USDA United States Department of Agriculture

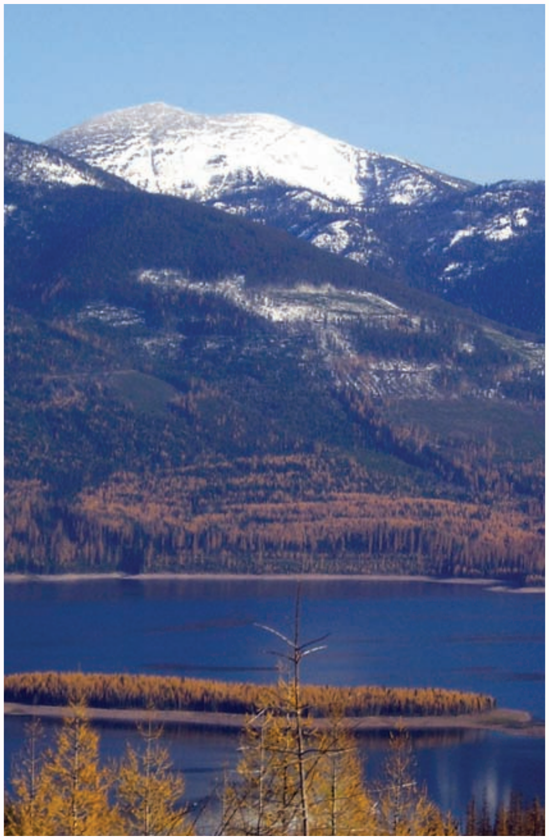
Forest Service

Rocky Mountain Research Station

Proceedings
RMRS-P-54
September 2008

Third Forest Vegetation Simulator Conference

Fort Collins, Colorado
February 13–15, 2007




Havis, Robert N.; Crookston, Nicholas L., comps. 2008. **Third Forest Vegