFC	*99*	2	0		
Follow-up	SEKI	*93*	2	6	2.0	.361
	WFC	*97*	2	2		
Wildfires usually result in the death of the majority of animals in the area.						
On-site	SEKI	12	*66*	22	6.3	.042
	WFC	3	*79*	18		
Follow-up	SEKI	9	*71*	20	2.0	.361
	WFC	7	*79*	13		
Prescribed fire or controlled burns effectively reduce amounts of fuel in most forests.						
On-site	SEKI	*70*	9	21	1.6	.447
	WFC	*77*	4	19		
Follow-up	SEKI	*90*	2	8	7.8	.019
	WFC	*78*	6	16		
Prescribed fires or controlled burns reduce the chance of high-intensity wildfire.						
On-site	SEKI	*89*	3	9	3.6	.162
	WFC	*91*	6	3		
Follow-up	SEKI	*91*	3	6	.19	.906
	WFC	*90*	3	7		
A history of suppressing wildfires has increased the risk of a destructive fire in the western United States.						
On-site	SEKI	*68*	10	23	.54	.762
	WFC	*69*	12	19		
Follow-up	SEKI	*75*	8	18	2.5	.277
	WFC	*84*	4	12		

[a]The most correct responses are indicated by italics.

Attitudes—Participants also responded to a series of five statements regarding their attitudes toward fire management issues (Table 3). The first four items were based on prior research (Stankey 1976, Loomis and others 2001, Shindler and Toman 2003). The final item about thinning was included because previous studies suggest citizens may be concerned that thinning is simply an attempt to increase timber harvests on public lands (Shindler and others 2002, Shindler and Toman 2003). Results here indicate considerable uncertainty (don't know responses) about thinning activities even following exposure to outreach activities.

Overall, on-site responses were positive toward fire management, indicating a generally high level of support for treatments initially. There were no differences between SEKI and WFC on-site responses; however, agreement with management burning of underbrush differed in follow-up responses. While statistically significant, these differences have relatively minor implications for fire managers; in both cases a strong majority support periodic burning.

Changes Within Locations

Knowledge and Attitude Indices—A primary objective of this study was to examine the influence of participation in outreach activities on knowledge and attitudes. To assess change in understanding we created an index based on *within*-site participant performance on knowledge questions (responses presented in Table 2). A correct answer was coded as 1 while incorrect and "not

Table 3—*Between*-site differences in responses to belief statements measuring attitudes toward fire management issues.

	Location	Percent of respondents				
		Agree	Disagree	Don't know	X^2	Significance
All fires, regardless of origin, should be put out as soon as possible.						
On-site	SEKI	16	78	6	2.4	.295
	WFC	9	85	6		
Follow-up	SEKI	3	93	4	1.3	.511
	WFC	6	90	4		
Managers should periodically burn underbrush and forest debris.						
On-site	SEKI	84	3	13	1.4	.494
	WFC	82	6	12		
Follow-up	SEKI	86	2	13	7.1	.027
	WFC	82	8	10		
Prescribed fires or controlled burns are too dangerous to be used.						
On-site	SEKI	5	83	12	1.8	.393
	WFC	6	88	6		
Follow-up	SEKI	2	93	5	4.7	.091
	WFC	6	85	9		
Prescribed fire or controlled burns should not be used because of potential health problems from smoke.						
On-site	SEKI	6	81	14	.16	.920
	WFC	4	82	13		
Follow-up	SEKI	3	86	12	.77	.678
	WFC	5	82	13		
Thinning for fuel reduction will lead to unnecessary harvesting.						
On-site	SEKI	15	51	34	2.7	.253
	WFC	19	57	24		
Follow-up	SEKI	18	55	27	1.2	.538
	WFC	21	59	21		

sure" responses were coded as 0; scores were then summed. Each participant received a score from 0 to 5. Using paired t-tests, on-site and follow-up indices were compared (Table 4). Mean knowledge scores significantly increased among SEKI participants, while scores at the WFC remained similar.

An index was also created for attitude scores based on responses presented in Table 3. Each variable was recoded with a response of 1 indicating a positive attitude toward fire management and 0 indicating either a negative attitude

Table 4—Within location changes—Knowledge and attitude indices.

	Mean response	
	SEKI	WFC
Knowledge index		
On-site	3.81	4.10
Follow-up	4.21	4.26
t-statistic	5.864	1.120
Significance	<.001	.267
Attitude index		
On-site	3.78	3.98
Follow-up	4.11	4.04
t-statistic	4.446	.414
Significance	<.001	.680

or don't know response; responses were then summed. Each respondent received an index score from 0 to 5 for the five attitudinal statements. As with the knowledge indices, the WFC scores remained similar throughout the study period while attitudes toward fire management improved significantly at SEKI.

Trends in individual change—Comparisons of mean index scores indicate whether an aggregate change occurred among the sample at each location, but do not provide an assessment of changes experienced by individual participants. To explore such changes we created two new variables, knowledge and attitude change, by pairing index ratings across the study period and subtracting the on-site from the follow-up scores. Thus, if a respondent answered two questions correctly in the pre-test and four on the post-test, their knowledge change would be two. These variables provide a measurement of change for each study participant.

The knowledge and attitude change variables revealed two important points (Table 5). First, preliminary observation suggested that respondents who showed the greatest amount of change were those with the lowest initial scores. To quantify this apparent difference, we used a t-test to compare the mean change between respondents with low (0-3) versus high (4-5) initial index scores. Mean change was significantly greater among those with lower initial index ratings. Specifically, respondents with low initial understanding or support were significantly more likely to experience positive shifts in knowledge or attitude following exposure to outreach activities.

Second, a substantial number of respondents in each location experienced a positive shift (increase of one or greater in index scores). At SEKI, 39% of respondents improved their performance on quiz questions and over one-third had more supportive attitudes following participation in outreach activities. Although slightly lower at the WFC, still more than 30% of respondents demonstrated higher knowledge and attitude scores in the follow-up.

Table 5—Within location changes—Trends in participant change.

	Mean response	
	SEKI	WFC
Knowledge change[a]		
Low initial knowledge group mean change[b]	1.16	1
High initial knowledge group mean change[c]	–0.01	–0.1
t-statistic	8.32	2.70
Significance	<.001	0.01
Percent of respondents with positive knowledge change following outreach participation	39%	31%
Attitude change[a]		
Low initial attitudes group mean change[b]	1.44	1
High initial attitudes group mean change[c]	–0.12	–0.31
t-statistic	9.29	4.78
Significance	<.001	<.001
Percent of respondents with positive attitude change following outreach participation	34%	32%

[a] Change was calculated by pairing responses and subtracting pre-test from post-test scores.
[b] Initial index score was 0-3.
[c] Initial index score was 4-5.

Factors Influencing Change

The number of outreach activities available at SEKI provides an opportunity for further exploration of the influence of program and participant characteristics on responses. Of particular interest is the influence that type of outreach experience (interactive or unidirectional) has on knowledge and attitude change. Certain SEKI activities (conversations with agency personnel, guided interpretive tours, evening naturalist programs, and visits to the Giant Forest Museum) were coded as interactive; all others (park newsletter, brochures, other visitor centers, and self guided trails) were treated as unidirectional. Each respondent then received a score based on their participation in interactive activities. Scores ranged from 0 (for no interactive experiences) to 4 (for participation in each interactive activity).

We then created two multiple linear regression models to assess the relative influence of respondent and program characteristics on knowledge and attitude change (see Table 6). Independent variables in both models include demographics (gender, age, education, urban-rural residence), individual relevance of fire topic (as measured by amount of prior thought given to wildfire), and participation in interactive activities. Because our findings suggest initial knowledge and attitudes may influence participant change, each model also includes the appropriate on-site index (e.g., the on-site knowledge index is included in the knowledge change model and the on-site attitude index in the attitude change model). Lastly, the models also included knowledge or attitude variable.

F-test results indicate that both models are statistically significant. Furthermore, each explains at least half of the variance in participant change as indicated by the R-squared statistics. Among the four demographic variables, gender and age significantly influenced knowledge change, while age and education had significant impacts on attitude change. Males and younger participants were more likely to increase in knowledge; older individuals and those with lower education levels were more likely to experience an attitude shift. Interestingly, despite prior research that has identified differences between urban and rural residents (Brunson and Steel 1996), residence type did not influence change in either model. Personal relevance of wildfires had

Table 6—Regression models testing influence of variables on knowledge change and attitude change at SEKI.

	Knowledge change		Attitude change	
	Standardized coefficient	Significance	Standardized coefficient	Significance
Gender (males = 1, females = 2)	–.140	.007	–.059	.240
Age	–.120	.020	.136	.007
Education	.080	.132	–.167	.001
Urban-rural residence	–.013	.800	–.041	.412
Relevance of fire topic	.173	.001	.102	.047
Participation in interactive activities	.134	.007	.045	.361
On-site knowledge index	–.702	<.001	—	—
Attitude change	.133	.011	—	—
On-site attitude index	—	—	–.692	<.001
Knowledge change	—	—	.106	.039
F-statistic	26.844	<.001	28.673	<.001
Adjusted R squared	.500		.518	

a significant effect; in both models, those who had previously thought more about wildfire were more likely to experience positive change.

Participation in interactive outreach activities significantly contributed to knowledge change; however, a corresponding influence on attitudes was not recorded. In both models, the variables with the largest influence on participant change were initial knowledge or attitudes (as measured by the on-site indices); standardized coefficients were –.702 and –.692 for on-site knowledge and attitude indices respectively. The negative coefficients reflect that respondents with low initial knowledge or attitudes were significantly more likely to experience a positive increase throughout the study period. Findings here demonstrate a significant association between knowledge and attitudes even when accounting for the influence of other variables; participants who experienced an increase in knowledge were also significantly more likely to experience a positive change in attitude.

Discussion

Recent policy directives require substantial public participation in developing fire management strategies. Successful participation depends upon the ability of resource professionals to communicate relevant information via effective outreach methods. Findings presented here provide information about participant understanding of and attitudes toward fire management, track changes following outreach participation, and assess factors that contribute to knowledge and attitude change. Several important points emerge from this study.

First, participants had relatively high knowledge and supportive attitudes before exposure to outreach activities. In many cases, responses were more positive than had been recorded in prior studies (Cortner and others 1984, Loomis and others 2001, Shindler and Toman 2001). While the research approach targeted individuals who generally may be more experienced with natural resource issues than the public at large (e.g., they chose to spend their leisure time at a natural resource site), the increase in scores over prior studies were substantial, even when compared with research that targeted wilderness visitors (Stankey 1976, McCool and Stankey 1986). Overall, responses here show a greater appreciation for the role of fire, as well as an increasing recognition of the consequences of fire suppression and the beneficial outcomes of the use of prescribed fire.

Likely contributors include recent agency emphasis on outreach promoting fire and fuel management as well as media coverage that has increased in both volume and depth. In particular, while media stories still highlight dramatic fire events, there has been increased attention paid to the factors contributing to fire activity (e.g., long-term fire suppression resulting in increased fuel loads) as well as potential responses by management agencies. Results here suggest this increased exposure has resulted in higher initial awareness of fire and a basic acceptance of some fire management practices among the general public. The management implication is that outreach activities and messages will need to become more sophisticated to continue to be relevant to an increasingly knowledgeable public.

Second, despite high levels of understanding and support, there appeared to be some uncertainty about thinning treatments. While previous research has found substantial support for thinning in some forest communities (Shindler and Toman 2003, Brunson and Shindler 2004), citizens have also expressed reservations with thinning treatments as a new means to conduct "business as usual" and increase timber harvests on public lands (Shindler and others 2002). Indeed, much of the discussion in the popular press regarding the Healthy Forest Restoration Act has focused on whether the legislation would facilitate removal of large, mature trees (for example see McCarthy and others 2003, New York Times Editorial Desk 2003). Findings here suggest greater discussion within communities will likely be necessary before proceeding with large-scale thinning projects. Outreach activities can play an important role here, particularly interactive programs, as research has shown that personal contact can reduce the controversy surrounding thinning decisions (McCaffrey 2004).

Third, although prior research has suggested differences in citizen perspectives among locations (Manfredo and others 1990, Brunson and Shindler 2004), findings here were generally similar across study sites. This may partly be an artifact of our research approach. Specifically, contacting individuals at a recreation site (outside of their community) and not at their residence potentially reduces the influence of local contextual factors on citizen responses. That is, they may have responded to questions about fuel treatments in general rather than thinking about a prescribed burn near their back yard. It is important to note that while there appears to be good understanding and high support for the concept of fuel management practices, gaining acceptance among local residents for specific treatments will require more than general interpretive messages. The implementation of specific projects will require effective communication tailored to ecological and social issues at the local, and perhaps the neighborhood, level (Brunson and Shindler 2004).

Lastly, the data presented here demonstrate that outreach activities can positively influence citizen understanding and support. While only SEKI responses demonstrated an aggregate increase, approximately one-third of participants at both locations experienced some positive change throughout the study period. These program effects are particularly remarkable given the high initial scores as participant change is less likely when knowledge or attitudes are already well-developed (Dillard and Peck 2000). Results further reveal that participants with low initial knowledge or less positive attitudes were more likely to experience improvements across the study period. This trend was evident in both locations; even though there was not an increase in aggregate scores at the WFC, those with low initial scores were positively influenced. Importantly, populations with low understanding or less supportive attitudes are a key target audience of agency personnel and results here suggest they are likely to benefit the most from outreach activities.

Factors Influencing Change

A primary objective of these case studies was to assess factors that contribute to knowledge and attitude change. Of particular interest is the influence of interactive versus unidirectional outreach activities on participant responses. *Within*-location changes show that SEKI participants (exposed to interactive formats) experienced a significant improvement in knowledge and attitudes while the WFC responses (following a unidirectional experience) remained similar throughout the study period. While suggestive, these results may be confounded by additional variables. For example, SEKI responses were initially lower, albeit slightly, and these individuals may have been more susceptible to change. In addition, most SEKI respondents participated in multiple outreach activities; thus, knowledge and attitude changes may be influenced by greater exposure to fire-related information.

The regression models also provide mixed evidence. While participation in interactive activities positively influenced knowledge change, results provide no evidence of a corresponding impact on attitudes. Ultimately, findings here are suggestive but inconclusive on the influence of interactive outreach experiences. Our inability to identify potential effects may be a consequence of the measures used in this study. We replicated measures used by others, but the high initial performance may indicate it is time to increase the level of sophistication in our tests. A different set of knowledge and attitude measures may be necessary to identify change and assess contributory factors among an increasingly informed public.

Regression findings also provide information on additional influencing factors among SEKI respondents. Demographic variables had mixed effects; influences were either inconsistent or contradictory between the models. Thus, findings do not suggest a particular portion of the population to target through communication activities. Personal relevance of fire management had positive effects on knowledge and attitude change. The implication here is that residents in the wildland urban interface are prime candidates for outreach programs and messages will likely be more successful when crafted to demonstrate their application to local issues of concern.

Also noteworthy is the strong association between knowledge and attitude change. While substantial research has identified a correlation between knowledge and support for fire management activities (e.g., McCool and Stankey 1986, Carpenter and others 1986, Shindler and Toman 2003), such associations are not evident for all natural resource issues. For example, attitudes toward clearcutting are unlikely to change simply on the basis of new information (Bliss 2000). The consistency of these findings over time suggests that outreach activities may have a greater influence on support toward fire than other management issues. Accordingly, resource professionals may see greater dividends by focusing their outreach efforts to communicate the fire and fuel message.

Conclusion

Effective communication is essential to building the understanding and support necessary for sustainable resource management. Findings here suggest two basic levels of communication are useful. One is general information dispersal; this usually involves broad messages that can be conveyed by unidirectional, mass communication formats such as newspapers, brochures and public service announcements. Messages delivered through this format are typically created for general public consumption and, as such, provide few opportunities to target specific audiences. Because it is difficult to ensure that information is received and understood, their effectiveness as an educational tool is limited. Indeed, as Atkin writes, "campaign messages that have the broadest reach can deliver only a superficial amount of information and persuasive content that is seldom customized to the individual recipient" (2001, p. 56). However, these programs can still be beneficial; they are typically inexpensive and can contribute to building awareness for important issues or projects (Atkin 2001, Jacobson 1999). Moreover, unidirectional activities, as demonstrated here, can positively influence citizens with low initial knowledge and a lack of formal opinions about these programs.

The second level of communication is more focused in scope and usually includes opportunities for interaction at the community or individual level.

Because such outreach activities target local priorities and specific environmental contexts, they will likely be more effective at influencing citizen understanding and acceptance (Brunson and Shindler 2004; McCaffrey 2004). Indeed, as citizen understanding of fire management becomes increasingly sophisticated, the flexibility of interactive activities to provide context-relevant information will become even more important. Of the factors that contributed to knowledge change in this study, the type of outreach experience was the only one that managers can directly control.

The take-home message from these case studies is that effective outreach goes beyond simply using standardized tools to provide information. As demonstrated here, outreach success is not only a result of the information provided but also the method of delivery. Indeed, "the availability of information does not necessarily mean that it will reach its audience or be effective once it gets there" (McCaffrey 2004, p. 12). Successful communication requires effective planning including consideration of the communication objective, the nature of the topic, and audience characteristics including prior knowledge and attitudes (Jacobson 1999). Fire and fuel management are resource issues that offer a real opportunity for achieving success through communication and outreach. The public has long looked to management professionals to provide sound information and leadership regarding fire issues (Shelby and Speaker 1990). As findings here suggest, managers can use this leadership role to influence public understanding and generate positive attitudes for management activities.

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Reduction of Potential Fire Behavior in Wildland-urban Interface Communities in Southern California: A Collaborative Approach

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Abstract*—This manuscript details a collaborative effort that reduced the risk of wildfire in an affluent, wildland-urban interface community in southern California while simultaneously minimizing the environmental impact to the site. FARSITE simulations illustrated the potential threat to the community of Rancho Santa Fe in San Diego County, California, where multimillion-dollar homes were located immediately above a designated open space area that consisted primarily of 60-year-old, decadent chaparral. Post-treatment fire behavior simulations demonstrated the potential ability to moderate fire behavior.*

Results of the fire behavior modeling led to a recognition for the need for fuels treatments by both homeowners and regulatory agencies that were originally adverse to any type of treatment. Through a collaborative process, these diverse stakeholders worked to create and maintain an effective fuel treatment that was cost effective and environmentally sound. This shared approach by fire personnel, homeowners, and regulatory agencies in Rancho Santa Fe is a success story that could be a template for interface communities throughout southern California.

Introduction

Nowhere in the United States is the increasing trend of destructive fires in the wildland-urban interface (WUI) better exemplified than in southern California. Coupled with a burgeoning population that continues to expand into explosive chaparral fuels, there is an ever-increasing potential for widespread destruction to human life and property. For example, eight fires in southern California have grown to over 100,000 acres in size, including the 2003 Cedar Fire in San Diego County, which burned over 273,000 acres (California Department of Forestry & Fire Protection 2005a). And in terms of structures lost, 14 of the 20 most destructive fires in California occurred there, again led by the Cedar Fire, which consumed 4847 structures (California Department of Forestry & Fire Protection 2005b).

To reduce the costs and losses associated with wildfires, fire agencies allocate their limited resources to two primary strategies in the WUI. The first strategy is to maximize success of initial attack by funding additional suppression equipment and personnel. Alternately, pre-fire fuels treatments are a second strategy meant to reduce fire behavior, thereby increasing suppression success and decreasing number of structures lost. While proven effective in numerous fire events, the second strategy is seemingly more difficult to implement due largely to sociopolitical factors such as perceived degradation of viewsheds and costly and timely navigation through environmental review.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Pre-fire fuels management is also more difficult to measure success as treatments are not necessarily meant to eliminate fire spread. For example, fuel treatments in the 2002 Rodeo-Chediski fires in Arizona significantly reduced fire intensity and rates of spread within the treatments, yet did little to impede spread across the landscape as the fire's path simply flanked the treatments and continued unabated (Finney and others 2005). In the WUI, success of fuels treatments may be measured by any number of metrics, including initial attack success, percentage of homes survival, and others. Additionally, other metrics of success could include the degree to which the treatments retained the positive benefits of vegetation such as scenic beauty, carbon sequestration, mitigation of heat island effect, stormwater retention capacity, and others (Dicus and Zimmerman in review).

For WUI areas in southern California, we broadly define a successful project as one that is

(1) completed on the ground,
(2) cost effective,
(3) environmentally sound, and
(4) effectively modifies fire behavior to an extent that minimizes structures consumed.

Based on the preceding metrics, a case study that examines the relative success of a fuel modification project in Rancho Santa Fe, California follows.

Community Overview

Rancho Santa Fe is an unincorporated community of 3,252 people (2000 U.S. Census) that is located approximately 20 miles north of San Diego, California (figure 1). The community is a classic example of a wildland-urban intermix, where homes are interspersed between designated open space parcels of mostly unmanaged vegetation. It has been designated by the State as a *Very High Fire Hazard Zone*.

The high value of homes in Rancho Santa Fe set it apart from most WUI communities. Data from the California Association of Realtors reveal that the median home price there exceeded $2.5 million in 2005. Further, as of the 2000 census, Rancho Santa Fe had the highest per capita income of any community in the United States with over 1000 households.

In the absence of Santa Ana winds, fuels will have the greatest effect on fire behavior and is subsequently the greatest threat to homes. Topography consists mostly of gently rolling slopes and drainages. Weather is Mediterranean and is greatly moderated by proximity to the Pacific Ocean. Property owners, by ordinance, must "maintain an effective fuel modification zone by removing, clearing, or thinning away combustible vegetation and other flammable materials from areas within 100 feet of any structure" (Rancho Santa Fe Fire Protection District Ordinance No. 02-01). It is the responsibility of individual property owners to create and maintain this buffer. However, if the 100 ft buffer around a structure exceeds the property line of a specific homeowner, it is the responsibility of the adjacent landowner to manage vegetation on his own property so as to maintain the 100 ft buffer for all structures. In many instances in Rancho Santa Fe, the 100 ft buffer from structures extends into adjacent open space parcels.

Fuels in the interspersed open space parcels consist largely of decadent, highly volatile brush that has not burned in over 60 years. Vegetation in the

Figure 1—Location of Santa Rancho Fe, San Diego County, California.

open space areas is typical of southern California chaparral, consisting of such native species as scrub oak (*Quercus berbidifolia*) and chamise (*Adenostoma fasciculatum*). Further, exotics such as red gum eucalyptus (*Eucalyptus camaldulensis*) and pampas grass (*Cortaderia jubata*) are commonly found there.

The open space areas are the responsibility of the Rancho Santa Fe Association (hereafter, Association), a homeowners association that administers a protective covenant of land use rules in the area. All members of the Association are responsible for paying for the maintenance of the open space parcels, regardless if individual property owners are directly affected. The only vegetation management in these areas had been to periodically cut the brush along horse trails that crossed through the middle of the open space areas, which would have minimal effect on the spread of wildfire.

Structural and wildland fire protection is provided by the Rancho Santa Fe Fire Protection District (hereafter District), which serves a 42-square mile area surrounding Rancho Santa Fe. The District, however, is in a designated State Responsibility Area for wildland fire protection, and is thus also served by the California Department of Forestry and Fire Protection. This designation served to facilitate the fuels treatments that will be discussed later.

Of note, the District has adopted a shelter-in-place approach for residents of some newer subdivisions during a wildfire because homes there have been built with extremely fire-resistant construction materials and have District-approved landscaping. The District contends that sheltering in the fire-resistant structures during a wildfire would be safer than attempting to evacuate along winding roads adjacent to potentially burning vegetation.

The older, previously developed community of Rancho Santa Fe, however, is not as fire resistant as the newer developments. Commonly, private residences sit atop ridges above the aforementioned open spaces and would receive immense convective heating from burning of the explosive chaparral fuels. Further, several of the residences still have wood shake roofs, which have been shown to be especially susceptible to combustion from burning embers (Cohen 2000). Thus, even with a 100 ft managed buffer around structures, risk to many residences remains high.

Project Implementation

One particular area in Rancho Santa Fe had long been a concern to the District. This area was in a chaparral-filled canyon with homes regularly located at the tops of the ridges in natural chimneys and saddles (figure 2). A formal risk assessment across the District confirmed that this area was at elevated risk of loss during a fire event. Given the pre-treatment conditions of the open space parcel in question, the District expected to lose a minimum of eight homes during a wildfire event.

Given the value of these homes and the historic behavior of wildfires in the area, members of the insurance industry were also extremely concerned with potential losses from wildfire. Because of their high replacement costs,

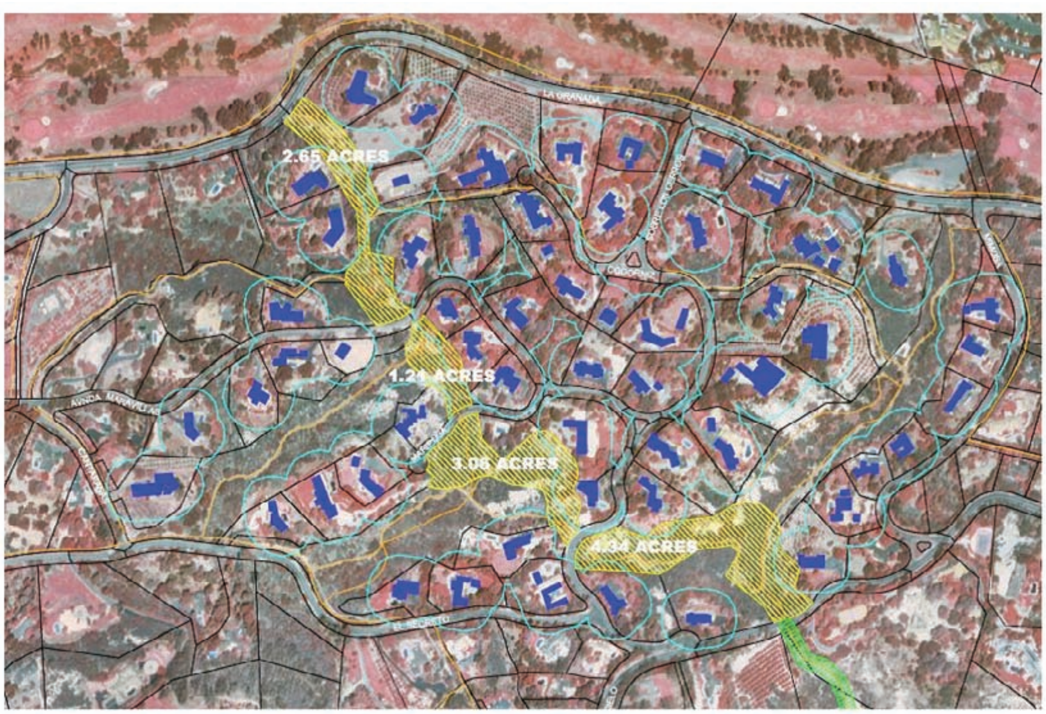

Figure 2—Aerial photograph of the El Secreto fuel modification project in relationship to homes in Rancho Santa Fe, California.

destruction of only a few homes in Rancho Santa Fe would cause a tremendous loss to the industry, translating into an increase in rates for not only San Diego County, but potentially for homeowners across southern California.

FARSITE simulations from a single, likely ignition point during historic 50% and 97% weather illustrate the pre-treatment potential fire behavior in the area (figures 3 and 4, respectively). Even with a 100 ft buffer around the homes, many would likely experience intense convective heating, if not direct flame impingement. Pertinent weather and fuel values for all simulations are provided in table 1 and were determined by FireFamilyPlus analysis of historic weather data from the nearby Flores RAWS station. A custom fuel model (fuel model 20) was utilized to simulate fire spread within the 100 ft buffer. Figures 3 to 5 depict extent of spread and flame length (ft) for a 1-hour simulation (5-minute visible time steps) where all inputs were held constant.

The District contacted the Association regarding unmanaged vegetation on the open space parcels that were within 100 ft of structures and provided suggestions for mitigation. The District did not take a heavy-handed approach with the Association, but instead sought an open dialogue with the Association so as to make them aware of the hazards and recommend solutions that were in the best interest of the community.

Modeling efforts were presented to members of the Association who, while not understanding the nuances of wildland fire behavior modeling, appreciated the potential for a significant fire event. Subsequent simulations that

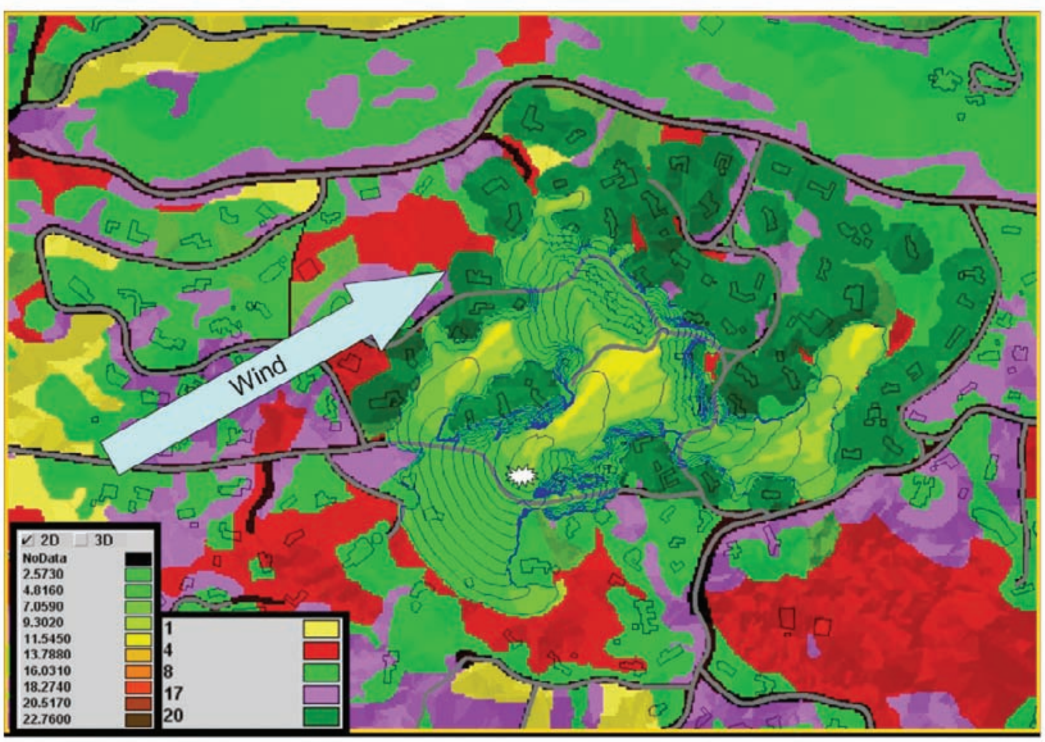

Figure 3—Pre-treatment FARSITE simulations from a single ignition point (in white) under 50th percentile weather and wind conditions (August). Flame length (ft), 5-minute time steps, and background fuel models are depicted.

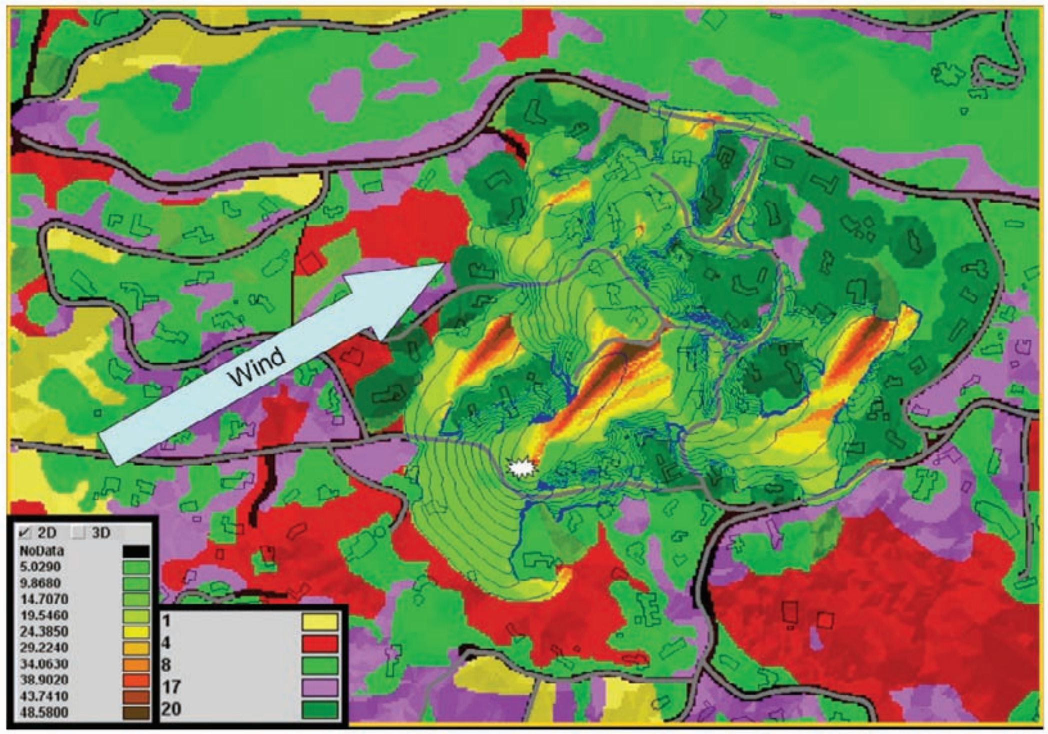

Figure 4—Pre-treatment FARSITE simulations from a single ignition point under 97th percentile weather and wind conditions (August).

Table 1—Average and extreme (August) weather, wind, and fuel moisture inputs used in FARSITE simulations in Rancho Santa Fe, California. Values obtained from FireFamilyPlus analysis of nearby Flores RAWS station.

Variable	Percentile	
	50th	**97th**
Max Temp[1]	76	85
Min RH[2]	22	13
Wind Speed[3]	10	20
1-hr FM[2]	6	3
10-hr FM[2]	8	5
100-hr FM[2]	10	7
Herbaceous FM[2]	60	30
Live Woody FM[2]	80	60

[1] °F
[2] Percent
[3] mph

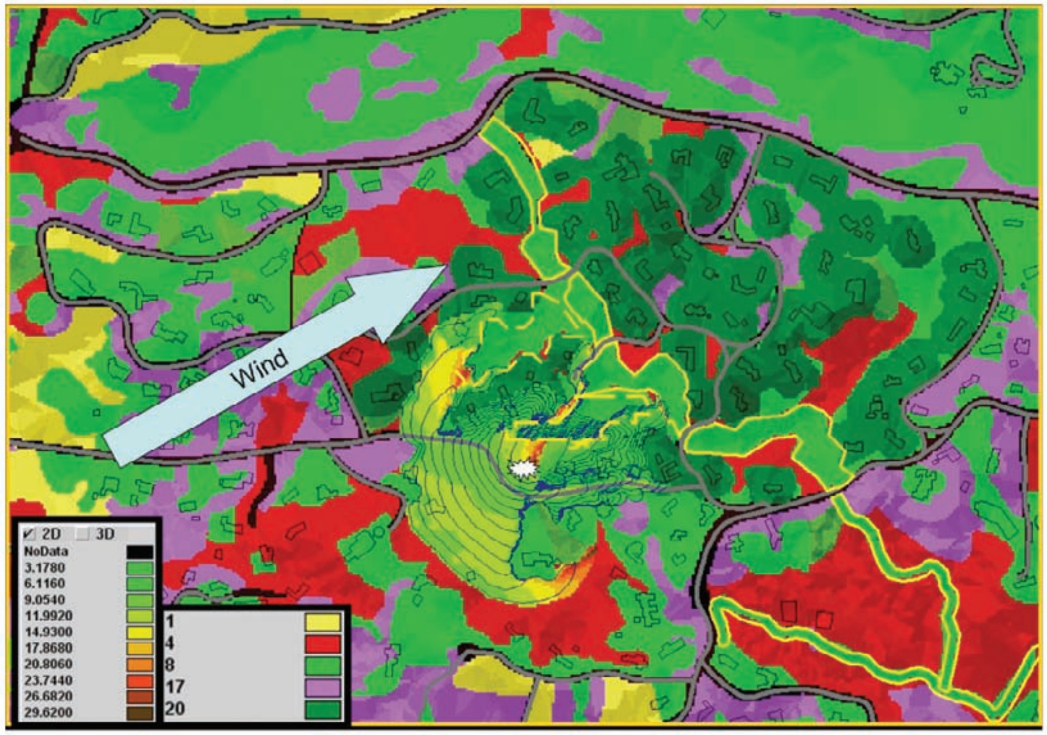

Figure 5—Post-treatment FARSITE simulations from a single ignition point under 97th percentile weather and wind conditions (August).

accounted for a fuels treatment in the area (conversion to fuel model 8) clearly illustrated the potential benefits of those treatments to adjacent landowners, even under 97% weather conditions (figure 5). The District explained to the Association that any fuels treatment would not stop a wildfire, but would reduce the fire intensity, thereby reducing the threat to nearby structures and increasing chance of initial attack success. The Association Board of Directors created and distributed a simple but compelling brochure to their members that detailed the need to allocate funds for the project as it would benefit all members of the Association, not only the homeowners adjacent to the proposed fuel modification.

The Association was initially somewhat hesitant to initiate fuels modifications in these areas based not on perceived degradation of views or environmental impacts, but instead on the potential cost of treatments. Indeed, initial estimates from contractors on the 11.26 acre (4.65 ha) El Secreto project ranged from $65,000 to over $200,000. District personnel worked with the Association to explore other, more economically feasible options.

The District sought assistance from publicly funded crews because the project area was within a designated State Responsibility Area for fire protection and was by law, technically open to the public (even though the Association attempts to discourage outside access as much as possible to the open space parcels). CDF-administered inmate crews were subsequently contacted. At first, the community members were extremely adverse to inmate crews in the community due to perceived safety concerns. Association Board Members visited the applicable correctional facilities to personally investigate the crews and subsequently provided assurance to their members that the inmate crews would pose no threat to the neighborhoods. That assurance, in addition to the extremely low estimated cost of the implementing the project ($30,000), eventually won the community over.

After CDF contracts were established, the Association notified the California Department of Fish & Game (CFG) of their intent to carry out the fuels modification project per guidelines established in a preexisting Memorandum of Understanding between CFG, the U.S. Fish and Wildlife Service (USFW), CDF, the San Diego County Fire Chief's Association, and the Fire District's Association of San Diego County. The MOU states that after notice of intent to clear vegetation for fire protection purposes is given, CFG and USFW biologists have the option to review the project for compliance with endangered species requirements, and may suggest voluntary, alternative measures if deemed feasible and warranted. While the District was responsible for establishing the need and proposed mitigation measures in the project, they purposely did not write the notice of intent to CFG in an attempt to avoid any potential interagency political wrangling.

Because the proposed El Secreto project exceeded the 100 ft buffer established in the MOU, CFG and USFW regulators required additional review. Once again, FARSITE simulations were used to justify the extent of the project. After analyzing the simulations, they agreed to an on-site review of the project area. The on-site review confirmed to the regulators that a majority of the vegetation in the proposed project area was dead and that removal of these fuels would not negatively impact habitat there. The regulators required that no more than 50% of the vegetation be removed, which was unreasonable in some locations as over 80% of the existing vegetation was dead at that time. They further requested that all flammable exotic species such as eucalyptus and pampas grass be removed, by herbicides if necessary, which was beyond the original scope of the District but welcomed.

Upon approval by CFG and USFG regulators, female inmate crews from the local Rainbow Camp began the project, demonstrating both outdoor savvy and the care needed to properly treat the area. Of interest, while initially adverse to inmate crews, homeowners quickly became enamored by the female crews and tried to offer cookies and cakes to them, which was against CDF policy of limiting contact between inmates and private citizens. The Association, however, was able to regularly provide Subway sandwiches to the inmates, which apparently increased both their productivity and care on the project. At the completion of the project, CDF invoiced the Association for $14,000, well below early estimates that exceeded $200,000 and the $30,000 for which the Association had budgeted. These savings will pay for future maintenance costs on the project.

The project had minimal negative environmental impacts and served to provide many positive benefits to the community. Indeed, only dead material was harvested during the project, which was subsequently chipped and spread on existing horse trails. This simultaneously eliminated green waste from entering the landfill and also mitigated erosion on the trails. Exotic pampas grass was eliminated from the project area with herbicide, but will likely return via seeds from ornamental plants on properties above the project. Further, anecdotal evidence suggests that there are more wildlife species present on the site after the treatment, but this may be a function of increased visibility of the area, which was marred by the abundance of dead vegetation. At the conclusion of the project, a shaded fuel break resulted that simultaneously lowered fire risk while having minimal impacts to the positive benefits that vegetation provide such as stormwater retention, improved air quality, and carbon sequestration. Whereas before there was an almost impenetrable mass of dead brush, the site is now regularly used by the community as a location to recreate.

Lessons Learned

By the metrics set forth at the beginning of this manuscript, the El Secreto Project was a success. Owing to a collaborative effort between local and state fire agencies, homeowners, and environmental regulatory agencies, the project was implemented on the ground after much planning, was relatively cost effective, and was environmentally sound. The ultimate test of the success of the project will come in a future, inevitable wildfire.

While this project is extremely beneficial to the properties immediately adjacent to the fuels project, it will have minimal impact to the spread of fire across the landscape, especially during a Santa Ana wind event, due to its relatively small size. However, the original strategy of the project was to maximize initial attack success on a fire occurring in the open space parcel, not stop a major wildland fire.

District personnel cite that the key to this project was the development of partnerships and collaboration with property owners and regulatory agencies. The District was instrumental in initiating meaningful dialogue between fire personnel, Association members, and regulatory agencies, which was vital to the scope and completion of the project. Collaboration does not imply "educating" the homeowners and regulators to the needs and desires of the fire agencies, but rather is meaningful communication where all viewpoints are considered to best serve the community. They also conclude that it is critical to adequately plan an environmentally sound and justifiable project before regulators participate in an on-site review of a project.

While pleased in the success of the El Secreto project, concerns over future projects remain. One concern is the regular turnover of CFG and USFG regulators in the region. Historically, many regulators seemed adverse to any type of vegetation management until a trust relationship had been developed with District personnel. With regular turnover, the fostering of mutual trust between the agencies will be hindered. There are also concerns about any future needed projects that might lie within the jurisdiction of the California Coastal Commission as they have historically been adverse to most vegetative management projects, regardless of the potential threats or species involved. Indeed, they were the only party that refused to sign the original MOU discussed earlier.

Because of the success of this program, other local communities now regularly seek to contract with the inmate crews, which could potentially limit the District's ability to use them for future projects. It is hoped that the strong working relationship forged between CDF and the District as well as the relatively central location within the CDF responsibility area will insure Rancho Santa Fe has access to crews.

Also, the continued presence of wood roofs in the area is an immediate threat to the community, due to their susceptibility of combustion from fire brands. Of interest, a portion of the residents in this affluent community are asset-wealthy, but simply do not have the means to replace their roofs with fire resistant materials. These property owners consist primarily of retirees who purchased their home in the 1970s or earlier when home prices were significantly less; while their home equity has appreciated exponentially, they live today on fixed incomes. A recent grant to FEMA for a cost-sharing program to replace fire-prone roofs remains pending. The grant would fund 70% of the costs of roof replacement, with a cap of $40,000 per residence.

There are also concerns about undeveloped lots adjacent to parcels with structures. As with the Association's open space parcels, those property owners are responsible for modifying vegetation within 100 ft of a structure, regardless if their individual property is developed or not. Property owners of the undeveloped lots, many living outside the state, have sometimes resisted the District's attempts to enforce the 100 ft buffer. While preferring a collaborative approach to generate solutions that mitigate the threat, the District is sometimes forced to send outside contractors to those sites, subsequently billing the noncompliant property owners for work completed there.

Acknowledgments

This project was funded by the California State University Agricultural Research Initiative. We are grateful to Mark Carpenter of KTU&A Landscape Architecture and Planning, San Diego, California, for providing critical GIS and FARSITE data files.

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Fire Management in the Inter Galatic Interface or 30 Years of Fire Management at Merritt Island National Wildlife Refuge/ Kennedy Space Center, Florida

Frederic W. Adrian[1]

***Abstract**—Prescribed burning is essential on Merritt Island National Wildlife Refuge. Not only is it needed to manage the volatile fuels, but also to manage the complex system of fire maintained habitats found here. Fire management on the Refuge presents unique challenges. In addition to the restraints to prescribed burning that are common to many prescribed burning programs, Refuge fire managers must also consider the special needs of an operational space port. By using an active program of education, demonstration and negotiation with the Space Center, the Refuge has been able to maintain a prescribed burning program that has reduced the detrimental effects of unwanted wildland fires when they occur.*

Introduction

Merritt Island National Wildlife Refuge (Refuge) is located on the east central coast of Florida in Brevard and Volusia Counties (figure 1). The majority of the Refuge is an overlay of the National Aeronautics and Space Administration's (NASA) John F. Kennedy Space Center (KSC). The U.S. Fish and Wildlife Service (Service) administers these lands and waters under an interagency agreement. This agreement gives the responsibility for land management activities for KSC's non-operational lands to the Service. Included in these management responsibilities are wildland fire suppression and prescribed burning. The Refuge also has agreements with Canaveral National Seashore (CNS) to assist with both prescribed burning and wildland fire suppression and with the Cape Canaveral Air Force Station (CCAFS) to assist in prescribed burning. Together, these four federal agencies manage over 180,000 acres of relatively undeveloped coastal barrier islands and lagoons.

This coastal ecosystem is quite diverse. Schmalzer and others (2002) list 803 native plants on the Refuge and adjoining federal lands, with, 38 taxa listed as endangered, threatened or of special concern by the State of Florida. This wide array of plant species has been grouped into 20 native wetland and upland vegetative communities (U. S. Fish and Wildlife Service 2006). The Refuge's habitats provides protection and management opportunities for 10 regularly occurring federally listed threatened and endangered wildlife species, as well as for 36 species of federal management concern and 47 wildlife and plant species listed by the State of Florida (Epstein and Blihovde 2006). In addition, over 300 species of migratory and resident birds, 30 species of mammals, and 71 species of reptile and amphibians have been recorded on the Refuge (Adrian and others 2006).

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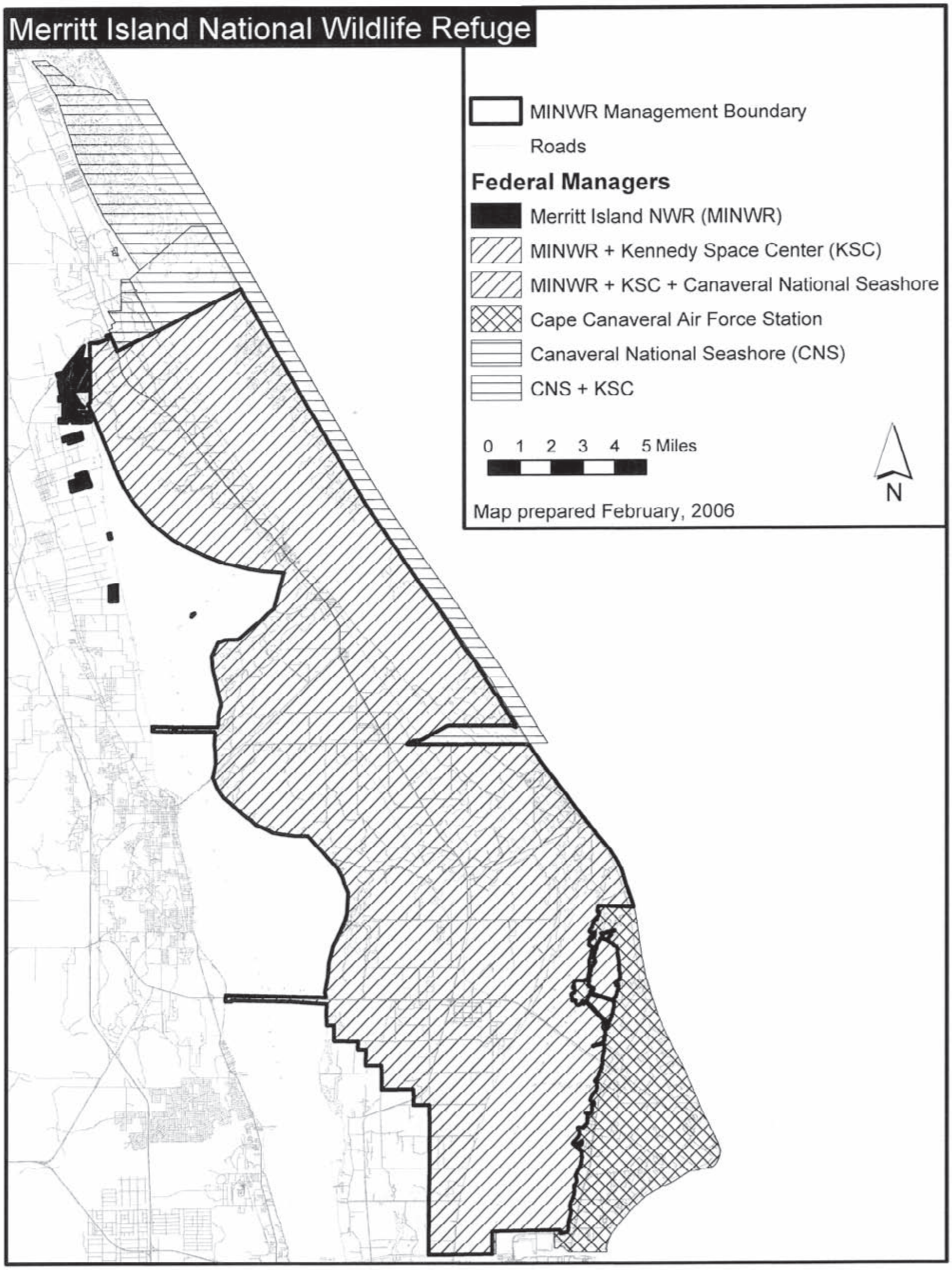

Figure 1—Location of Merritt Island National Wildlife Refuge and other federal agencies.

Fire History And Fire Ecology

Fire has been a component of the Florida ecosystem since before humans occupied the landscape. The National Weather Service Office in Melbourne, Florida states that Florida is the "lightning capital of the United States", with over 22,000 lightning strikes occurring in Brevard County alone each year (National Weather Service 2005). In historic times, lightning frequently ignited fires, which spread readily throughout the landscape. Examination of charcoal deposits in lake sediments show that fires have occurred in south central Florida for 50,000 years (Watts and Hansen 1988). It is logical to assume that fire has been instrumental in favoring the selection of fire-adapted traits in the Florida's vegetation.

Fire Maintained Vegetative Communities

Of the almost 77,000 acres of non-open water habitat on the Refuge, approximately 55,000 acres support plant communities that can be considered fire maintained. Without periodic fires, the characteristics of the four important fire-maintained vegetative communities on the Refuge described below would change drastically.

Oak Scrub: Oak scrub occurs on xeric sites. The shrub layer plants found here include sand live oak (*Quercus geminata*) myrtle oak *(Q. myrtifolia*) and Chapman's oak (*Q. chapmanii*) along with some palmetto (*Serenoa repens*). Occasionally, a sand pine (*Pinus clausa*) overstory is present. Historically oak scrub stands were low and open with many sandy patches.

The fire regime in the oak scrub can be described as intense and stand replacing. Oak scrub is difficult to ignite. In many cases, lightning fires started in more flammable areas, such as the flatwoods, and ran into the scrub areas. When ignited however, the oak scrub burns vigorously. Rates of spread are rapid and flame lengths of 40 to 50 feet were not uncommon. The natural fire return interval was between five and seven years. Stands of oak scrub regenerated quickly from root sprouting (Schmalzer 2003).

Scrubby Flatwoods: The scrubby flatwoods community is found on slightly wetter sites than the oak scrub. The shrub species found in the oak scrub are also found here, but palmetto is much more abundant. More mesic species such as gallberry (*Ilex glabra*) and *Lyonia* spp. are also present. In historic times a scattered overstory of south Florida slash pine (*P. elliottii* var. *densa*) was present. Both the oak scrub and the scrubby flatwoods are habitat for the federally threatened Florida scrub-jay (*Aphelocoma coerulescens*) and are the focus of a much of the Refuge's upland management activities.

Under natural fuel loadings, fires in the scrubby flatwoods were generally confined to the shrub layer, with overstory consuming fires only occurring during periods of extreme weather. Rates of spread were normally moderate as were the flame lengths. The fire return interval was between three and seven years. Most of the shrub layer vegetation regenerates from sprouting.

Pine and Palmetto Flatwoods: The pine and palmetto flatwoods community is found on the more mesic soils of the Refuge. The shrub layer is predominately palmetto with some gallberry, *Lyonia* spp. and wax myrtle (*Myrica cerifera*). Wire grass (*Aristida stricta* var. *beyrichiana*) is common. An overstory of south Florida slash pine is common, with some stands of pond pine (*P. serotina*) present in the wetter areas. Historically, fires kept the understory low and open, and the overstory scattered to moderately dense. The pines in the flatwoods provide nesting habitat for the bald eagle (*Haliaeetus leucocephalus*).

The historic fire regime in the flatwoods consisted of moderately intense fires that occurred every three to five years. The understory of the flatwoods burns vigorously and completely. Much of the vegetation is highly flammable. Species such as palmetto contain resins and oils which ease ignition and increase rates of spread. As was the case in the scrubby flatwoods, fires in the canopy were infrequent and occurred during periods of drought or when fuel loads became excessive.

Marshes: Both saltwater and freshwater marshes occur on the Refuge. The saltmarshes, the majority of which are now impounded, occur along the edges of the lagoon system on the Refuge. The native vegetation is primarily sand cordgrass (*Spartina bakerii*) a tall grass with some short grasses such as saltgrass (*Distichlis spicata*) mixed in. The freshwater marshes, or swales, also contain sand cordgrass along with some *Andropogon* spp. The swales are intermingled with the upland vegetation described above and are important in the flammability of those landscapes.

The historic fire regime was similar in both types of marshes. It can best be characterized as rapidly moving, intense fires with a fire return interval between two and four years. Fires usually consumed all of the vegetation and the stand was regenerated by sprouting (Schmalzer and others 1991). These frequent fires kept the stands of grass in an open condition. They also reduced the encroachment of woody species such as wax myrtle and salt bush (*Baccharius* spp.)

Human Fire Use

Evidence exists that Native Americans used fire extensively prior to the arrival of the first European explorers (Robbins and Myers 1992). The journals of many of the early explorers indicate that in the southeast, Native Americans used fire to clear fields and drive game as well as for communications and warfare. Many of these fires were set outside of the natural fire season.

The early European settlers used fire extensively for many reasons. Turpentine operations burned in winter, cattlemen burned in the spring and hunters burned in the fall. These activities, combined with the naturally ignited summer fires resulted in fire on the landscape throughout the year.

The past 50 years have seen controversy over the use of fire. Ranchers, timber companies, wildlife managers and others have continued to use fire, much of the time outside of the natural fire season. During the 1950s and 1960s there was a concerted effort to stop burning the landscape. In addition, efforts to suppress wildfires were increased. This was especially true at KSC.

Changes in the Ecosystem

The removal of fire from the ecosystem caused major changes in the landscape. Pine stands in the flatwoods and scrubby flatwoods communities became dense and overgrown. Mesic forests began to invade marshes where frequent fires once kept this encroachment in check (Duncan and others 1999). The oak scrub increased in height and density becoming difficult to ignite except under extreme fire weather conditions (Schmalzer and Adrian 2001).

These changes to the habitats affected the wildlife utilizing them. The thickness of the scrub vegetation made the oak scrub and scrubby flatwoods less suitable for the Florida scrub-jay and other scrub fauna. Unburned marsh grasses made movement difficult for secretive birds such as black rails (*Laterallus jamaicensis*). In some cases, brush in the marshes was thick enough to shade out grasses changing the habitat entirely.

Fuel loads increased in all of these vegetative communities. When fires did start, they burned with greater intensity than in the past. This was especially critical in the pine flatwoods. While historic fires tended to stay in the shrub layer, the increase in pine density resulting from the lack of fire increased the potential for crown fires. This removed nesting substrate for the bald eagle.

Refuge Fire Management

Early Fire Management

Fire management on the Refuge has changed considerably over the past three decades. Between the time the Refuge was created in 1963 and 1981 little active fire management was done. A review of the somewhat sketchy early Refuge records shows a few small prescribed burns, and occasional suppression activities. During this time, the responsibility for suppression of wildfires was confused with the Refuge taking action on some fires, and with KSC Fire (primarily a structural fire organization) suppressing others. Training of Refuge personnel was minimal and equipment was typically converted military vehicles and other used equipment.

Fuels Management Prescribed Burning

With little fire activity in the ecosystem, fuel accumulated to a point where it was only a matter of time before severe fires would occur. This happened in the summer of 1981 when 46 wildfires burned over 17,000 acres and two firefighters were killed. This calamity initiated the second phase of fire management on the Refuge. Training of wildland firefighters was increased, new equipment was purchased, and a contract helicopter was acquired for both fire suppression and prescribed burning.

An aggressive prescribed fire program was begun with fuels management as the primary objective. During this time period, burn units were large, with some up to 4,000 acres. Between 1982 and 1992 the Refuge had 108 prescribed burns totaling 121,743 acres with an average size of 1,127 acres.

Most units were designated using existing natural and man made-barriers. It was normal to find several different vegetation communities within a single burn unit. This meant that fire prescriptions could not be tailored to meet specific requirements for individual communities. This phase of the Refuge's prescribed burning did meet the overall objective of reducing the fire danger. In 1992, a year with similar weather conditions to 1981, the Refuge experienced 45 wildfires, but only 378 acres were burned and no injuries or fatalities were experienced.

Habitat Management Prescribed Burning

In the early 1990s fire management objectives began changing from simply reducing fuel loads to meeting wildlife and habitat management objectives. Beginning in 1993 the Refuge began to subdivide the larger units in an attempt to focus more on the burning requirements of the individual vegetative communities and the wildlife species they supported. Of primary importance was the maintenance and restoration of oak scrub habitat for the threatened Florida scrub-jay. Also of great interest was maintaining nesting substrate for the bald eagle in the flatwoods and managing habitat for black rails and other marsh birds in the grassy wetlands.

The size of the subdivided burn units was greatly reduced. Between 1993 and 2002 the Refuge had 202 prescribed burns totaling 93,402 acres in fire maintained habitats. The average burn size was 460 acres. Although some large burns are still conducted, especially in the marshes, it is expected that the trend for more burns covering smaller areas will continue. This is especially true as the Refuge continues to restore scrub habitat.

Space Exploration and Its Effect on Prescribed Burning

Many of the constraints and restrictions on prescribed burning on the Refuge are common to other fire programs. Concerns such as safety of firefighters and the public, increasing urbanization, fickle weather, staffing and funding shortages that are encountered on other stations are likewise present here. In addition to these considerations, this Refuge must deal with an active space port. While the Refuge fire program was evolving, the mission of the KSC was also changing. The Apollo and Saturn V programs were phased out in the late 1970s and the new Space Transportation System (STS) or Space Shuttle program was beginning.

At first, with limited launches and non-sensitive payloads, Shuttle operations had little impact on fire management operations. Burning was prohibited forty-eight hours prior to a scheduled launch and twenty-four hours prior to landing. Pre-launch concerns included danger while fueling the spacecraft, exposure of the orbiter to the elements and increased ground and air traffic just prior to launch. Pre-landing concerns revolved around smoke causing visibility problems in the Orbiter's glide path and anomalies (mishaps) during the landing itself. This soon changed. When KSC was determined to be the primary emergency landing site, rather than Edwards Air Force Base in California, burning was severely curtailed the entire time the Shuttle was in orbit. Although this was ten to fourteen days per space mission, with only two to three launches per year, sufficient burning could still be accomplished. However, as the number of launches increased, lost burning opportunities became substantial.

Additional constraints were established as plans progressed for the launch of the $2.2 billion Hubble Space Telescope (HST) in 1990. Original prescribed burning restrictions for the HST called for no burning within 25 miles of clean rooms where components of the telescope were being processed. This would shut down burning on the entire Refuge for the six to nine months of the Hubble's residency on the KSC. This situation did not bode well for the Refuge's fire management program. Especially since the HST was the first in a series of space-based observatories and other smoke sensitive spacecraft that were expected to be launched over the next fifteen years.

Along with restrictions on burning from space operations on KSC, the Refuge had to deal with CCAFS. At CCAFS, each different type of launch vehicle had its own set of managers, payload processors, and bureaucracy. Additionally, some of the payloads were military missions and much of the information about timing was secret. When it came to getting authorization to burn, almost anyone in either the KSC or CCAFS chain of command could trigger a no-go for the fire. Refuge fire managers spent countless hours fielding phone calls, explaining the reasons for burning and begging to get permission to execute a burn.

The situation was quickly becoming untenable. There was a time when it appeared that all of the issues in force would reduce burning on the Refuge to a point where fire would no longer be a viable tool. It was obvious to all fire knowledgeable people that not burning would lead to a continued increase in the amount of very flammable vegetation. This would not only lead to a serious public safety problem from possible wildfires, but would also prevent effectively managing habitat for the numerous wildlife species found on the Refuge. Some way had to be found to provide for the integrity of both the space program's mission, and the purposes and objectives of the Refuge.

Conflict Resolution

The first step in the resolution process was to educate all of the concerned parties about the reasons for burning. The best selling point was the possible impact of severe wildfires that would occur if the vegetation on the Refuge/KSC was not burned on a regular basis. Here we had some help from Mother Nature. While the memory of the fires of 1981 were still vivid, burn approvals were relatively easy to obtain. As institutional memory faded, approval became more difficult. Florida's bad fire season in 1998 refreshed NASA's collective memory when fires shut down operations for almost a week. This situation precipitated much discussion as to how find more windows of opportunity for burning.

The second factor that helped sell the importance of burning was the Endangered Species Act. The Florida Scrub-jay Recovery Plan identifies the Refuge as having one of the four Primary Core Recovery Units (PCRU) for the threatened Florida scrub-jay (U. S. Fish and Wildlife Service, 2003). In the early 1990s jays were discovered on the site where the Space Station Processing Facility was to be constructed. As part of mitigation for continued use of this and other areas in scrub-jay habitat, NASA agreed to assist the Refuge in restoring overgrown scrub (Schmalzer and others 1994). Since burning is a critical component of scrub restoration, this compelled the KSC to work more aggressively to find windows for burning.

Along with establishing the need for burning, it was also necessary to demonstrate a level of competence in fire management activities. Although the vast majority of prescribed burns nationwide are executed with minimal impact to the surrounding areas, the small percentage of burns that do cause problems are well documented by the media. This situation can cause concern to neighbors when the Refuge announced that a burn is forthcoming. We in the fire community are well aware of the amount of planning, training and skill required to carry out a successful prescribed burn. In many cases however, those we deal with outside our community are not. In most situations, knowledge helps combat the fear of the unknown. This proved to be the case when dealing with NASA managers.

The importance of good communication in solving the problems between space operations and Refuge fire activities cannot be over emphasized. To ensure proper information flow, meetings were set up with all interested parties. In addition to stressing the needs for an active prescribed burning program, a presentation on the behind the scenes work that goes on was given. The extensive training given to burn bosses, firing specialists, air operations staff and other key fire personnel was detailed. The prescription development process, including smoke screening, environmental parameters, equipment and staffing needs were explained. It was also pointed out that the Service requires that a qualified burn boss of appropriate skill level from outside the Refuge review the prescription. At the same time, NASA managers had a chance to express their concerns, ask specific questions concerning fire operations and, most importantly, meet Refuge fire managers face to face.

To further establish our credentials, key NASA managers were invited to observe burns. They were given the whole burn day experience, from the crew briefing to the critique at the end of the day. The overall result of these discussions and observations was an improved level of confidence in the Refuge's ability to conduct a successful burn. It was also important not to hide anything. All of us that have done any burns know that things can go wrong that are beyond our control. The most notable problem is fickle weather. NASA recognized the need for them to be able to initiate emergency protection measures for sensitive areas, such as clean rooms, should this occur.

Once the importance of burning was established, restrictions negotiated down to an agreeable level and comfort levels established, the final piece of the puzzle was to formulate a comprehensive burn notification process. The Space Center's dispatching office agreed to be the focal point for this endeavor through its Joint Base Operations Support Contract (JBOSC) Duty Office. In its early stages the Duty Office received the Refuge's request to execute a burn, and then notified telephonically a long list of interested parties. Not only was this time consuming, but there was still the problem of almost anyone being able to trigger a no-go situation. Over the years this system was improved. Through negotiations with NASA Test Director (NTD), Payload Processing, the Center Director and the Commander of the Air Force Station, this list of people that could actually cancel a burn was reduced to less than ten. All others on the notification list were only provided information. Any concerns had to be forwarded to one of the decision makers. The Duty Office also fielded most of the questions concerning the burn and only passed on to Refuge fire managers those calls they could not handle. The final step was to send all correspondence electronically.

Compromises Achieved

The process of education and confidence building resulted in a compromise that was acceptable to all parties. NASA managers recognized that burning is an essential part of managing the vegetation types that exist on the Refuge/Space Center. They also realized that no burning would eventually result in unacceptable impacts on both the space program and the environment. On the other side, Refuge fire managers became more aware of the sensitivity of spacecraft to smoke and the possible economic and scientific impacts should damage occur to these craft. Both parties recognized the need for compromise and communication.

Through negotiation, the original 25 mile radius burn prohibition when sensitive payloads were present was reduced to a more manageable six miles. Burns were allowed while the Orbiter was in space so long as all its systems were "nominal" and Edwards Air Force Base was available for emergency landings. Lines of communication helped find times in payload processing streams where burning could be done with minimum risk to space craft. Refuge and NASA managers meet several times a year to discuss upcoming operations on both sides that may come into conflict.

A Measurement of Success

The real question is: Did all this effort to find ways of maintaining a prescribed burning program in the middle of an operational space port have any measurable results? One way to quantify the results is to determine if the effects of wildfire events in years similar to 1981 were in any way less catastrophic. In 1981, there were 40 wildfires burned a total of 19,335 acres. Four fires were over 1,000 acres in size, with the largest being 6,300 acres. The average fire size was 483.8 acres. There were also two fatalities. When 1981 is compared to several subsequent severe wildfire seasons, one can see a considerable difference in acres burned and average fire size as shown in table 1.

The first of these seasons occurred in 1992. Several years of below normal rainfall preceded this fire season, as was the case in 1981. Forty-eight wildfires were ignited during the spring and summer. However, only 1,404 acres were burned, most of this was in one 1,200 acre fire which occurred when resources were spread thin on a day when several fires were started. The average fire size was 29.7 acres. There were no injuries to firefighters or other personnel, nor were any structures damaged.

Another bad fire season occurred six years later in 1998, when 25 wildfires burned 5,555 acres. As in 1992, multiple starts exceeded initial attack capabilities and several fires burned together to account for 4,090 acres of this total. The average fire size was 222.2 acres. While this is much larger than the average size in 1992, it is still less than half of what was experienced in 1981. Again no injuries occurred and no structures were damaged.

The drought that began in 1998 continued through 1999 and 2000. In 1999, 16 fires burned a total of 1,219 acres. Once again, one large fire that burned 1,084 acres. The average fire size this year was 76.2 acres. No injuries resulted and no structure damage occurred. By 2000, the drought had abated somewhat. More thunderstorms resulted in 25 starts a third again more than the previous year. This year only 319 acres were burned, with the biggest fire only amounting to 150 acres. No injuries or structure damage resulted.

The Refuge burns between 15,000 and 20,000 acres in a normal year. Even in these strenuous wildfire seasons a number of prescribed burns were completed. It is difficult to determine how much of this reduction in acreage burned should be attributed to the fuels reduction resulting from prescribed burning. Training of personnel and improved equipment certainly played a role. However, without the consistent application of prescribed fire to the Refuge's landscape, more acreage would have been burned by unwanted wildland fire in 1992 and the years of 1998 through 2000. More importantly, the risk to Refuge firefighters suppressing of these fires would have been greater.

Table 1—Comparison of severe fire years at Merritt Island National Wildlife Refuge.

Year	Number WF	Acres burned	Av. Fire size	Largest fire	Number Rx fires	Acres burned
1981	40	19,335	483.8	6,300[a]	2	3,690
1992	48	1,404	29.7	1,200	8	7,552
1998	25	5,555	222.2	4,090	20	5,605
1999	16	1,219	76.2	1,084	19	2,380
2000	24	319	13.3	150	25	7,414

[a] Four fires were over 1,000 acres.

Conclusions

Carrying out an prescribed fire program on Merritt Island National Wildlife Refuge presents some unique challenges. The dialogue between Refuge fire managers and the various components of the Nation's space program is an ongoing process. As the space program changes, new points of conflict will arise and new ways to meet the objectives of all the agencies involved must be developed.

Managing fire at Merritt Island National Wildlife Refuge has many unique aspects, but many of the conflict resolution processes described here are applicable in other places. Certainly talking with neighbors and other concerned parties is necessary to sell a burning program. It is likewise important for fire managers to learn the specific concerns of those who live and work in the vicinity of burns. Establishment of communication channels through homeowner associations, the media and personal contact is essential to obtaining the support of the community for a burning program. Allow the public to see the degree of professionalism that is a part of the burning activities.

It is also important to be honest. No amount of planning, no amount of training nor the best forecast in the world can guarantee that nothing will go wrong. However, up front discussions of this possibility and the presence of a good contingency plan can go far in mitigating a bad situation should it occur. Remember, use discretion and care. History has shown that one mishap can undo years of successful confidence building. In spite of all this, the experience of the Refuge's fire program shows that, with perseverance, and initiative, an effective prescribed burning program can be developed under difficult circumstances.

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Measuring Success in Your Fuels Program: From the Report Card to Valuable Learning

Paula Nasiatka[1] and David Christenson[2]

Abstract—*How can a unit learn in everyday fuels programs and from program reviews? How can a unit move from living in the "report card" culture to discovering more effective ways to improve what it knows and how it learns? Six specific tasks are critical to organizational learning according to David A. Garvin of Harvard Business School. By engaging in these tasks a unit can significantly improve both its programs and its learning. To further assist field units, an organizational learning survey has been recently developed by the Harvard Business School in cooperation with the Lessons Learned Center. This tool is designed to measure how a unit learns. By examining the learning environment, learning processes and leadership one can measure a unit's level of learning and its improvements over time.*

Introduction

Fuels programs around the country are faced with their programs being evaluated in periodic program reviews. These reviews often follow a report card format rather than a true learning format. This paper is aimed at two audiences: fuels programs at the unit level and those who serve on program review teams. Unit level fuels programs who take the time to practice the six critical tasks of a learning organization and periodically take the learning survey should find they are better prepared for program reviews. Program reviewers who incorporate the six critical tasks into their reviews and then share the unit lessons and effective practices will improve the wildland fire organizational learning environment.

Critical Tasks in Fuels Programs

According to Garvin, a learning organization tries to accomplish six tasks:

1. Collect intelligence about the environment.
2. Learn from the best practices of other organizations.
3. Learn from its own experiences and past history.
4. Experiment with new approaches.
5. Encourage systematic problem solving.
6. Transfer knowledge throughout the organization.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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These six critical tasks can be directly applied in wildland fire fuels programs:

1) In c*ontinually collecting intelligence about the fuels environment*, make certain to collect critical information and regularly incorporate it into your planning and implementation. Search, inquiry and observation are the three methods for collecting intelligence. When searching, use comparisons and remember to cross-check to validate the accuracy of the information. When using the inquiry method, be exploratory by asking open-ended questions. Observation is particularly important when a lot of the tacit knowledge at a unit is in individuals' heads. If "we know more than we can tell" than the observation method is particularly effective in program reviews. Although program reviews generally take place in the off season, everyone can learn more effectively if a review is done during a prescribed fire or wildland fire use event because lessons and effective practices can be more clearly illustrated.

2) *Learn from the best practices of other organizations by* looking at successful processes other fuels or fire management programs are using and see how they may be applied in your unit. One way to do this is through the Wildland Fire Lessons Learned Center's myfirecommunity.net Web site which serves as an online community center for the interagency wildland fire community. The member directory identifies current projects on which individuals are working, particularly in fuels. The neighborhoods are specifically designed for communities of practice (networks of people) to share knowledge about their fire management programs.

Lessons Learned Center Information Collection Team reports (ICT) are another way to learn about the effective practices of other fuels organizations. Two recent ICTs have focused on wildland fire use (WFU) programs both from a unit that had its first WFU to a unit with a 35 year history. Both of these reports are at: http://www.wildfirelessons.net/ICT.aspx

3) *Learn from your own experiences and past history* by continually examining your unit's past performance. Use the After Action Review (AAR) process to learn from each project whether it be a mechanical fuels treatment, prescribed burn, or WFU. The four questions in an AAR are: 1) What was the plan? 2) What actually happened? 3) Why was there a difference? and 4) What are we going to do next time? (sustain/improve) To properly use the AAR process, it is imperative to take the answers to the fourth question and incorporate what will be sustained and improved into short and long-term planning. Units that successfully do this actually assign individuals to be responsible for incorporating the recommendations into the fuels program planning process.

4) *Experiment with new approaches* that you learn from other fuels programs or come from your unit AAR process. Try a different approach especially if what you have been doing has not been working the way you want. It is extremely important to listen to unit members who have a different perspective and be open to adopting a new idea.

5) *Encourage systematic problem solving* among all members of your unit. Follow a systematic path while trying to solve a problem by looking at what was planned, what happened, and *why* it happened. It is common to try and correct a problem without analyzing what happened and why.

6) *Transferring knowledge throughout the organization* is the true test of being a learning organization. Make sure you set aside time during planning and information meetings to share new knowledge with your fuels and fire

management staff as well as other units. The Lessons Learned Center is your resource center for sharing what you have learned beyond the scope of your own unit. The AAR Rollup is the format for units to record and share their lessons and effective practices. The Rollup captures the successes, challenges, training curriculum and unresolved issues recommendations. Individual units and program reviewers should submit these to the Lessons Learned Center. The AAR Rollup form can be found at: http://www.wildfirelessons.net/AAR.aspx

Organizational Learning Survey

The Lessons Learned Center has been cooperating with Harvard Business School as they developed the first of its kind organizational learning survey to help individuals and units measure their strengths and weaknesses in relation to the six critical tasks of organizational learning. During the summer of 2005, approximately 200 interagency wildland fire personnel took the draft survey online. Members of the wildland fire community completed it as an individual working unit, a wildland firefighting crew, or as an incident management team member. Initial results illustrated that the wildland fire community rated well in the sections compared with three other organizations that completed the survey.

The survey tool has three sections:

1) Learning culture and environment – this includes the interpersonal climate, how differences are valued and the openness to new ideas.
2) Learning Processes – six processes assessed are experimentation, information collection, analysis, education, training and information transfer.
3) Leadership – eight different aspects of how managers communicate and relate to employees are evaluated.

The survey tool is in its final completion stages and should be online for the wildland fire community and other organizations to use in May 2006. Individuals will be able to take the survey and have their scores measured against others in the wildland fire community. From the survey scores, individuals and units can see what areas they are strong or what areas need work. Units can then take the survey periodically to further improve their fuels programs.

Conclusion

Units can continually improve the learning environment of their fuels program by using the six critical tasks of a learning organization. Program reviewers can move away from a report card format by incorporating the six critical tasks into their reviews. Fuels programs and program reviewers should share the knowledge with the Lessons Learned Center so others in the wildland fire community can also learn from them. The organizational learning survey will also assist fuels organizations in measuring their effectiveness as a learning organization in comparison with others in the wildland fire community.

Acknowledgment

David A. Garvin, Harvard Business School professor and author of the book *Learning in Action: A Guide to Putting the Learning Organization to Work* is credited for the six critical tasks of a learning organization. Acknowledgments also go to David A. Garvin, Francesca Gino and Amy Edmonson of Harvard Business School for developing the first of its kind organizational learning survey.

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Fire Weather

Predicting Fire Season Severity in the Pacific Northwest

Paul Werth[1]

Abstract*—Projections of fire season severity that integrate historical weather and fire information can be used by fire managers when making decisions about allocating and prioritizing firefighting resources. They enable fire managers to anticipate fire activity and pre-position resources to maximize public and firefighter safety, reduce environmental impacts, and lower firefighting costs. This research determines the potential severity of fire seasons in the Pacific Northwest by using statistical techniques that correlate weather data and annual-acreage-burned figures for five fire management agencies in Washington and Oregon (U.S. Forest Service, Bureau of Land Management, Bureau of Indian Affairs, Oregon Department of Forestry, and Washington Department of Natural Resources). Weather and fire trends for the 1970 to 2004 time period were calculated, and thresholds for above average, average, or below average fire seasons were determined based upon annual acres burned. Eight weather parameters were then correlated using scatter diagrams, contingency tables, and multivariate regression equations to predict above average, average, or below average fire seasons based upon projected acres burned. Results show considerable variance in predictors by fire agency with accuracy rates of 60 to 85% for predictions of above average fire seasons and 85 to 90% for average and below average fire seasons.*

Introduction

Several considerations affect fire managers' decisions regarding allocation of firefighting resources including: (1) public and firefighter safety (2) the potential effect of fires on local environments, and (3) the increasing impact of firefighting costs on agency budgets. Over the past several years, the Northwest Interagency Coordination Center has demonstrated that pre-positioning resources throughout Washington and Oregon in advance of fire outbreaks, improves their effectiveness in achieving all three of the above-listed goals. The obvious question arises, "How do fire managers determine the most effective placement of resources prior to the fire season?" One tool they use is a pre-season assessment of historical weather and fire information that produces projections of expected fire season severity for any given area in the Pacific Northwest. This research takes that assessment to the next level by applying statistical techniques to weather and annual acres-burned data for five, fire management agencies in Oregon and Washington, including the U.S. Forest Service, Bureau of Land Management, Bureau of Indian Affairs, Oregon Department of Forestry, and Washington Department of Natural Resources.

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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Data

The assumption that wildland fire severity is primarily driven by low fuel moisture has historically directed research towards drought (Westerling and others 2002; Hall and Brown 2003) as a pre-season, predictor of fire season severity. This research also uses drought, but expands the list of potential predictors to include: seasonal precipitation, mountain snowpack, snowmelt date, and the sea surface temperature of the Pacific Ocean.

Monthly precipitation figures for seven weather stations in Washington and Oregon were used in this analysis. The seven stations used were Medford, Portland, Redmond, Burns and Pendleton in Oregon, and Yakima and Spokane in Washington (fig. 1) They were selected based on their location near fire-prone areas and completeness of record since 1970. Monthly precipitation data was divided into four groups: (1) winter (November-March), (2) spring (April-May), (3) June, and (4) summer (July-August). June is a group by itself because precipitation during the month of June can significantly impact the duration of significant fire danger.

Snow pack water equivalency (SWE) data for the Columbia River Basin of Washington, Oregon, Idaho and portions of British Columbia, Montana, and Wyoming was also used in this analysis. The April 1 SWE is of particular importance because the snowpack typically peaks around April 1st. SWE figures for May 1st were used to determine the rate of spring snowmelt in the mountains. SWE data was used to track the annual snowmelt date at 39 Natural Resources Conservation Service (NRCS) SNOTEL sites in Washington and Oregon from 1986 to 2005 (fig. 2). These sites represent every major river basin and different elevations within Washington and Oregon.

Historic Palmer Drought Severity Index (PDSI) values for climate zones in Washington and Oregon were collected from the National Climatic Data Center (NCDC) database. Average March values for each state along with the number of climate zones classified in moderate drought were used in this research.

Monitoring sea surface temperature anomalies in the central Pacific Ocean is essential in determining the phases of the El Niño / Southern Oscillation (ENSO). The warm phase, commonly called El Niño, is characterized by abnormally warm sea surface temperatures in the central and eastern equatorial Pacific Ocean. The cool phase of this natural cycle is called La Niña. El Niño often results in warm, dry winters and below normal snow packs in the Pacific Northwest. La Niña has the opposite effect, producing cool, wet winters and above average snow packs. Both phases appear to have minimal effect on summer weather in the Pacific Northwest. The Multivariate ENSO Index (MEI) combines six variables (sea-level pressure, zonal and meridianal components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky) to monitor ENSO. Negative values of the MEI represent the La Niña phase while positive values indicate El Niño. Bi-monthly values of MEI were retrieved from the NOAA-CIRES Climate Diagnostics Center in Boulder, Colorado.

The Eastern North Pacific (ENP) (fig. 3) sea surface temperature index is a component of the Pacific (P) index (Castro, McKee, and Pielke 2001*)* that combines tropical and North Pacific SSTs into one index. The P index has been correlated with upper-level atmospheric circulation patterns over the North Pacific Ocean and the Western and Central United States. It has also been correlated to the onset of the Southwest Monsoon and precipitation anomalies in the Great Plains states. Data to compute the ENP was downloaded from the Comprehensive Ocean Atmospheric Dataset (COADS).

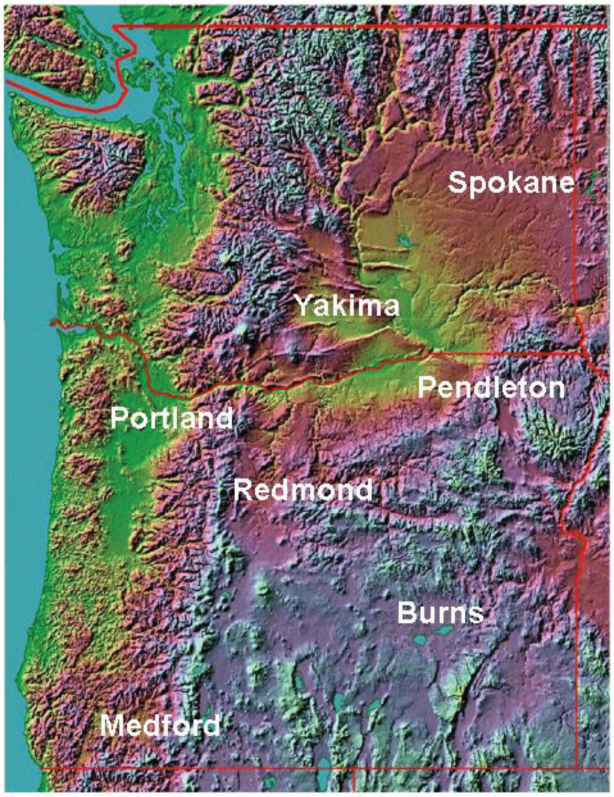

Figure 1—Seasonal Precipitation Stations.

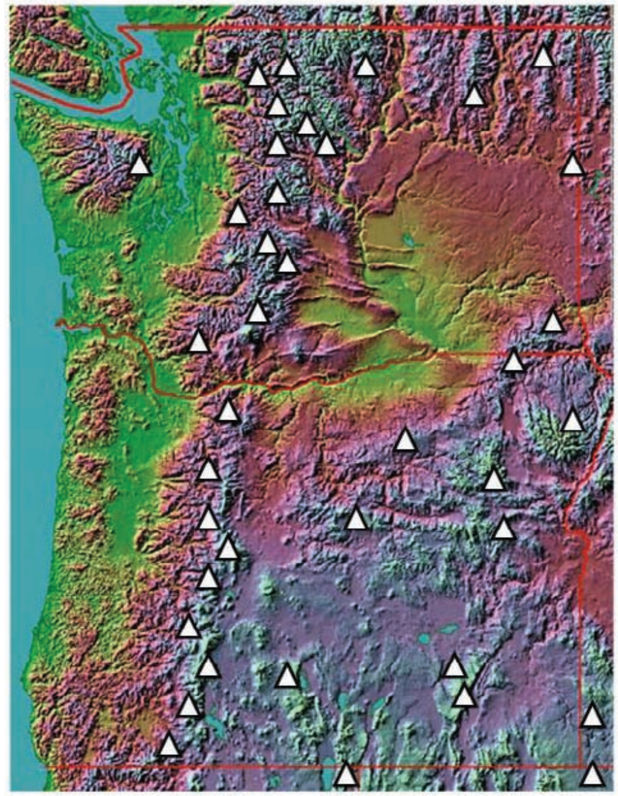

Figure 2—WA and OR SNOTEL Stations.

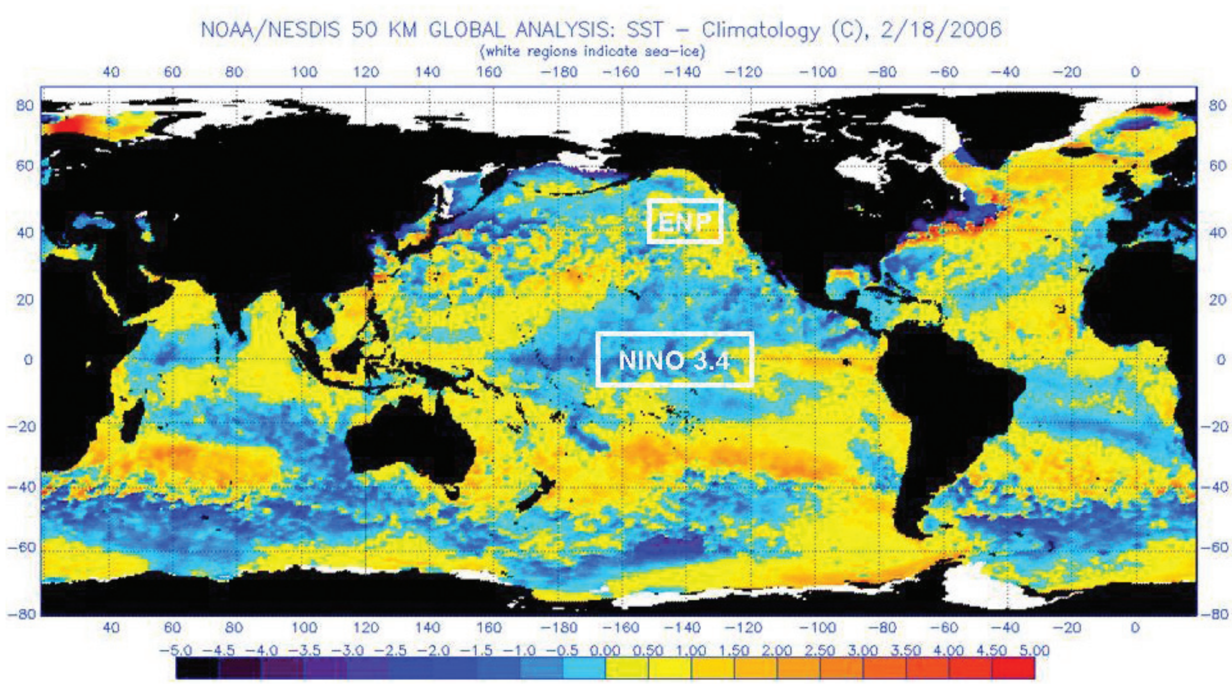

Figure 3—ENP and NINO 3.4 Pacific SST Regions.

Area-burned figures (in acres) for federal- and state-protected land in Washington and Oregon was obtained from the Oregon Department of Forestry (ODF), Washington Department of Natural Resources (DNR), and the Northwest Interagency Coordination Center annual summaries dating back to 1970. The acres burned statistics include both lightning and human-caused fires.

Weather and Area Burned Trends

The first step in determining the significance of seasonal precipitation on fire season severity in the Pacific Northwest is to determine whether there are long-term trends in both weather and fire data. This was accomplished by constructing time lines for each dataset and then performing a regression analysis to determine whether there are identifiable trends in the data. Linear regression equations were developed for each data set in the form of: $y = mx + b$. The equation algebraically describes a straight line for a set of data with (x) the independent variable, (y) the dependent variable, (m) the slope of the line, and (b) the y-intercept. The sign (+ or –) and magnitude of m signify whether the independent variable is increasing or decreasing and at what rate.

Regression analysis indicates decreasing winter rainfall (November-March) and Columbia River Basin April 1 SWE since 1970 (figs. 4 and 5). The decrease is more apparent in SWE, indicating warmer winter temperatures are also a contributor in addition to decreased precipitation. However, the trend in spring rainfall (April and May) is for wetter conditions (fig. 6). Rainfall amounts for July and August also show a trend toward drier weather during the summer in the Pacific Northwest (fig. 7).

Similar regression techniques were used to establish trends in acres burned for federal and state land management agencies in Washington and Oregon. All agencies trend toward more acres burned per year, especially since the mid-1980s. This is most evident in the U.S. Forest Service data (fig. 8), which shows the largest trend in acres burned of all the agencies.

Defining Fire Season Severity

Defining fire season severity is a difficult question, one that may have many answers. Some base it on the total number of fires or the number of days in high to extreme fire danger; others use the number of large fires during the year. In order to predict fire season severity, one must first define it. The standard used in this research is the annual acres burned by fire agency. The dataset includes thirty-five years of annual acres burned by agency from 1970 to 2004. Data was sorted by agency and by year from the highest to the least number of acres burned. Data was then divided into thirds, or terciles. Years in the top tercile, (i.e., those with the largest number of acres burned,) were classified as “Above Average” fire seasons. Years in the middle tercile were classified as “Average” fire seasons, and years in the bottom third were classified as “Below Average” fire seasons. This classification was performed for each of the five federal and state fire agencies. Threshold acres were identified for each category as displayed in this graph for the Bureau of Land Management (BLM) (fig. 9).

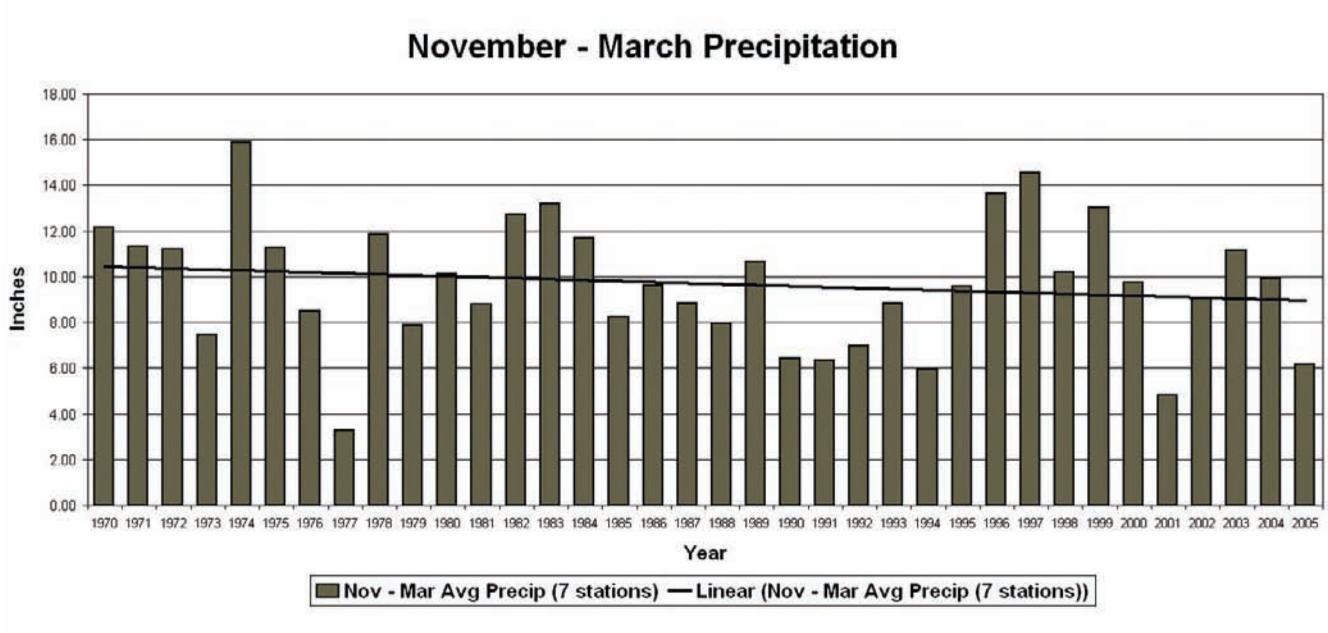

Figure 4—Winter Precipitation Trend.

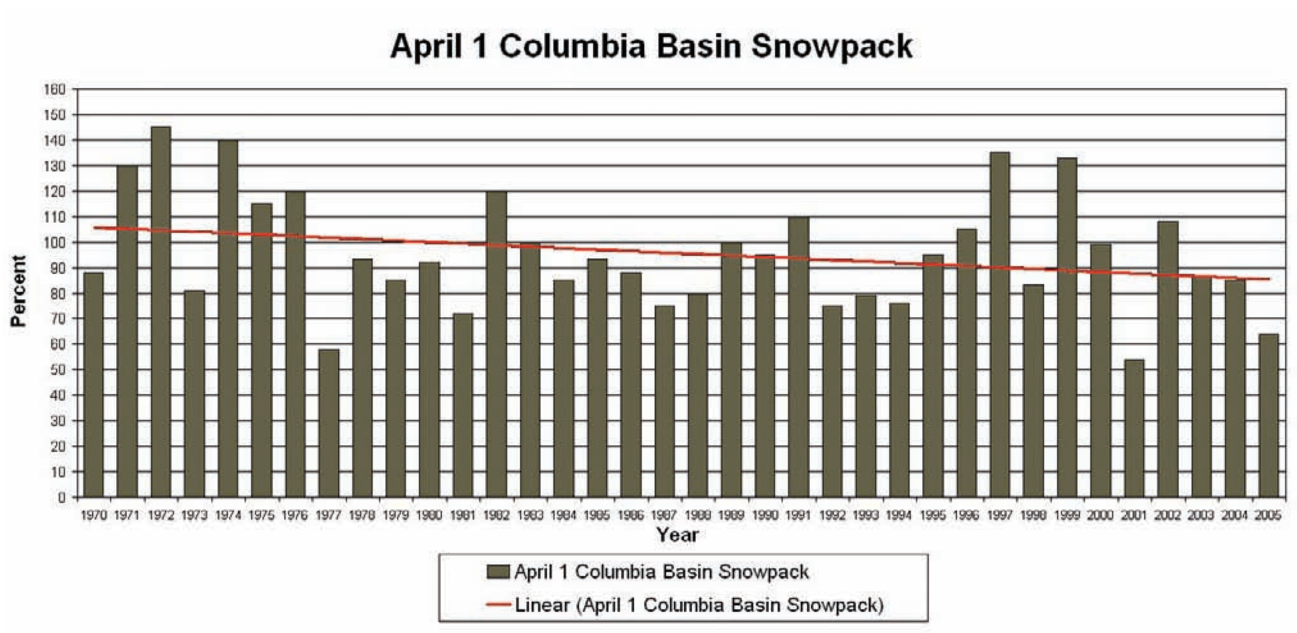

Figure 5—April 1 Columbia Basin Snowpack Trend.

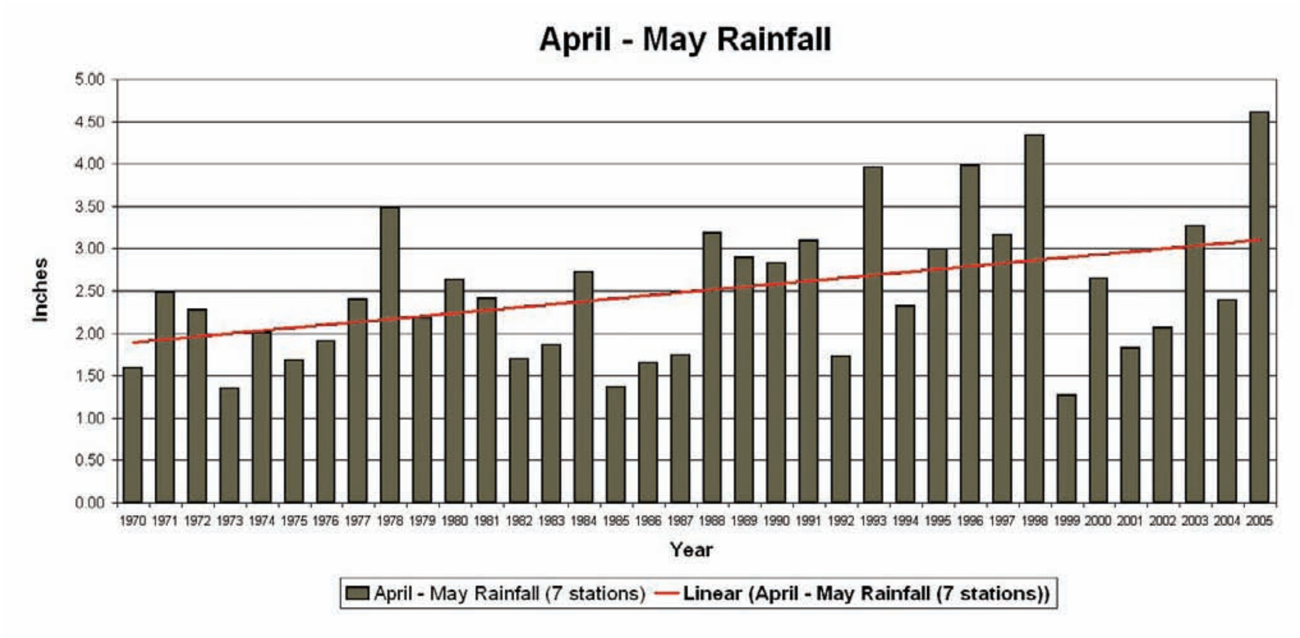

Figure 6—Spring Rainfall Trend.

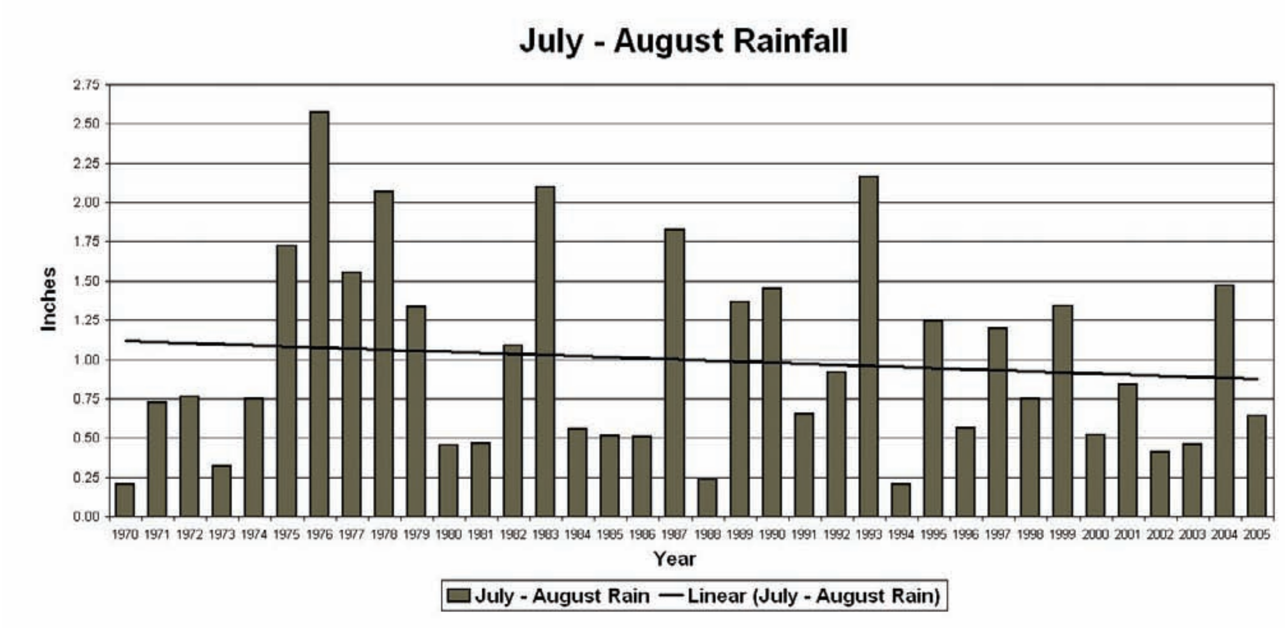

Figure 7—Summer Rainfall Trend.

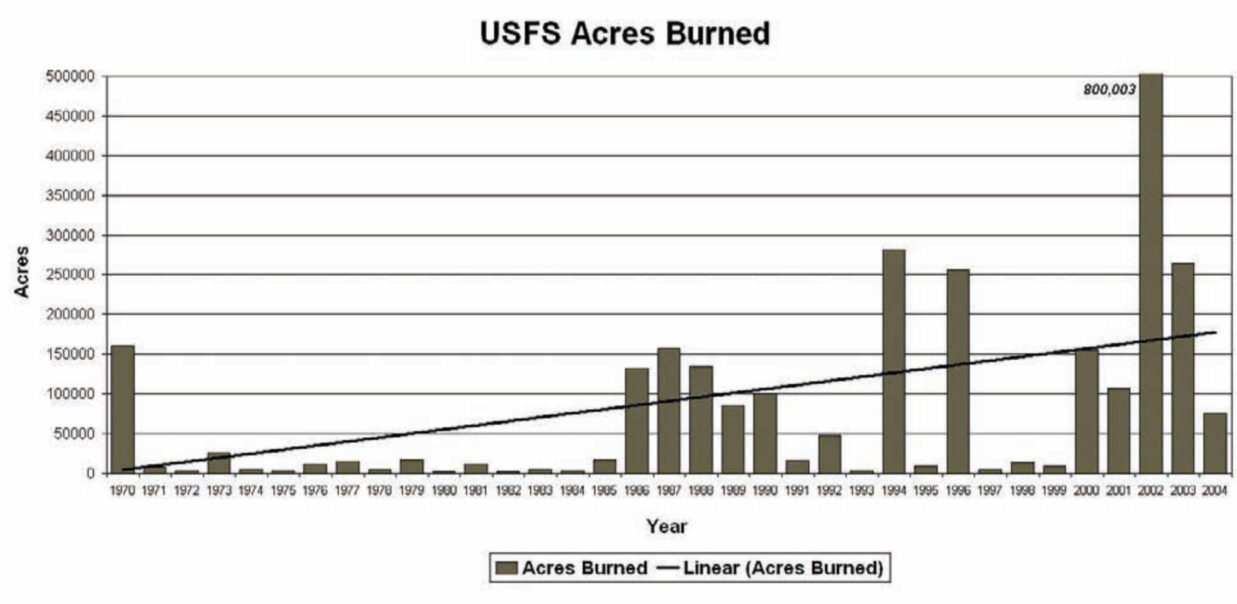

Figure 8—USFS Acres Burned Trend.

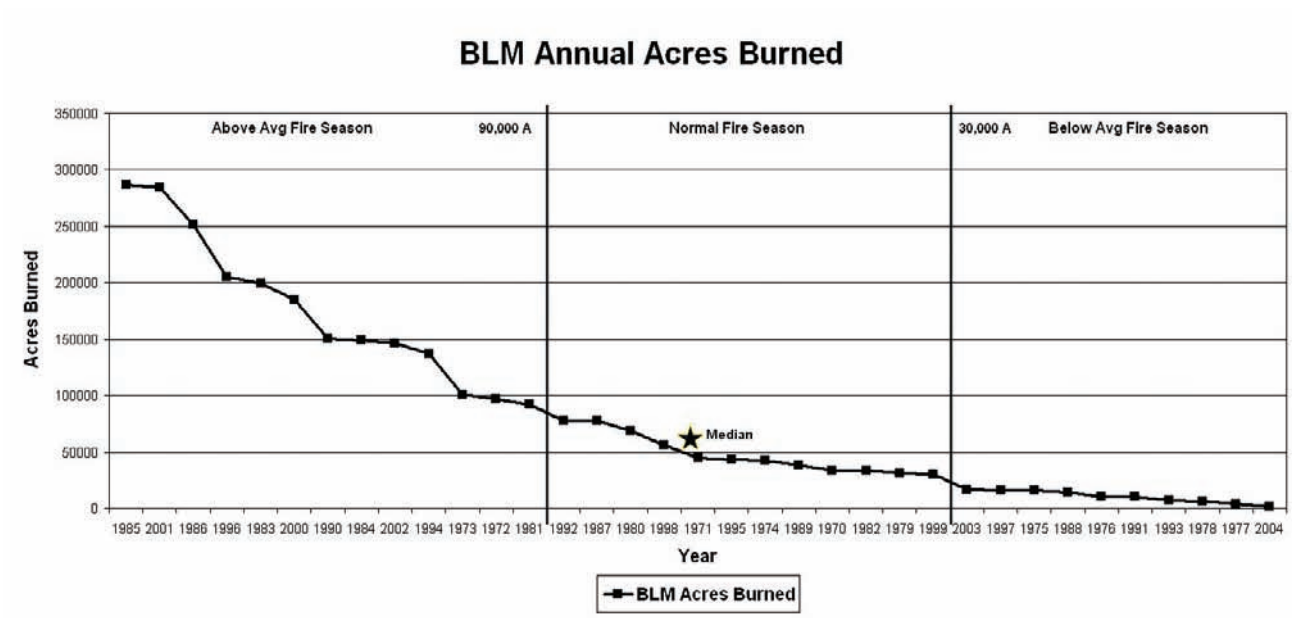

Figure 9—Sorted BLM Acres Burned and Severity Thresholds.

Analysis Methods

Various statistical techniques were used to determine which variables would be the best predictors of fire season severity. Polynomial regression analysis was used to create multivariate forecast equations. Graphical regression was also used in conjunction with contingency tables. All analysis was performed using Microsoft Excel.

Multivariate Equations

The first step in this process was to identify which variables (seasonal precipitation, snow pack SWE, spring snowmelt date, March PDSI, and Pacific SSTs) were the best predictors of acres burned for each agency. Each variable was ranked from best to worst based on its correlation (R-squared value) with acres burned. Table 1 displays the rankings of each variable by agency. Overall, summer rainfall (July/August) was the best predictor, with March PDSI, April 1 SWE, and May 1 SWEs a close second. There were considerable differences in the predictor rankings by agency.

However, even the best predictors did not do a good job of forecasting acres burned alone. Much better results were achieved when all the variables were used. This was accomplished by creating multivariate (multiple regression) equations unique to each fire agency using all the variables. Each variable was “weighted” according to its correlation factor. The equation forecasting acres burned took the form $y=a_1(m_1x_1^2+n_1x_1)+...+a_n(m_nx_n^2+n_nx_n)+b$, where (y) is the dependent variable (acres burned), (x_1) through (x_n) the independent variables, (a_1) through (a_n) are variable weighting factors, (m_1,n_1) through (m_n,n_n) are coefficients of each independent variable, and (b) a constant.

The resulting equation predicts acres burned by fire agency using either observed or forecasted values as input for each independent variable.

Scatter Diagrams and Contingency Tables

A second method of predicting acres burned is the utilization of scatter diagrams and contingency tables. This technique plots one variable against the other (i.e., April 1 SWE versus Spring Precipitation) on an x-y scatter diagram, and then labels the intersection of those two variables as either an “Above Average” fire season or not. In this manner, threshold values for each variable can be constructed, dividing the diagram into “YES - high probability” or “NO - low probability” risk areas of fire season severity (fig. 10). The results from multiple scatter diagrams, correlating a selection of variables, are then input into a 2-way YES / NO contingency table (fig. 11) that predicts the probability of an “Above Average” fire season and the range of acres burned in similar years dating back to 1970.

Table 1—Correlation Factor Ratings by Agency.

Parameters	USFS	BLM	BIA	ODF	WDNR	Ave Rank
Winter Rain	9	7	8	3	3	6.00
Apri1 1 Snowpack	5	3	5	4	5	4.40
Spring Rain	4	5	2	5	7	4.60
June Rain	3	7	4	8	8	6.00
Summer Rain	1	1	1	5	1	1.80
March PDSI	6	6	6	1	2	4.20
April ENP	2	7	9	7	9	6.80
Snowmelt Date	6	3	2	9	4	4.80
May 1 Snowpack	6	2	6	2	5	4.20

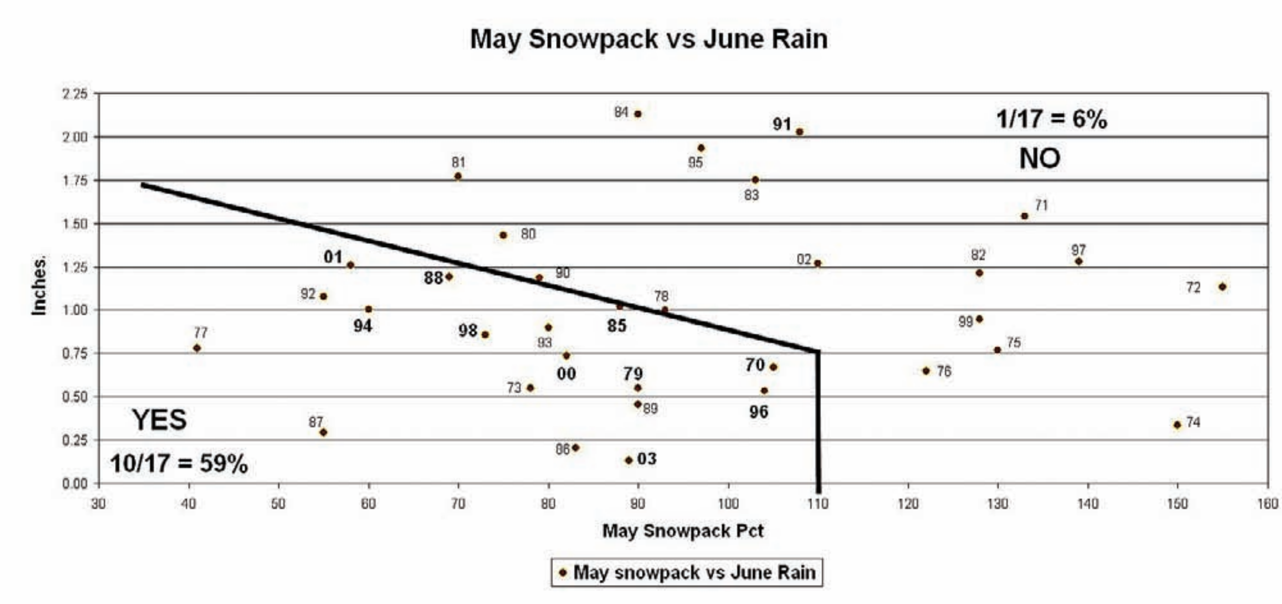

Figure 10—WA DNR May SWE vs June Rain.

		April 1 Snowpack vs June Rain						
		Yes		*No*		*Total*		
April 1 Snowpack vs Spring Rain	*Yes*	5/6	0.83	2/8	0.25	7/14	0.50	*Yes*
	No	1/1	1.00	0/5	0.00	1/6	0.17	*No*
	Total	6/7	0.86	2/13	0.15			
		Yes		*No*				

Figure 11—USFS YES/NO Contingency Table.

Results

The combination of scatter diagrams, contingency tables, and multivariate equations produces the following outputs used to predict the severity of fire seasons in the Pacific Northwest:

- a definition of fire season severity (above average, average, below average) based on acres burned by fire agency,
- the projected acres burned for the coming fire season, and
- the probability of an "Above Average" fire season.

The program is based on thirty-five years of weather and fire data (1970 to 2004). The relatively small number of data points is near the minimum needed to draw confidence in the statistical analysis. However, significant changes in firefighting strategy, resource availability, and wildland fuel regimes over the years produce additional uncertainty if data from years prior to 1970 is included. Thus, the current evaluation of how well the program performs is based upon "dependent" rather than 'independent" data. Statistics in future years will be able to provide more relevant verification.

Accuracy rates indicate the program will produce correct forecasts of fire season severity in Washington and Oregon in 70 to 85% of the years on which the data was based. A forecast of an "Above Average" fire season should verify correctly 60 to 85% of the time, and a forecast of "average" or "below average" 85 to 90% of the time. There appear to be better accuracy rates in predicting acres burned in timber fuels compared to grass / brush fuels, which isn't surprising when considering the sensitivity of fire spread rates in grass fuels.

2006 Northwest Fire Season

Early projections of 2006 fire season severity in Washington and Oregon are based on correlations with past fire seasons and the following factors: weak La Niña conditions, a wet winter, lack of drought, an above normal snowpack, and projected late spring snowmelt dates. Additional assumptions are that spring and summer will experience "near normal" or "typical" precipitation patterns (i.e., periodic rains through June, followed by dry weather during July and August) and there will be an average amount of lightning.

Considering the above factors, it is highly unlikely that Washington and Oregon will experience a severe fire season in 2006. However, the threat of large fires will vary considerably by fuel type. Forest fuels in the mid and higher elevations of the Cascade and Blue Mountains will have the lowest probability of sustaining large fire growth. The threat of large fires will be the highest in grass fuels, primarily in the "High Desert" of central and southeastern Oregon. Other locations that may experience a greater chance of large fires are the pine forests along the lower eastern slopes of the Cascades and the lower slopes of the Blue Mountains, where grass is the primary carrier of fire. Table 2 displays the severity forecast for each of the five federal and state agencies, as well as the projected acres burned.

In general, western Washington and western Oregon, including the crest of the Cascades, will likely see a *Below Average* fire season. Eastern Washington can expect an *Average* fire season. Eastern Oregon may also see a *Below Average* fire season in the Klamath Basin and most of the Blue Mountains. Central and southeastern Oregon are projected to experience an *Average to Above Average* fire season (fig. 11).

Table 2—Projected 2006 Acres Burned by Agency.

Agency	2006 Fire season	Probability of an above average fire season	Projected 2006 acres burned	Threshold acres burned for an above average fire season
USFS	Average to below average	10%	25,000 to 50,000 acres	120,000 acres
BLM	Average to above average	40%	50,000 to 90,000 acres	90,000 acres
BIA	Average to above average	30%	10,000 to 20,000 acres	20,000 acres
ODF	Average to below average	10%	5,000 to 9,000 acres	14,000 acres
WADNR	Average to below average	10%	4,000 to 9,000 acres	10,500 acres

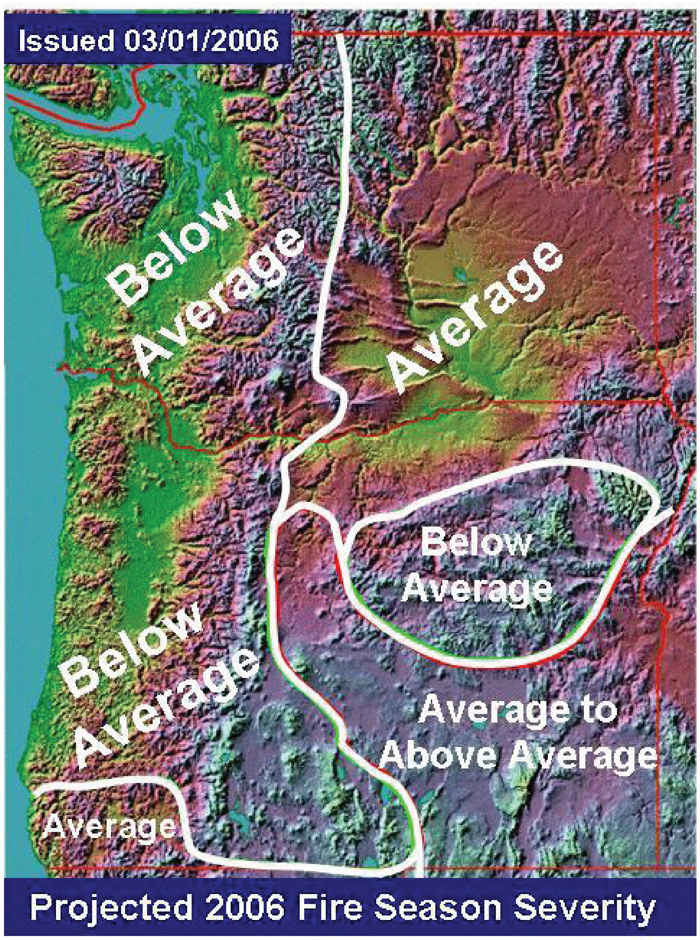

Figure 12—Northwest Fire Season Severity.

Summary and Conclusions

Potential fire season severity in the Pacific Northwest is projected using statistical techniques correlating weather data and annual-acreage-burned figures for five fire management agencies in Washington and Oregon. Weather and fire trends for the period 1970 to 2004 are calculated. Thresholds for above average, average, or below average fire seasons were determined based on annual acres burned. Eight weather parameters were correlated using scatter diagrams, contingency tables, and multivariate regression equations to predict above average, average, or below average fire seasons based on projected acres burned. Future modifications to this research may include replacing existing variables with new and better variables, and the development of equations that predict firefighting costs and resource needs. Although this research is specific to the Pacific Northwest, the concept of using multiple predictors to forecast fire season severity is adaptable to other areas, nationally and internationally.

Acknowledgments

The author thanks Brian Potter, AirFIRE Team Seattle WA, USDA Forest Service; Tony Westerling, University of California, San Diego; and John Werth, National Weather Service for their helpful comments and suggestions in the review of this paper.

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Employing Numerical Weather Models to Enhance Fire Weather and Fire Behavior Predictions

Joseph J. Charney[1] and Lesley A. Fusina

Abstract—*This paper presents an assessment of fire weather and fire behavior predictions produced by a numerical weather prediction model similar to those used by operational weather forecasters when preparing their forecasts. The PSU/NCAR MM5 model is used to simulate the weather conditions associated with three fire episodes in June 2005. Extreme fire behavior was reported across the Southwest, Great Basin, and Southern California Incident Areas during this time period. By comparing the simulation results against reports of extreme fire behavior, the ability of the model to differentiate between the three episodes is assessed, and relationships between weather conditions and extreme fire behavior are suggested. The results of these comparisons reveal that the most extreme fire behavior occurred in locations where near-ground temperatures were the highest. While relative humidity did not vary substantially across the three episodes, variations in temperature led to a greater potential for evaporation and fuel drying, which could have been a factor in the observed extreme fire behavior. Additional analyses reveal that the diurnal variations in mixed layer processes also explain some of the variability in fire behavior in the episodes.*

This paper represents a step towards realizing the full potential of atmospheric physics models for fire weather and fire behavior forecasting. As researchers and operational personnel come to understand the relationships between fire behavior and atmospheric processes that can be predicted by weather forecast models, these concepts can be tested in the broader context of day-to-day fire weather forecasting. Eventually, these techniques could provide additional information for the fire weather forecasters and fire managers, using tools that are already available and used routinely in weather forecast offices.

Introduction

The fire weather tools that are currently employed in National Weather Service (NWS) forecast offices are typically the product of empirical studies that were designed to establish statistical relationships between certain types of fire danger or fire behavior and observed weather conditions (see e.g. Fosberg 1978, Lavdas 1986, Haines 1988). As these indices were being developed by the fire weather community, the broader atmospheric science community was more focused on severe storms and hurricane research, and developed tools such as radar and high-resolution numerical weather prediction (NWP) models to aide in those research endeavors. As the research evolved, these tools became intrinsic to the operational weather forecasting process, and are now used every day throughout the world for forecasting extreme weather events.

Until very recently, these same tools were seldom if ever used as part of NWS fire weather forecasting, nor were they applied in research projects

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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trying to improve our understanding of fire-atmosphere interactions. While radar observations have limited application for fire weather forecasting, beyond determining when and where precipitation is and will soon occur, NWP models can provide temporally and spatially detailed information about numerous aspects of fire-weather that could directly or indirectly impact fire behavior. Researchers can employ these models to establish *physical* relationships between weather phenomena and observed fire behavior, rather than relying upon empirical and statistical relationships whose broad applicability is questionable (Potter 2002). These physical relationships lead to the development of new fire weather indices and diagnostic techniques (Charney and Keyser, 2003) that can, in turn, be passed on to operational fire weather forecasters for use in day-to-day fire weather forecasting. Fire weather forecasters can then implement these new tools to analyze output from existing NWP models, enabling them to provide guidance to fire managers making decisions that pertain to prescribed burn planning and ignition, as well as wildfire decision support that can help save lives and property.

This paper will examine the performance of an NWP model during three periods of June, 2005: June 17-18 (hereafter referred to as Episode 1), June 23-24 (Episode 2), and June 27-28 (Episode 3), during which very high to extreme fire indices were reported in Arizona, New Mexico, and Nevada. Despite the extreme fire indices, reports of extreme fire behavior varied considerably across the three episodes. We hypothesize that variations in weather conditions during these periods can help explain the variability in observed fire behavior. In section 2, we will detail the observed fire behavior reports. Section 3 will discuss the NWP model employed to study the weather conditions during the three periods identified above. Section 4 will present the fire-weather predictions from the NWP model, and discuss relationships between the simulated weather conditions and the observed fire behavior. Section 5 will include discussion and concluding statements.

Observed Fire Behavior

In May and June 2005, extreme fire indices were reported in the National Interagency Coordination Center (NICC) Incident Management Reports across the Southwest, Southern California, and Eastern Great Basin Incident Areas (see e.g. http://iys.cidi.org/wildfire/ for archived NICC Incident Management Reports). This extended period of extreme fire indices was associated with numerous fires during the period. For the purposes of this study, we choose to focus our attention on three periods in the last two weeks of June, during which particularly extreme fire behavior was reported, including rapid spread rates, crown fires, spotting and torching, and flame lengths of 50 to 80 feet.

Episode 1 occurred on June 17-18 (Fig. 1a). In the areas of interest, extreme fire indices were reported. Three large fires were reported in New Mexico and Arizona, two of which were designated as Wildland Fire Use (WFU) fires. The non-WFU fire in Arizona reported active but not extreme fire behavior.

Episode 2 occurred about a week later, on June 23-24 (Fig. 1b). During this time period, eight large fires were reported across central Arizona and more than twelve fires were active across southern California, southern Nevada, northwestern Arizona, and southwestern Utah. Extreme fire behavior was observed at all of these fires. The central Arizona fires were reported to

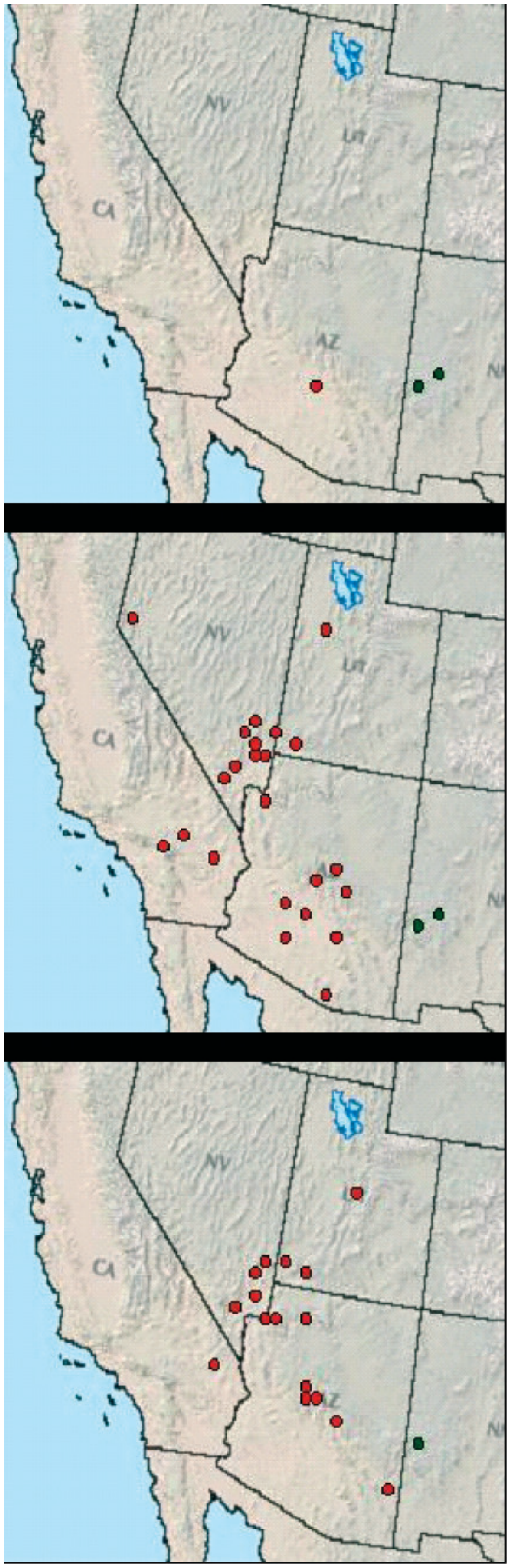


Figure 1—Locations of NICC Incident Management Reports of extreme fire behavior during large fire incidents on a) 17-18 June, 2005, b) 23-24 June, 2005, and c) 27-28 June, 2005. Red dots indicate wildfire incidents and green dots indicate large fires designated as Wildland Fire Use fires.

exhibit plume-dominated behavior, with active running and crowning, and rapid uphill rates of spread. Additionally, there was one report of thunderstorm activity in the vicinity of the fire generating downdrafts that impacted fire behavior. The fires in California, Nevada, and Utah exhibited extreme rates of spread and flame lengths. Gusty winds, flashing fuels, crowning, and dry thunderstorm outflow boundaries also inhibited firefighting activities in the area.

Episode 3 occurred three days later on June 27-28 (Fig. 1c). On these dates, the fires in central Arizona had slowed considerably, such that few reports of extreme fire behavior were submitted. Rapid spread rates, downdrafts from dry thunderstorms, and isolated torching were reported in California, Nevada, and Utah.

Overall, the reported fire behavior can be characterized as moderate to high in isolated areas during Episode 1, high to extreme across the region with very large flame lengths and running fires during Episode 2, and decreasing intensity with localized incidents of extreme fire behavior during Episode 3. It should be noted, however, that situation reports filed during and after large fire incidents do not accurately represent all of the variations in fire behavior across the region. It is quite probable that extreme fire behavior occurred on smaller fires that either went unobserved or unreported. The purpose of this study is to determine if the extreme fire behavior that *was* reported can be explained by changes in the weather conditions at those locations and across the region.

Numerical Weather Predictions

The variability in fire behavior reported during the three episodes could have been caused by a wide variety of mechanisms, including local terrain influences (e.g. north vs. south facing slopes), fuel moisture and fuel type, and varying weather conditions. Given that fire indices were reported as extreme throughout the period, and that fuel conditions are an important component of the fire indices, we assume for the purposes of this study that differences in fuel conditions were not the main reasons for the differences in observed fire behavior. Information is not readily available on all of these fires concerning the specifics of the local terrain. Thus, we propose to explore whether variations in weather conditions both at the ground and aloft can help explain the differences in observed fire behavior. We explore this question by using an NWP model. An NWP model is a physical atmospheric model that employs equations describing spatial and temporal variations in weather conditions at the ground and aloft to predict future weather conditions. An NWP model is initiated with observations that characterize the current state of the atmosphere, and then predicts the future weather from that observed state. NWP models allow weather forecasters to forecast the weather with some degree of accuracy multiple days in advance.

An NWP model can also be used to simulate the weather conditions of events in the past, using the observations from that time to initiate the model and then simulating the evolution of the weather conditions throughout the event. The main advantage of this technique is that the NWP models generate much more information about the weather conditions at the ground and aloft than can readily be observed. In the vicinity of a fire and across the region, this information can be analyzed to try to understand how the atmospheric conditions simulated by the NWP model might have impacted the fires.

The NWP model employed for this study is referred to as the Penn State University/National Center for Atmospheric Research Mesoscale Model version 5.3 (MM5) (Grell et al., 1995). This model has been developed over the last thirty years by the meteorological research community, and is one of the most widely used "mesoscale" models in the world. A mesoscale model is an NWP model that is designed to simulate the weather conditions across an area roughly 1/2-1/4 the size of the United States and resolve the detailed flows associated with thunderstorms, fronts, and other local weather phenomena. As indicated in the Introduction, these models are used routinely by NWS (and other) forecasters to produce forecasts of severe storms and precipitation systems.

We have employed the MM5 as a research tool to simulate the weather conditions associated with the three episodes defined in the previous section. Separate simulations were performed for the three episodes, such that hourly weather conditions at the ground and aloft were generated from 0000 UTC on the first day of each episode and continuing for 48 hours. Model output is generated in the form of a 3-dimensional cube of weather data (temperature, winds, humidity, clouds, rain, sunlight, etc) which can then be analyzed in detail. This output is then analyzed to produce horizontal maps and time series at specific locations.

Fire Weather Predictions

The model results for the three episodes indicate similarities that would be expected considering the season and the region, while also revealing some notable differences between the episodes. The surface weather conditions were very hot and dry throughout the three episodes, as one would expect climatologically. Figure 2 shows the surface relative humidity (RH) and wind speed and direction for episodes 1, 2, and 3. It is noteworthy that while there are variations in RH and wind speeds across the three episodes, the variations are not particularly noteworthy. The RH in central Arizona, southern California, and southern Nevada vary from between about 10-15%. While these are very low RH values, particularly for a model that is known to often overestimate RH, differences of this magnitude would not by themselves explain the observed differences in fire behavior. Similarly, the simulated wind speeds across the region were moderately high, with speeds of about 15 mph commonly occurring, but do not indicate pronounced variations among the episodes.

One of the huge advantages of working with NWP model output instead of observations is that the weather conditions aloft are as straightforward to generate as surface weather conditions. Thus, the model includes information about the diurnal evolution of the mixed layer for each of the episodes. This enables us to analyze the weather conditions in the layers of the atmosphere that are most likely to interact with a fire, rather than focusing almost exclusively on surface weather conditions. Figure 3 shows mixed-layer averaged temperatures for the three episodes. Clearly, the mixed-layer air in the areas where extreme fire behavior was reported was considerably warmer in Episode 2 than in Episode 1. However, this increase in temperature did not manifest as a pronounced change in RH. RH is often used by fire weather forecasters and fire managers to anticipate when the atmosphere will contribute to fuel drying and, by association, more extreme fire behavior. But RH is dependant upon temperature, such that a 20% RH at 30°C indicates a different impact

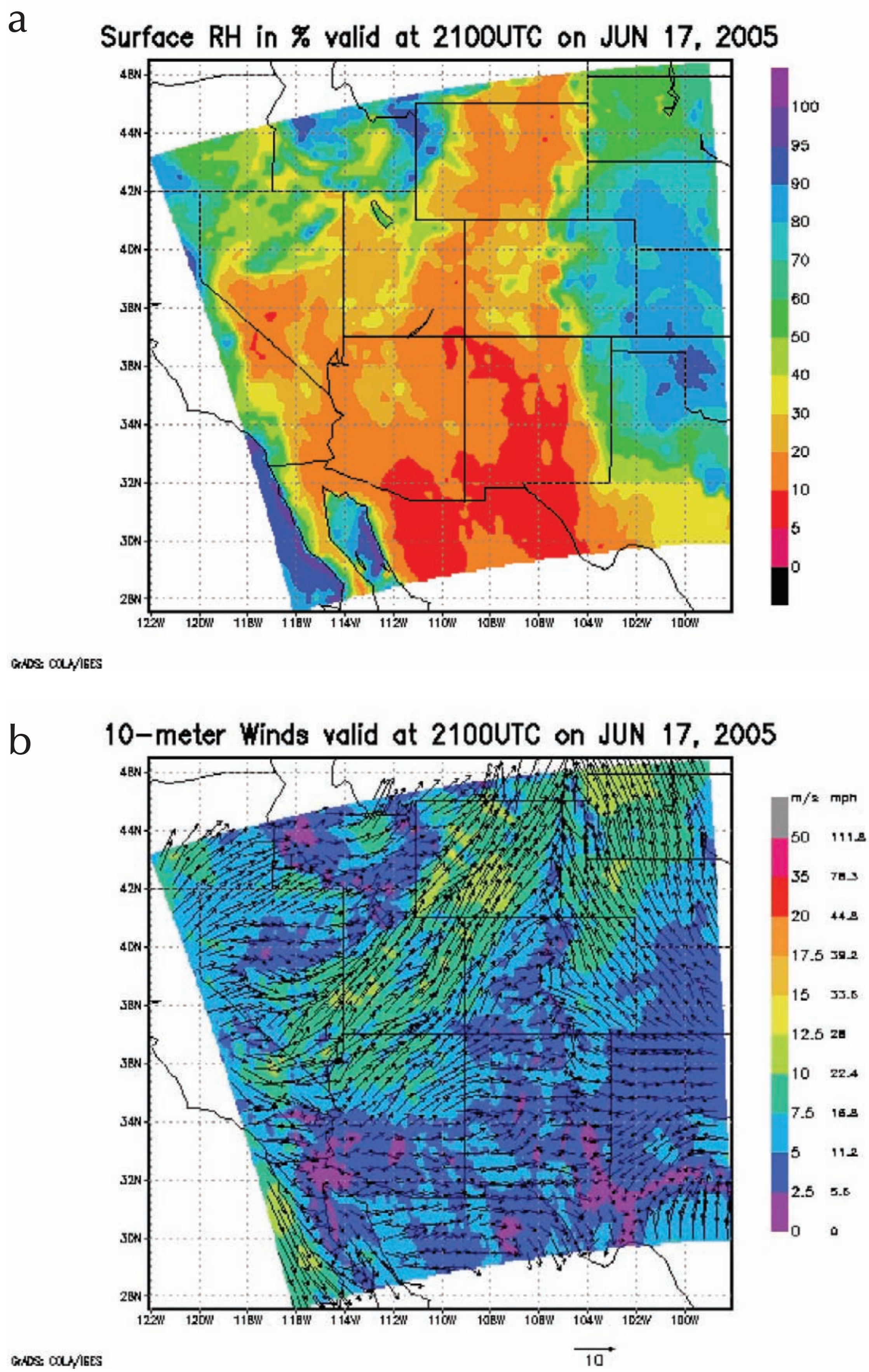
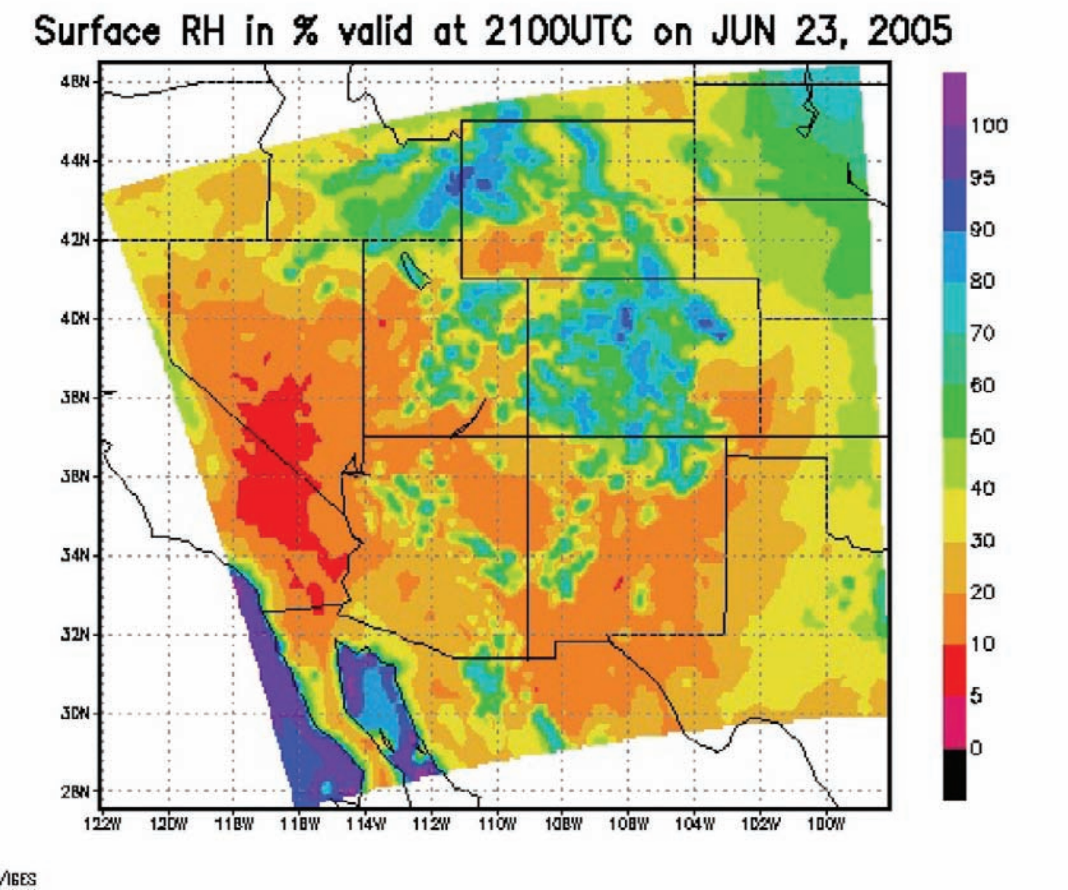


Figure 2—Simulated a) surface relative humidity and b) surface wind speed and direction for 2100 UTC 17 June, 2005. c) and d) are the same as a) and b) for 2100 UTC 23 June, 2005. e) and f) are the same as a) and b) for 2100 UTC 27 June, 2005.

c


Surface RH in % valid at 2100UTC on JUN 23, 2005
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44N
42N
40N
38N
36N
34N
32N
30N
28N
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120W
118W
116W
114W
112W
110W
108W
106W
104W
102W
100W
100
95
90
80
70
60
50
40
30
20
10
5
0
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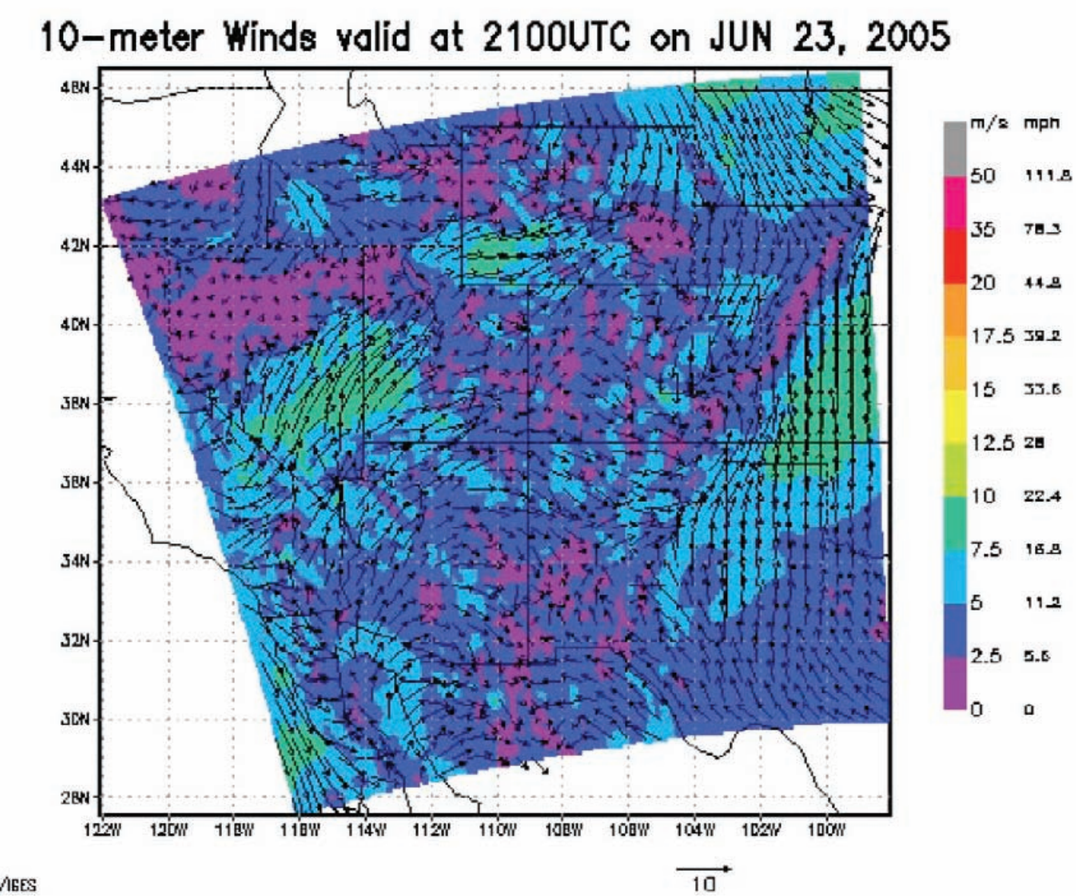
d


10-meter Winds valid at 2100UTC on JUN 23, 2005
48N
44N
42N
40N
38N
36N
34N
32N
30N
28N
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120W
118W
116W
114W
112W
110W
108W
106W
104W
102W
100W
m/s mph
50 111.8
35 78.3
20 44.8
17.5 39.2
15 33.6
12.5 28
10 22.4
7.5 16.8
5 11.2
2.5 5.6
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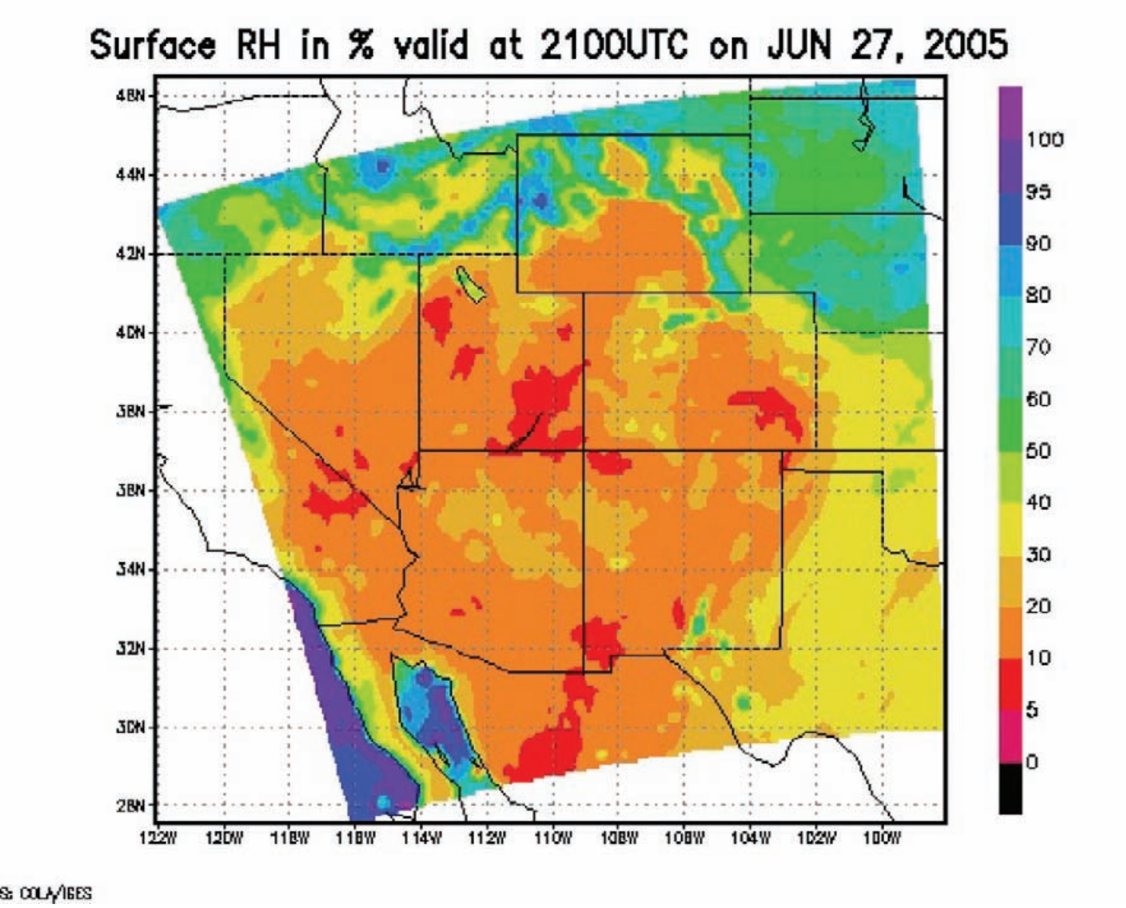
e


Surface RH in % valid at 2100UTC on JUN 27, 2005
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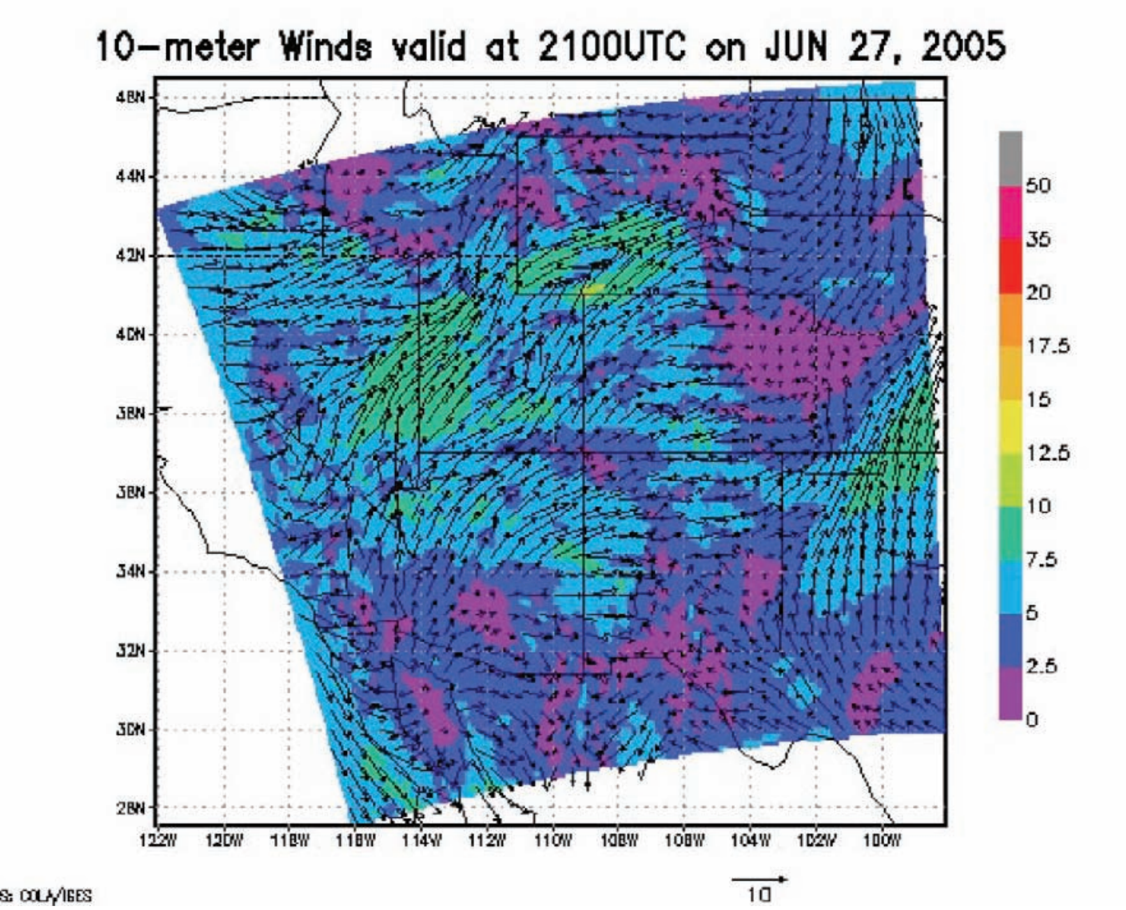
f


10-meter Winds valid at 2100UTC on JUN 27, 2005
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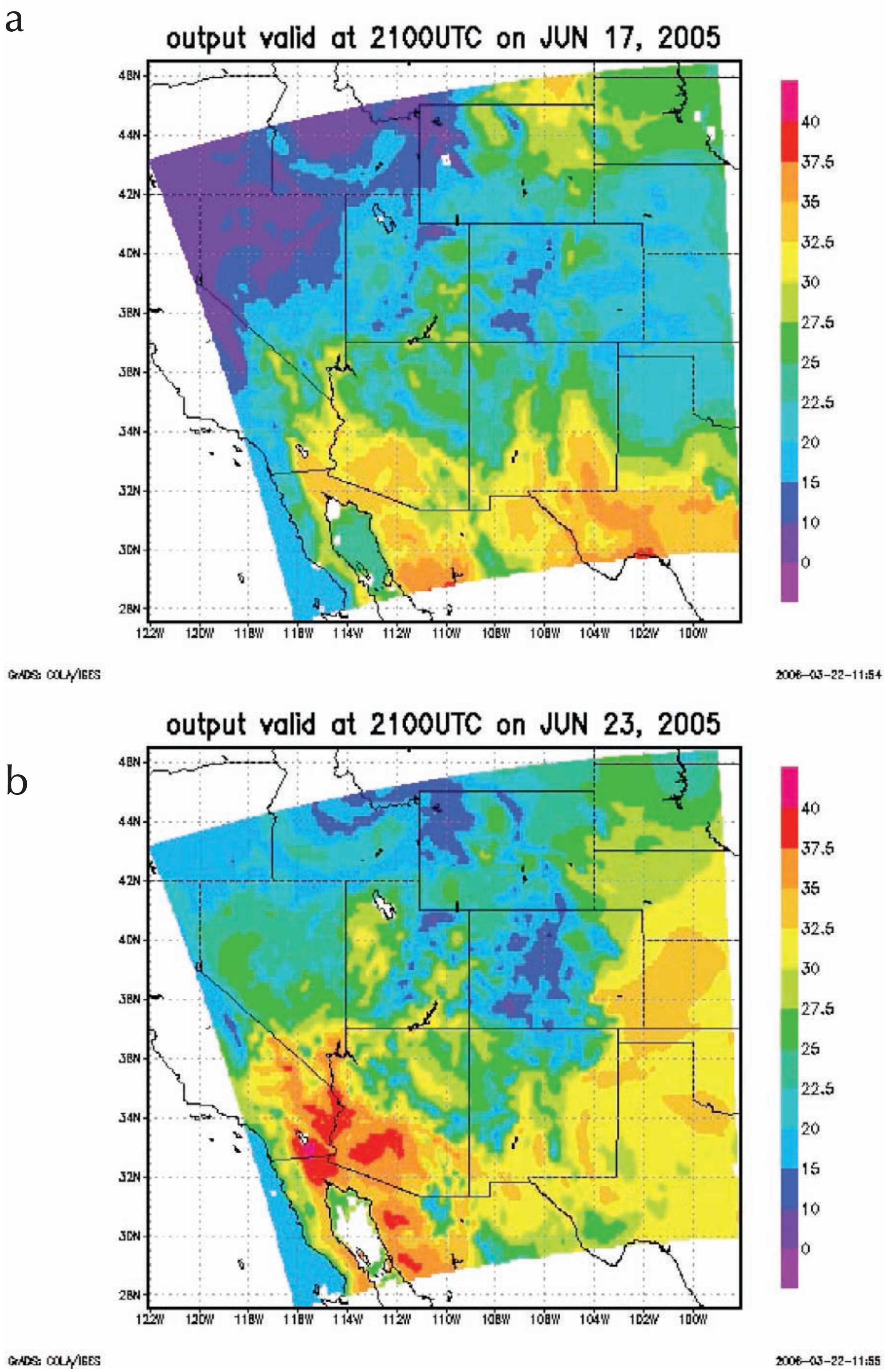
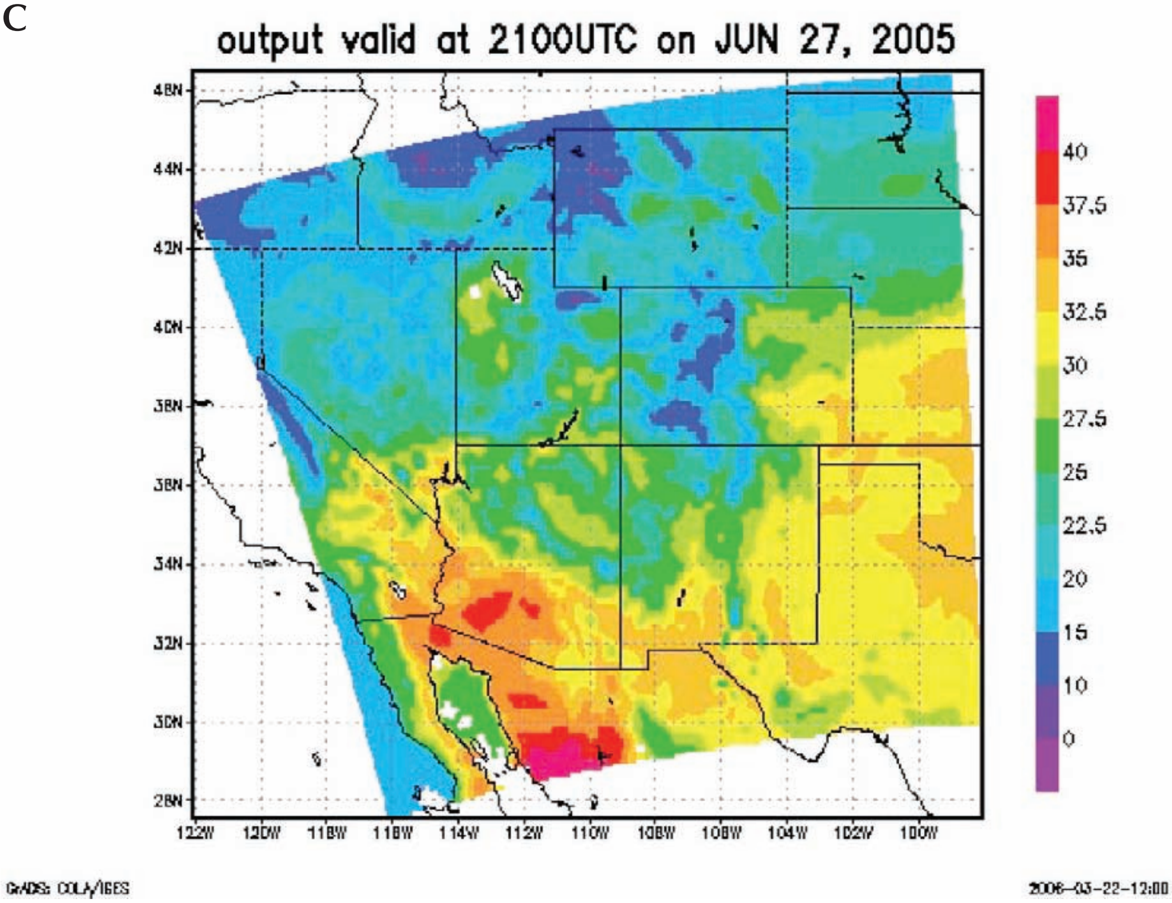


Figure 3—Simulated mixed-layer averaged temperature for: a) 2100 UTC 17 June, 2005, b) 2100 UTC 23 June, 2005, c) 2100 UTC 27 June, 2005.

C



on fuels than a 20% RH at 40°C. A more definitive quantity for the potential impact of humidity on fuel drying is the vapor pressure deficit (VPD), which indicates how much water vapor can be evaporated into a volume of air regardless of the temperature. Figure 4 shows mixed-layer averaged VPD for the three episodes. The VPD varies from around 3500 Pa in Episode 1 to about 6000 Pa in Episode 2 along the Arizona/California/Nevada border, which corresponds to an increase of over 70%. This sort of difference would be expected to have a noticeable impact on fuel moistures during a fire.

An NWP model also enables the analysis of fire-weather conditions at an arbitrary location in a region. When using an NWP model, a fire weather forecaster or fire manager can obtain weather data that is locally valid even when a weather station is not nearby. By combining this aspect of NWP data with the availability of weather data aloft at every location within the model area, new insights can be obtained into the diurnal evolution of weather conditions throughout the day.

The traditional classification of fire as surface, ground, or crown relates the fire's characteristics to fuel. Just as fuel in these three layers has different characteristics that influence the fire's behavior, the atmosphere is not the same at all heights. As a fire grows, and its plume deepens, air from higher levels descends to interact with the fire and fuels (Fig. 5). If that air is drier, hotter, or windier than air at the ground, it may cause dangerous and unexpected changes in the fire's behavior such as torching, runs, or spotting. Looking at the air that is influencing fire behavior at a particular time, we

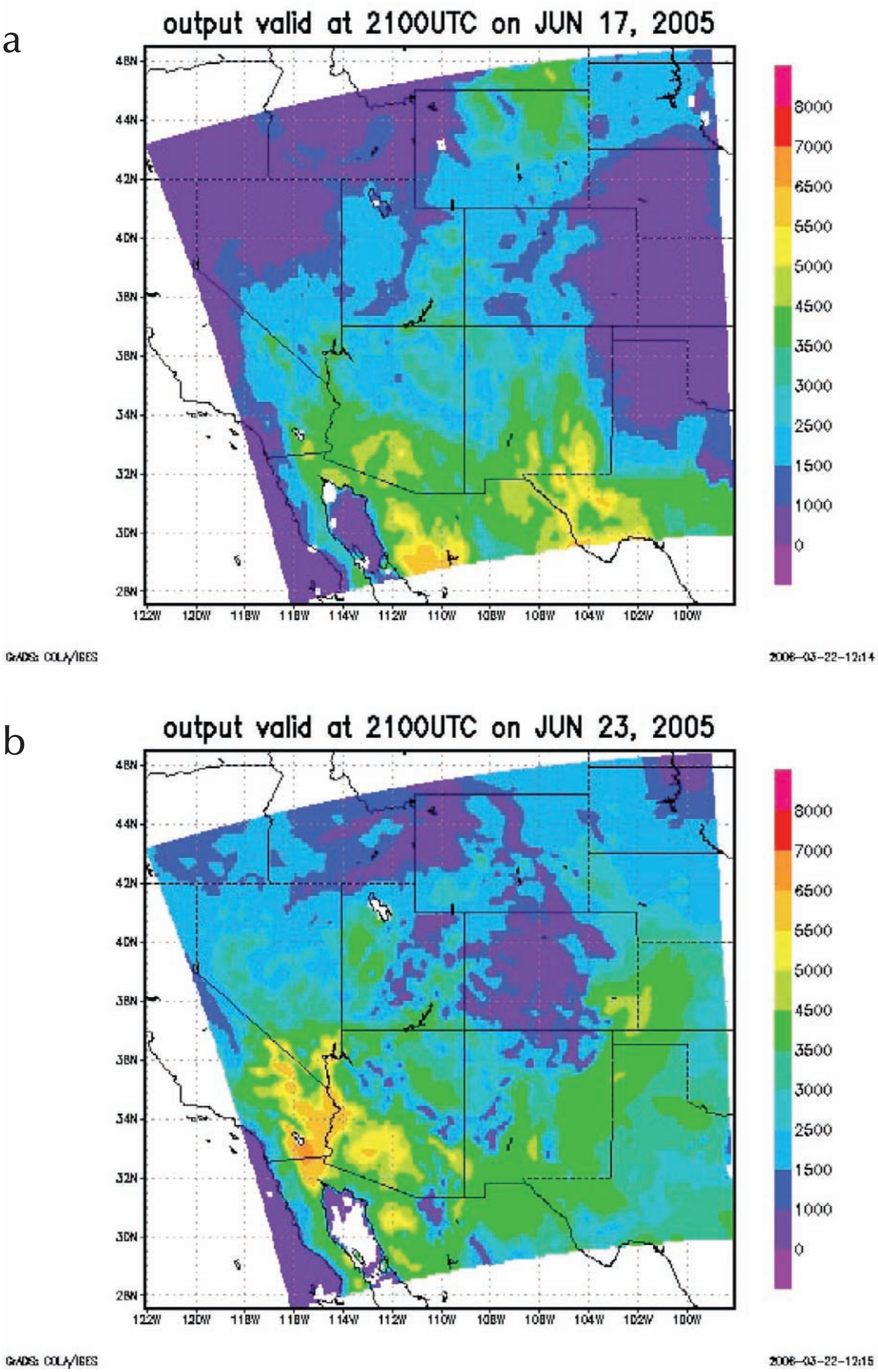
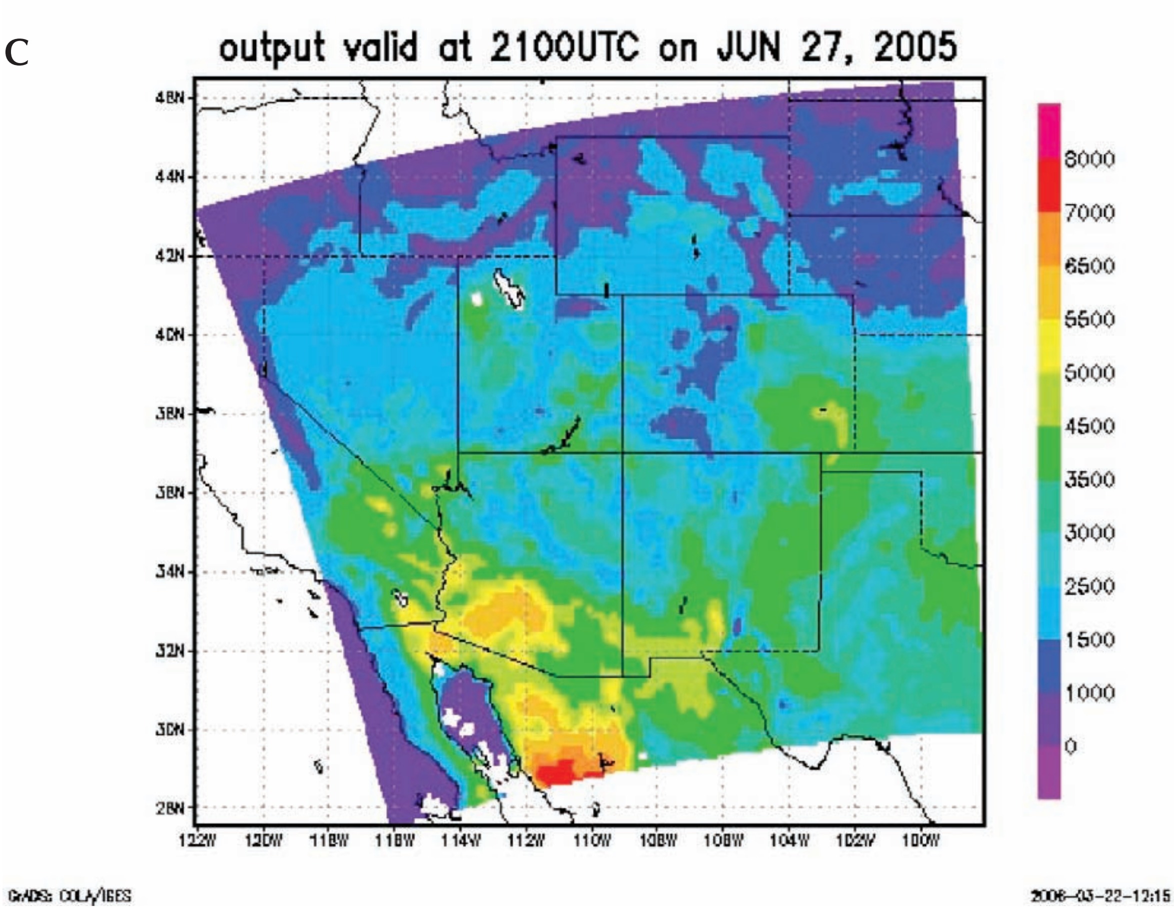


Figure 4—Simulated mixed-layer averaged vapor pressure deficit for: a) 2100 UTC 17 June, 2005, b) 2100 UTC 23 June, 2005, c) 2100 UTC 27 June, 2005.



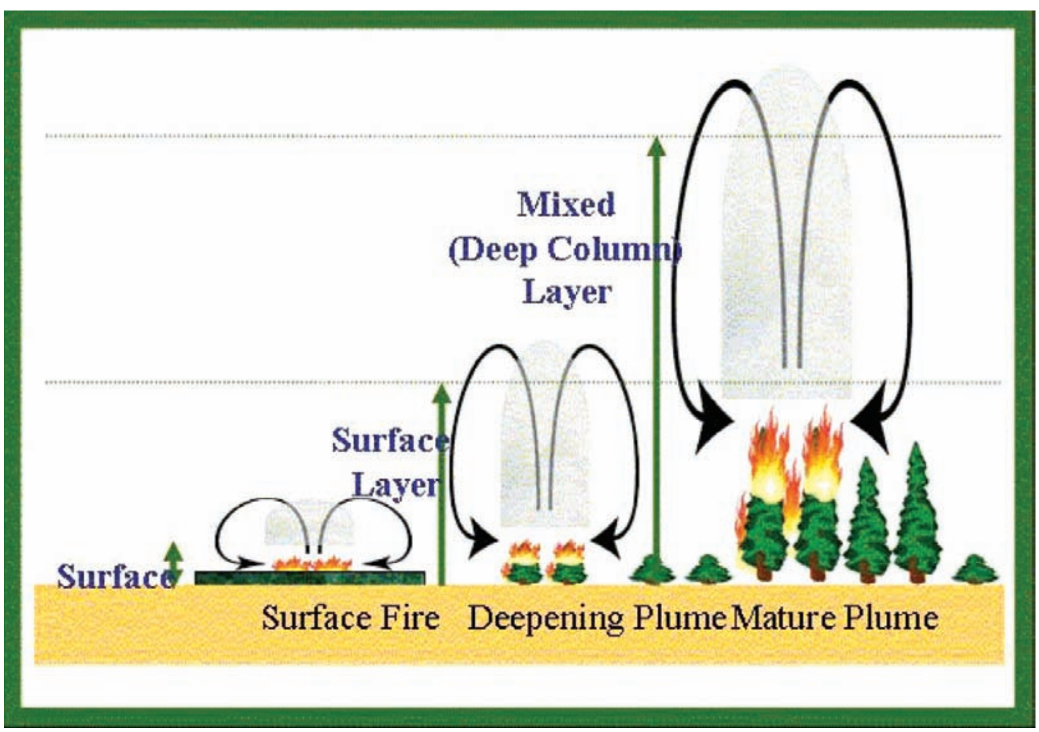


Figure 5—Conceptual diagram of the 3-layer model showing potential interactions between a fire and layers of the atmosphere.

ask three questions: 1) what type of air influences a fire while it is forming a plume, 2) what type of air influences a fire right after it ignites, and 3) what type of air influences a fire that has established an identifiable plume? These questions lead to a conceptual model which we refer to as the three-layer model (Potter, 2002; Charney et al., 2005), in which we employ the NWP model to calculate weather variables at the ground, averaged throughout the mixed layer, and averaged from the ground to a point 500 m above the mixed layer. By looking at how these quantities vary at a point through the day, the impact of mixed-layer processes on surface conditions can be diagnosed and, in some cases, predicted hours or even days in advance.

Figure 6 shows time series of 3-layer model quantities for Episodes 2 and 3 for a point in extreme southern Nevada. It is noteworthy that when the mixed-layer starts to grow during the daytime, the wind speed at the ground in both episodes increases and the RH decreases dramatically. This progression indicates the importance of mixed-layer processes in the development of dry and windy conditions for both episodes. The time series for Episode 2 suggests that prior to sunrise on June 23rd, the surface air was drier and windier than the air 500m above the ground. As the mixed layer grew after sunrise, this signal was eliminated and the usual structure of drier and windier air aloft than at the ground transpired. However, the unusual vertical structure prior to sunrise on the 23rd preceded the fire reports of extremely high flame lengths (50-80 feet) on the 23rd. Without exploring the details of the atmospheric processes that led to the formation of the anomalous structure during the night, we cannot state whether the fire reports and this unusual mixed-layer structure is related. But the anomalous the mixed-layer structure and anomalous fire behavior suggest that a possible cause and effect relationship should be explored in future studies.

Figure 7 shows a time series of 3-layer model quantities for Episode 3 for a point in central Arizona. The development of the surface and mixed-layer averaged winds is notable in this case. At sunrise, the winds were quite light, with values on the order of 3 mph. As the mixed layer grew through the day, surface wind speeds increased rapidly to about 15 mph. The wind speeds just above the mixed layer, however, remained sharply higher than the mixed-layer wind speeds throughout the day. This is noteworthy in that a strong fire circulation in that environment could “tap into” air above the mixed layer and transport momentum from outside of the mixed layer to the ground, leading to anomalously strong surface winds, possibly with gusts that are even higher than indicated by the time series. Furthermore, note that the strong winds aloft remained in place even after the mixed layer collapsed (e.g. when the green line in the plot disappears) indicating that even at night, this fire might continue to experience stronger winds than expected.

Discussion And Conclusion

The NWP model results presented in the last section indicate that variations in weather conditions associated with three fire episodes in late June, 2005 can help explain some of the variations in observed fire behavior. The simulations demonstrate that substantial differences occurred in the fire-atmosphere interactions during the episodes. And while these interactions appear to rely upon the presence of dry air, the simulations reveal that RH is not the best quantity for assessing the impact of dry air on fuel conditions, and by association, fire behavior. Since the most pronounced difference

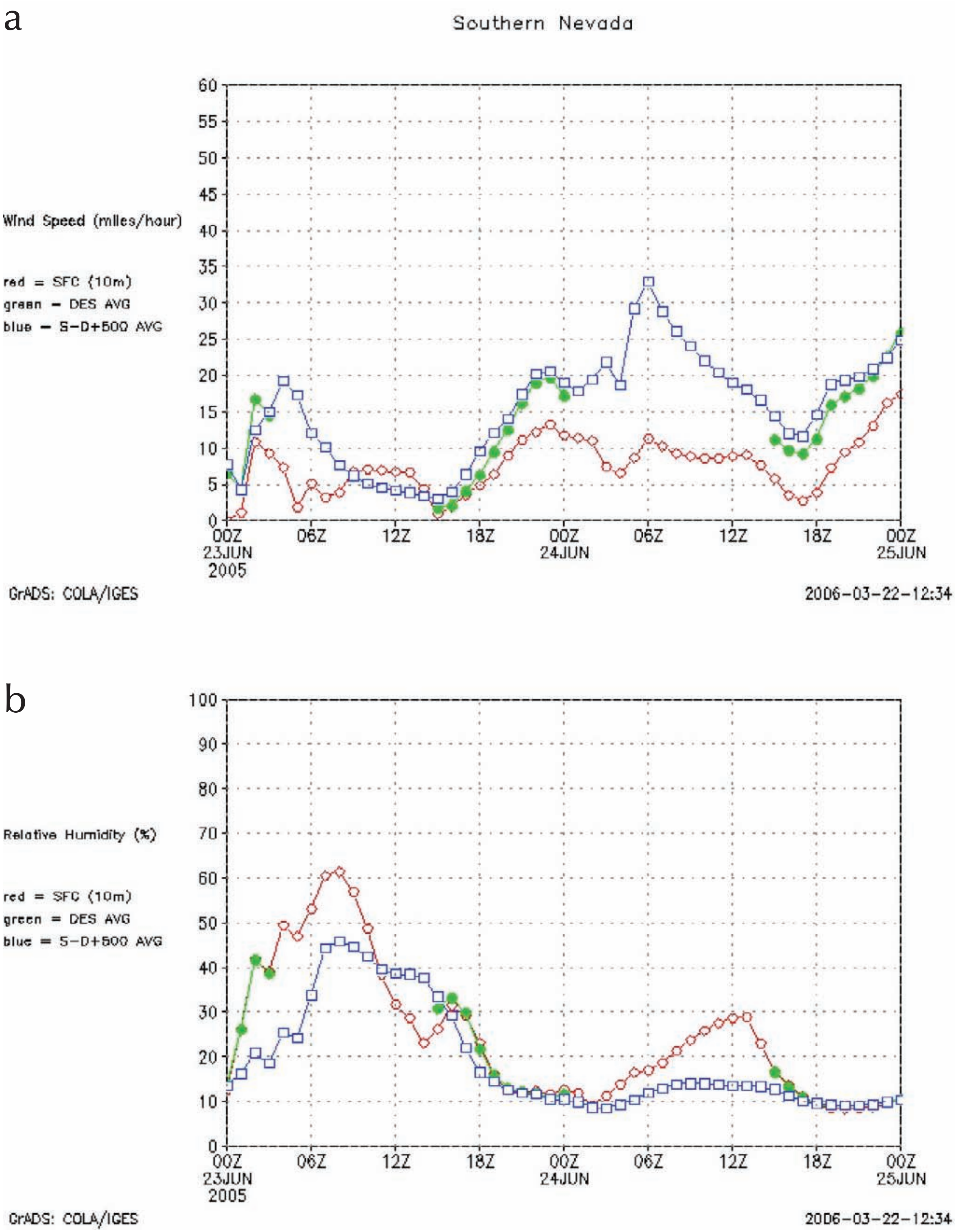
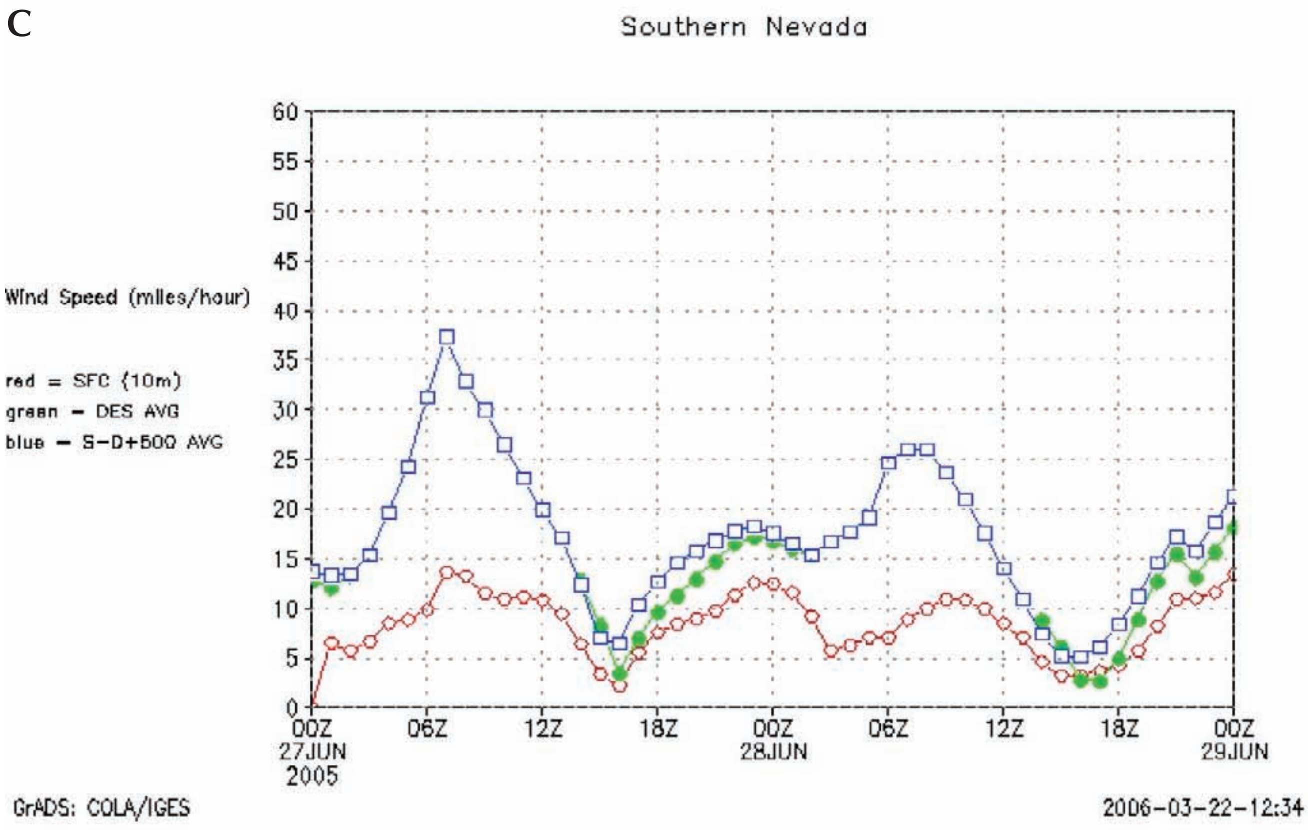


Figure 6—Time series in southern Nevada of a) surface wind speed, mixed-layer average wind speed, and mixed-layer + 500m average wind speed in mph and b) surface relative humidity, mixed-layer average relative humidity, and mixed-layer + 500 m average relative humidity from 0000 UTC 23 June through 0000 UTC 25 June 2005. c) same as a) from 0000 UTC 27 June through 0000 UTC 29 June 2005. d) same as b from 0000 UTC 27 June through 0000 UTC 29 June 2005.

c


Southern Nevada
Wind Speed (miles/hour)
red = SFC (10m)
green = DES AVG
blue = S-D+500 AVG
60
55
50
45
40
35
30
25
20
15
10
5
0
00Z 27JUN 2005
06Z
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GrADS: COLA/IGES
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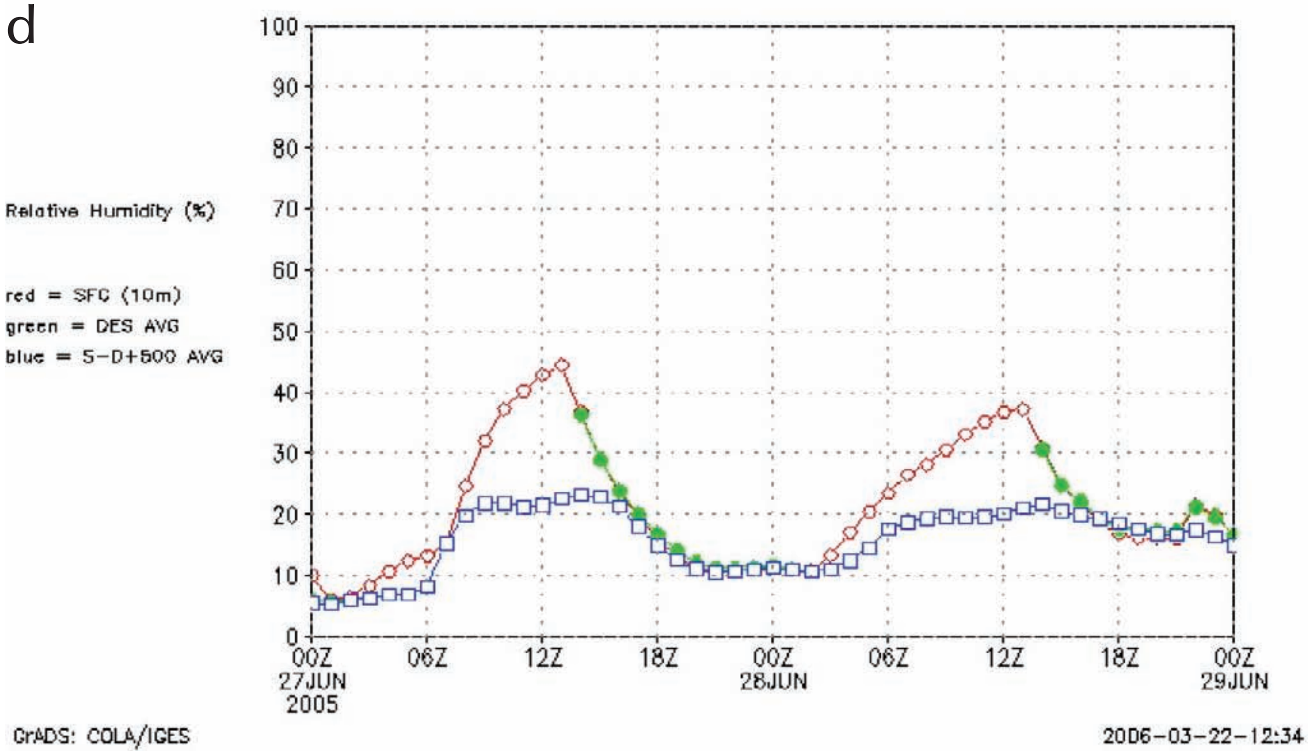
d


Relative Humidity (%)
red = SFC (10m)
green = DES AVG
blue = S-D+500 AVG
100
90
80
70
60
50
40
30
20
10
0
00Z 27JUN 2005
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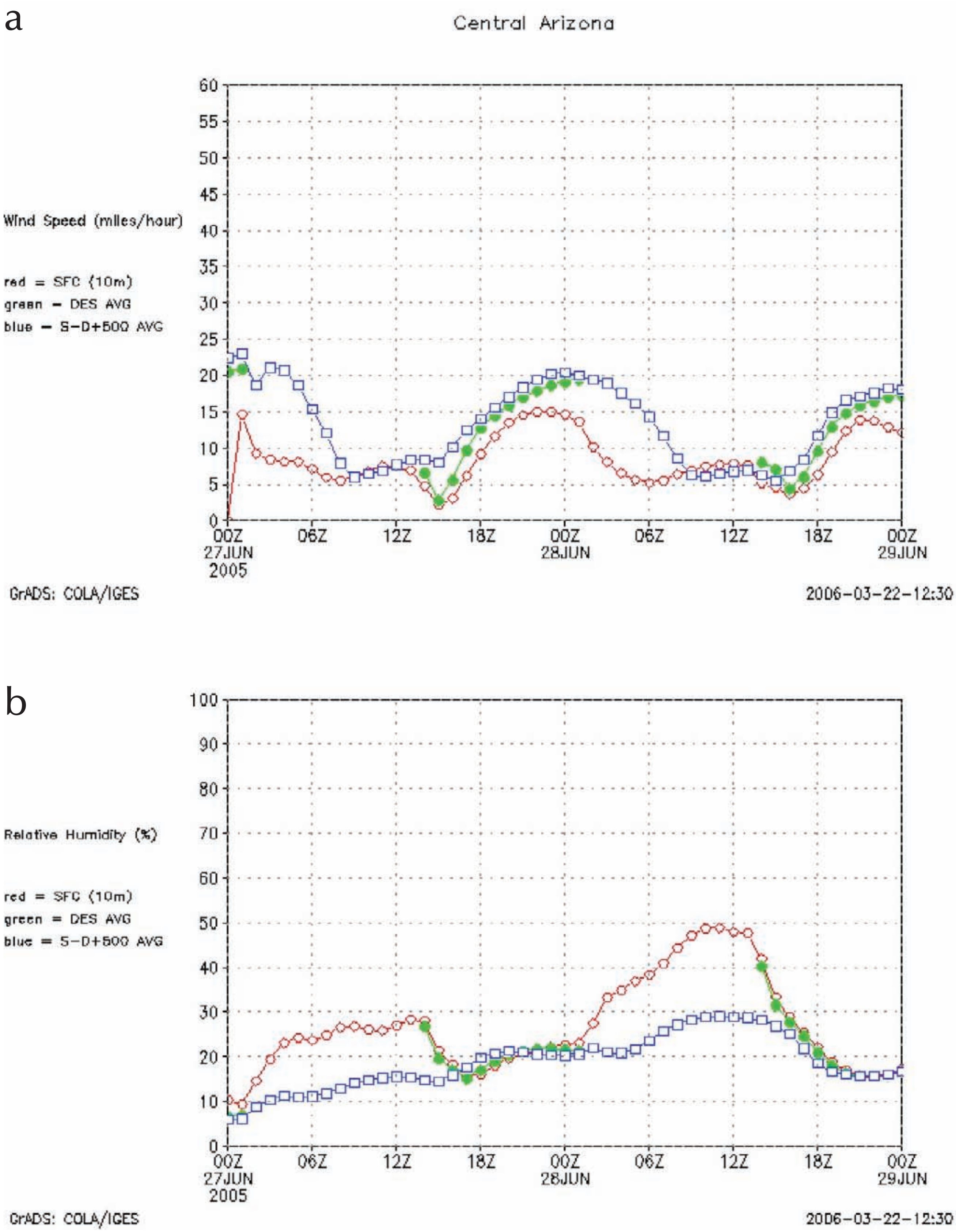

Figure 7—Time series in central Arizona of a) surface wind speed, mixed-layer average wind speed, and mixed-layer + 500 m average wind speed in mph and b) surface relative humidity, mixed-layer average relative humidity, and mixed-layer + 500 m average relative humidity from 0000 UTC 27 June through 0000 UTC 29 June 2005.

between the episodes was found in near-ground temperatures, RH would be expected to be ambiguous. However, the vapor pressure deficit shows a more pronounced change in conditions between the episodes, and in these situations, represents a more precise means of diagnosing the potential fuel drying due to atmospheric processes.

The potential for local conditions at the ground and aloft to affect the fires was addressed using the so-called three-layer conceptual model, which employs NWP model output to calculate the surface, mixed-layer, and mixed-layer plus 500 m winds and humidities. These analyses highlighted highly anomalous mixed-layer structures coinciding with the most extreme fire behavior reported during the episodes. In other locations, the analyses indicate the potential for a fire to tap into fast-moving air just above the mixed layer; air that could be mixed down to the surface and produce unexpected and potentially hazardous changes in fire behavior. The preliminary analyses of these time series indicate that the three-layer model could be used to anticipate the potential for anomalous fire behavior associated with diurnal variations in atmospheric mixed layer processes. Additional work is necessary, however, before the ultimate usefulness of this diagnostic tool can be determined.

This paper represents a step towards realizing the full potential of atmospheric physics models for fire weather and fire behavior forecasting. As researchers and operational personnel come to understand the relationships between fire behavior and atmospheric processes that can be predicted by weather forecast models, these concepts can be tested in the broader context of day-to-day fire weather forecasting. Eventually, these techniques could provide additional information for fire weather forecasters and fire managers, producing new information from tools that are already available and used routinely in weather forecast offices.

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WindWizard: A New Tool for Fire Management Decision Support

Bret W. Butler[1], Mark Finney[1], Larry Bradshaw[1], Jason Forthofer[1], Chuck McHugh[1], Rick Stratton[2], and Dan Jimenez[1]

Abstract*—A new software tool has been developed to simulate surface wind speed and direction at the 100m to 300 m scale. This tool is useful when trying to estimate fire behavior in mountainous terrain. It is based on widely used computational fluid dynamics technology and has been tested against measured wind flows. In recent years it has been used to support fire management decisions to improve firefighter and public safety, understand the environmental conditions associated with entrapment fires, improve prescribed fire prescriptions, and estimate fire potential. Outputs from this tool include tiff images, GIS shape files, and FARSITE wind input files.*

Introduction

Wind is one of the primary environmental variables influencing wildland fire spread and intensity (Rothermel 1972, Catchpole and others. 1998). Indeed, wind and its spatial variability in mountainous terrain is often a major influencing factor in the fire behavior associated with "blowup" fires (e.g., South Canyon Fire 1994, Thirtymile fire 2000, Price Canyon Fire 2002, and Cramer Fire 2003). The extent, elevation and orientation of mountains, valleys, ridges, and the fire itself, influence both the speed and direction of wind flows (figure 1). The lack of detailed wind speed and direction information is one major source of uncertainty in fire management decisions. Methods to obtain estimates of local wind speed and direction at the 100 to 300 m (300 to 900 ft) scale have not been readily available. In most cases, fire incident personnel estimate local winds based on weather forecasts and/or weather observations from a few specific locations, none of which may be actually near the fire. A computer based tool is described here that provides fire and land managers with the ability to determine local surface wind flows at the 100-300 m (300 to 900 ft) scale for a given synoptic wind condition. A brief discussion of how the tool's accuracy has been evaluated is presented followed by some examples of how this tool is being used in wildland fire management decisions.

Background

As computational and mathematical simulation capabilities have increased, methods for obtaining detailed wind information to support fire management efforts have been explored. Ferguson (2001) uses atmospheric scale models to assess the dispersion of smoke from natural and prescribed fires. Zeller and

In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to Measure Success: Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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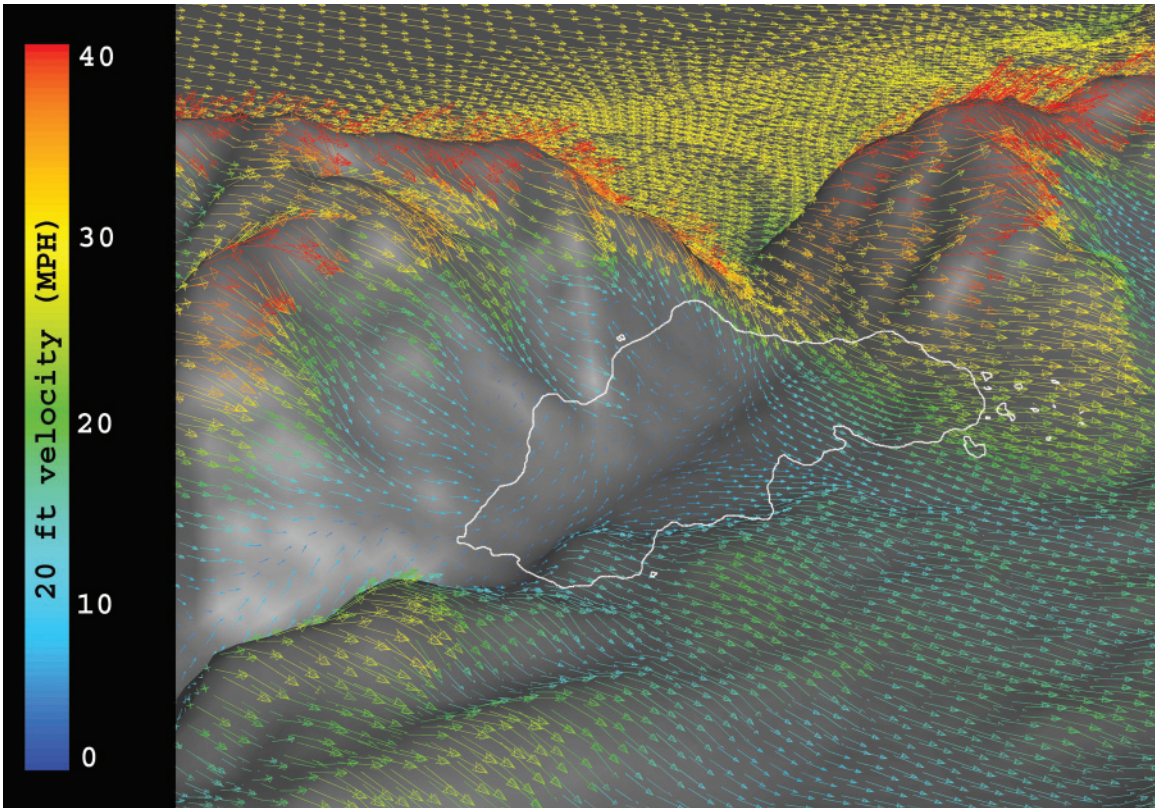

Figure 1—Example of a gridded wind simulation. The white line represents the fire perimeter. Wind speed and direction are indicated by the vectors, with length representative of relative speed and orientation representative of local wind direction. Vectors are also colored by wind speed.

others (2003) are exploring the application of meso-scale atmospheric flow models for the prediction of surface winds. The National Weather Service (NWS) has recently provided public access to the National Digital Forecast Database (NDFD). Meso-scale forecast data are available for the entire United States on a daily basis at scales ranging from 4 km to 36 km resolution. The NDFD currently provides 5.0 (soon to be 2.5) km resolution, 8-day digital forecasts (and GIS support) for the conterminous U.S. These approaches include all the important physical processes but suffer from relatively coarse scale surface wind predictions (nominally greater than 2000 m scale) and large computational requirements. Meso-scale models and weather service forecast models are not easily configured for "what if" applications wherein a single user using a laptop computer can simulate multiple scenarios ahead of time and explore their impact on fire intensity and growth.

Others have approached the problem from a fluid dynamics approach, for example Lopes and others (2002) and Lopes (2003) describe a software system that calculates a surface wind field and includes topographical influences. However, their system remains a research tool; they have not provided a process through which their system can be used operationally by fire managers.

We have commonly referred to our approach as gridded wind simulations. In the gridded wind approach, typically, the area of interest is 30 km by 30 km (18.6 miles by 18.6 miles) square with the fire located approximately at the center. The tool is based on the Fluent® and FloWizard® computational fluid dynamics software packages (http://www.fluent.com). The atmosphere is assumed to be neutrally stable. The simulation assumes a constant temperature flow and turbulence is modeled using the rng κ-ε approach (Jones and Launder 1972; Yakhot and Orszag 1986).

The tool has been termed WindWizard. The simulation process followed by the WindWizard tool comprises the following general steps:

1) Acquire and import into WindWizard an ASCII raster digital elevation data file (DEM) for the area of interest, generally on the order of 30 km by 30 km (18.6 miles by 18.6 miles) in size.
2) Automatically build a computational domain over the area of interest and divide it into computational cells with dimensions on the order of 300 m by 300 m by 100 m (900 ft by 900 ft by 300 ft) at the surface of the terrain. The result is 100,000 to 1,500,000 cells within the overall computational domain.
3) Compute a surface roughness parameter based on user input of the dominant plant species (forest, shrub, grass).
4) Solve the Navier-Stokes equations describing the wind flow over the earth's surface for up to 10 different wind scenarios based on user input of the ridge top or synoptic wind conditions. The user specified input wind is imposed as an inlet to the simulation domain and is uniform with height above the terrain surface.
5) Display and output the wind speed and direction 6m above the terrain surface at a resolution specified by the user.

Wind modeling for specific fires consists of simulating multiple combinations of free-air wind speed and direction. The different cases are selected to match forecasted scenarios or are based on historical weather patterns. The gridded wind simulation accounts for the influence of elevation, terrain, and vegetation on the general wind flow. We emphasize the gridded wind simulations are not forecasts but rather a snapshot at one point in time of what the local surface wind speed and direction would be for a given ridge top or synoptic wind scenario. WindWizard is a technique for determining the fine scale winds that result from a specific broader scale wind scenario. WindWizard has been used to predict and reconstruct fire behavior during ongoing fire incidents and to support fire investigations [i.e. Price Canyon Fire (Utah) -Thomas and Vergari (2002), Thirtymile Fire (Washington) - USDA Forest Service (2001), Cramer Fire (Idaho) - USDA Forest Service (2004), Storm King Mountain Fire (Colorado) - Butler and others (1998), Cedar Fire (California) - California Dept. of Forestry and Fire Protection (2004)].

The bottom line is that in all of the wind simulations completed so far, we have not observed any reason to believe that the simulated winds are not physically realistic representations of actual winds for similar free-air wind events. At the very least, the gridded wind tool represents a significant improvement over the previous method of using a single wind speed and direction obtained from a point measurement such as a weather station or observer.

Methods

Two methods have been utilized to quantify the accuracy and effectiveness of computational fluid dynamics (CFD) based wind simulations. The first compares simulated wind speed and direction against direct measurements.

The second compares fire growth simulations with and without the high resolution wind.

In comparisons against measured wind data (fig. 2), generally the modeled wind speeds were within 9 percent of those measured except for the leeward upper slope of the hill where the simulated wind speed was 32 percent greater than the measured value and is likely related to differences between the steady state calculations produced by the CFD-based model and the transient nature of turbulent eddies forming on the leeward side of the hill (Castro and others 2003). This result suggests that the CFD-based methodology may not capture the transient nature of the flow. Figure 3 indicates that simulated wind direction was within 13 degrees of the measured value for all locations (Butler and others 2004). The differences between the simulated wind direction and measured values were greatest near the base of the hill for both the upwind and leeward sides. These comparisons suggest that the CFD-based methodology for simulating surface wind flow over mountainous terrain can provide relatively accurate and useful information, but a valid evaluation requires comparison against additional data sets.

Metrics for quantifying the impact of this technology on wildland fire management decision making can be defined through two methods: 1) the degree of interest in and use of the tool as the fire management community becomes aware of it and 2) the response from fire managers as to its utility. One major focus of this project has been to take advantage of opportunities to assist IMT's by proactively producing wind simulations for their area of interest.

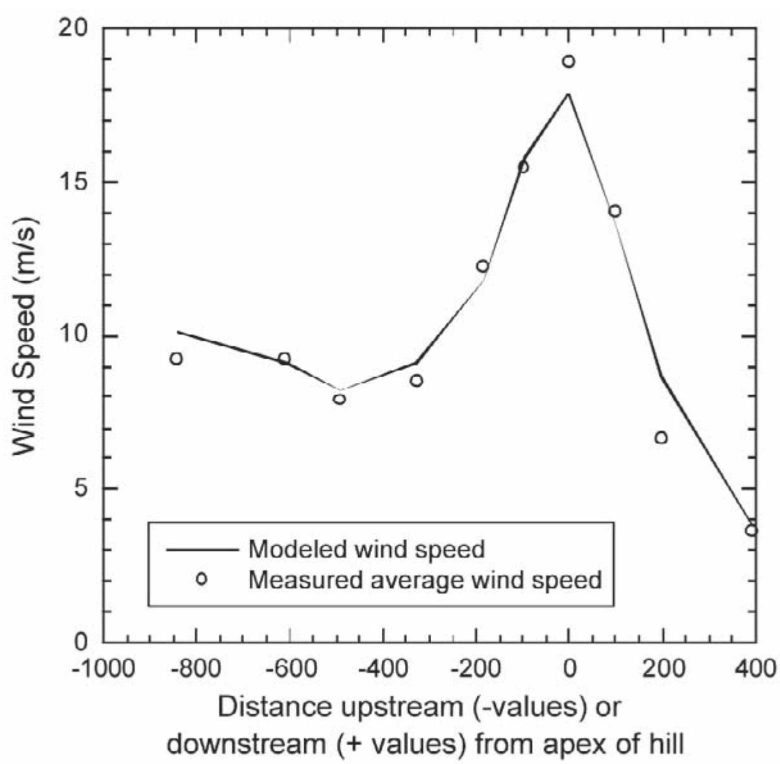

Figure 2—A comparison of measured and predicted wind speeds reported from the Askervein hill data set. Positive values represent distances downstream from apex and negative values represent upstream from apex.

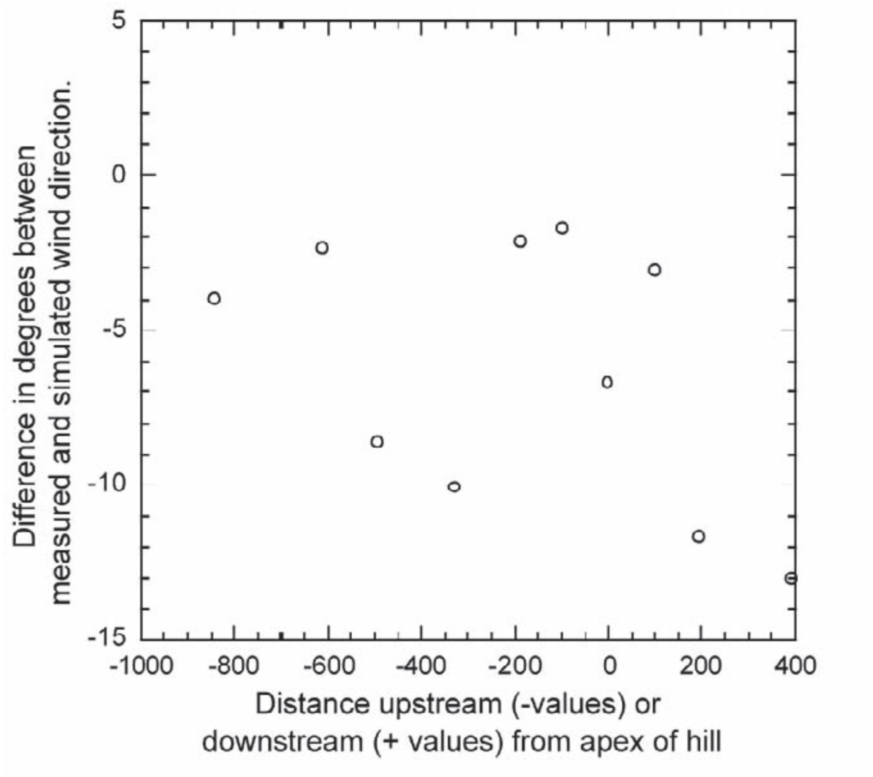

Figure 3—A comparison of the variation from the overall 210 degree flow direction for the measured and predicted winds from apex of Askervien hill. Positive values represent distances downstream from apex and negative values represent upstream from apex.

Discussion

Transfer of results from the wind simulations to fire managers and field personnel occurs in three forms: 1) Images consisting of wind vectors overlaid on a shaded relief surface image; 2) ArcView or ArcMap shape files of wind vectors and 3) files for use by the FlamMap and FARSITE (Finney 1998) programs. The images and files display the spatial variation of the wind speed and direction and can be used to identify high and/or low wind speed areas along the fire perimeter caused by the channeling and sheltering effects of the topography.

CFD based wind simulations have been used to provide wind input to a number of FARSITE fire growth simulations of previous fire events. In all of the simulations the accuracy of short term (< one day) fire spread projections, as compared to actual fire spread histories, has markedly increased. For example, figures 4 and 5 present fire growth simulations of the South Canyon Fire (Butler and others, 1998). The fire growth simulation developed from uniform wind direction (fig. 4) clearly does not match the actual fire perimeter. The fire growth simulation developed using the gridded wind (fig. 5) is a better fit to the actual perimeter. The South Canyon Fire comparison was chosen to point out that while the use of gridded wind increases fire growth simulation accuracy it does not guarantee perfect fit. The discrepancy between actual and simulated fire perimeters can be attributed to input information used by the fire growth simulation such as inaccuracies in the

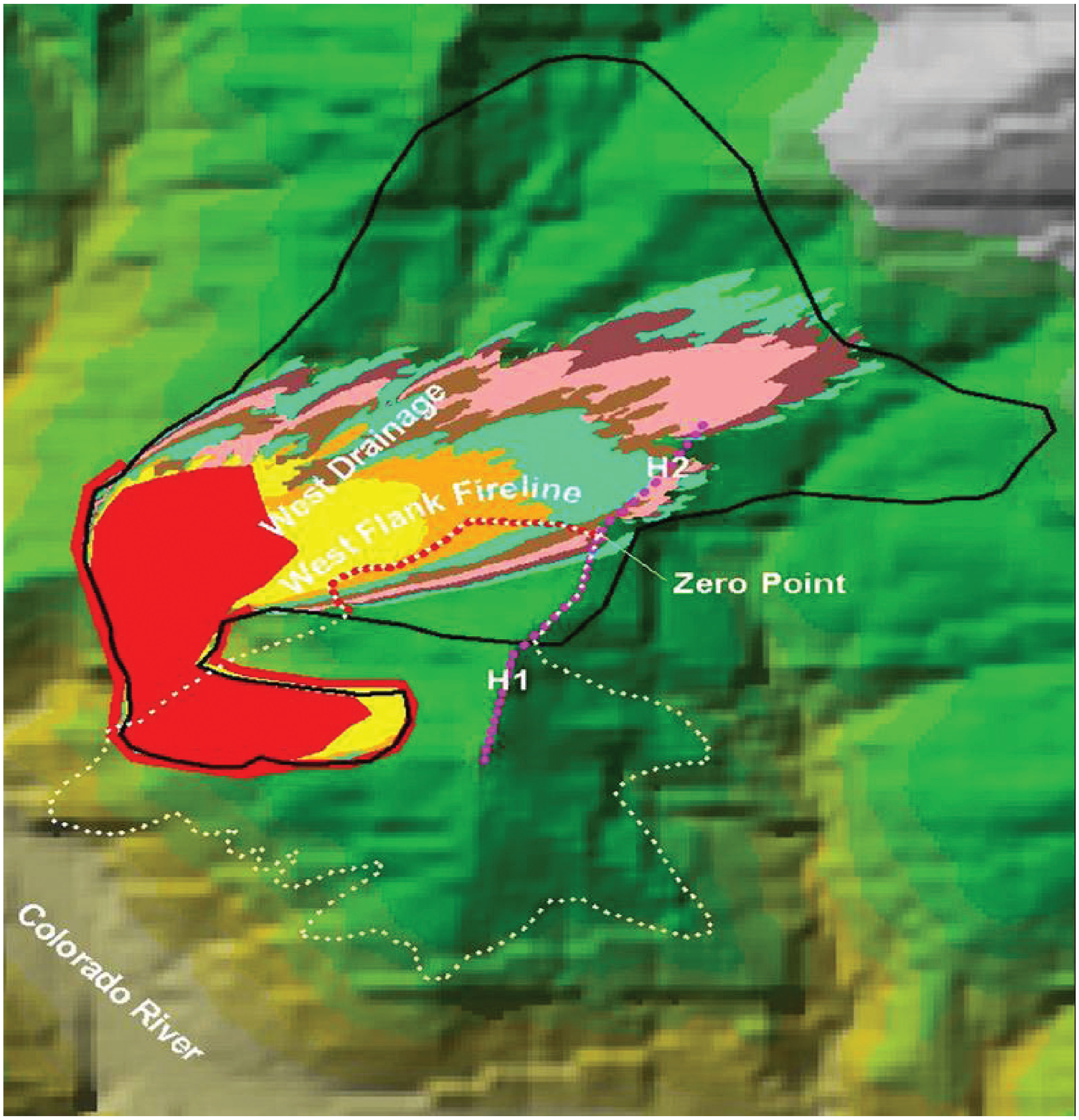

Figure 4—FARSITE simulation of the Storm King Mountain Fire assuming uniform wind speed and direction from the left to right (west winds). Black line represents actual fire perimeter at same point in time as last fire simulation. Fire growth simulations are shown as successive fire burned areas with color varying. Last perimeter is shown in light blue-green.

vegetation map. It could also be attributed to the wind field. It is important to emphasize that the gridded wind represents a "snapshot" of the flow field at one moment it time. In reality the wind field is varying in both time and space. The terrain present at the South Canyon Fire site would have induced strong turbulence in the surface wind. The eddies and transient flow created by that turbulence could significantly affect the fire growth.

Butler and others (2004) make a similar comparison for the Price Canyon Fire, the agreement between simulated and actual fire perimeters is very close when the gridded wind is included. The improvement in agreement between

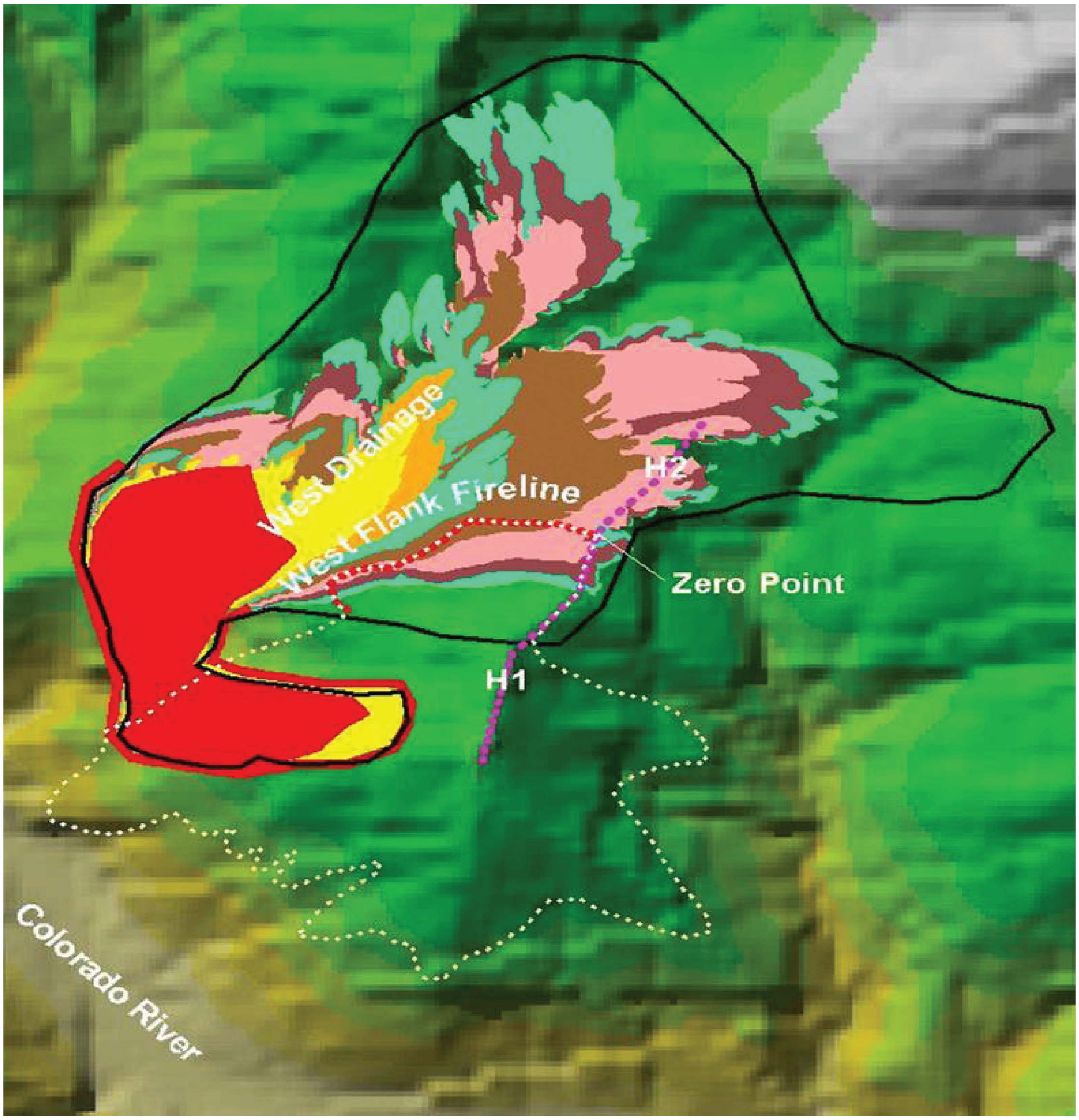

Figure 5—FARSITE simulation of the Storm King Mountain Fire using gridded wind data from CFD-based simulation. General wind flow input to CFD was aligned with the Colorado River gorge (west winds generally flowing diagonally from upper left to lower right). Black line represents actual fire perimeter at same point in time as last fire simulation. Fire growth simulations are shown as successive fire burned areas with color varying. Last perimeter is shown in light blue-green.

the fire growth simulations with the use of gridded wind indicates that the gridded wind is more representative of reality.

The CFD-based WindWizard tool represents a new technology not previously available to wildland fire teams and specialists. Consequently part of the research team's work during the past three fire seasons consisted of simply contacting the incident management teams to inform them of the new technology and supporting their fire management activities. Fire incident management teams (IMT) working in Montana, Colorado, Wyoming, California, Washington, Idaho, Arizona, Nevada and Utah have been supplied with custom wind simulations.

While it is subjective, one metric of the utility of the gridded wind as a fire management decision support tool is indicated by the responses from IMTs and fire specialists that are exposed to the technology. Generally, fire Behavior Analysts (FBANs), long term analysts (LTANs) and local fire specialists found the wind simulations to be highly useful for visualizing the channeling effect of terrain on the wind. The outputs from the WindWizard tool are being used in multiple ways: 1) to build shaded relief maps over which vectors representing wind speed and direction are placed. The maps could include fire perimeters. These maps proved useful in identifying synoptic wind conditions that might result in significant changes in fire intensity and spread. For example, given a particular wind scenario the WindWizard based wind simulations can be used to identify areas on or near the fire perimeter that might be exposed to high winds and thus potentially higher intensity fire behavior. 2) Others have used the tools to identify areas that are sheltered from synoptic winds and therefore may not be at high risk for high intensity fire. GIS shape files produced by the WindWizard tool can be easily used as another layer in addition to vegetation, terrain, resources, roads etc. in building images and analyzing relative fire risk on a spatial scale. 3) More recently, the FARSITE and FlamMap fire growth and potential fire behavior tools can easily ingest gridded wind data. In all cases, simulations of fire growth and potential have more closely matched observed and intuitively expected fire behavior with the use of gridded wind simulations. 4) Fire managers who have studied the gridded wind vectors displayed on maps have commented that the information presented would be useful in the appendices of fire management plans and could be useful for identifying potential fuel treatment areas. As the technology is used further new and innovative applications are found for it.

In all cases where it has been tested the WindWizard tool has provided wildland fire managers with an objective method for estimating local wind flows and the potential for changes in fire spread rate and intensity.

Conclusions

The research team has used this technology to support wildland fire management teams by completing more than 500 wind simulations for approximately 200 fire incidents located across the country. Additional uses for this tool are being found as more people become aware of and use the technology.

Because this technology is still new, many fire management teams are not aware of it or do not know how to access or use it. As stated previously the gridded wind simulations are <u>not</u> weather forecasts. While it is not a forecast, one of the real benefits of this approach is that it can be used in a “gaming” mode to explore the impact that various forecasted wind scenarios might have at the local scale on the fire, something not possible with meso-scale weather models.

Acknowledgments

Financial support for this project has been provided by the USDA Forest Service, The Joint Fire Science Program, John Szymoniak from the National Interagency Fire Center and Mike Hilbruner from the USDA Forest Service

Washington Office. Significant improvements have stemmed from suggestions and trials of the technology by many Interagency Fire Management Teams who have contributed time and effort as test cases for the gridded wind tool. Finally the contributions of individual FBANs and LTANs willing to take the time to explore this new technology have been invaluable to the development and improvement of WindWizard.

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Appendix: Presentations for which papers were not submitted for these proceedings

Invited Speakers

Is There a Normal Fire Regime in an Always Changing Environment?

Daniel Botkin, Research Professor, University of California Santa Barbara

Restoring Fire as an Ecosystem Process

Greg Aplet, The Wilderness Society

Conference Summary and Closeout

Jeff Jahnke, Colorado State Forester

Panels

Wildland Fire Use: It's not just for wilderness anymore.

Moderator: Carol Miller USDA Forest Service, Aldo Leopold Wilderness Research Institute

Panelists: Marcia Andre, Supervisor, Gila National Forest
Dick Bahr, Fire Use Specialist, National Park Service-NIFC
Tom Nichols, Deputy Fire Program Planning Leader, National Park Service-NIFC
Mike Rieser, FMO, Craig/Routt Fire Management Unit, Bureau of Land Management
George Weldon, Deputy Director - Fire, Aviation, and Air, Forest Service, Northern Region

How do we define success in fuels management?

Moderator: Jack Cohen, USDA Forest Service, Missoula Fire Laboratory

Panelists: Greg Aplet, The Wilderness Society, Denver, CO
Steve Arno, USDA Forest Service, Missoula Fire Laboratory, retired
Howard Roose, Bureau of Land Management, NIFC
Paul Langowski, USDA Forest Service, Region 2
Jon Keely, USGS Western Ecology Center, Sacramento, CA
Rocky Barker, Idaho Statesman, journalist & author, Boise, ID

Workshops

Science Synthesis and Integration: FuelsTools
Dave Peterson

Using Fireshed Assessments to Measure Landscape Performance
Bernie Bahro, K. Barber, L. Perrot, J. Sherlock, A. Taylor, K. Wright, and D. Yasuda

Introduction to state-and-transition modeling of vegetation change using the Vegetation Dynamics Development Tool (VDDT)
Leonardo Frid

Spatially explicit landscape-level modeling of vegetation change using the Tool for Exploratory Landscape Spatial Analysis (TELSA)
Leonardo Frid

FIREMON fire effects monitoring protocol
Duncan Lutes

Help with using the 40 new fire behavior fuel models
Joe H. Scott

A Suite of Fuel Management Tools: Fuel Characteristic Classification System, Natural Fuels Photo Series, and Consume 3.0
Roger D. Ottmar, Cynthia L. Riccardi, Susan Prichard, Robert E. Vihnanek, and Clint S. Wright

Fire and Fuels Extension to the Forest Vegetation Simulator (FFE-FVS)
Stephanie Rebain

Use of FlamMap for Fire and Fuels Planning
Mark A. Finney, Rob Seli, and Chuck McHugh

Fire Regime Condition Class: Concepts, Methods, and Applications (FRCC)
Steve Barrett

Oral and Poster Presentations

Modeling the Effects of Moderate Severity Burns on Fuel Loading in Northwest Wyoming Mixed Conifer Forests
Diane C. Abendroth, Mohammed A. Kalkhan and Karl E. Brown

Utilizing prescribed fire to restore endangered species habitat while managing potential negative effects to non-target endangered species
Russ Babiak

Stanislaus Stewardship and Fireshed Assessment Case Study: Measuring Landscape Performance
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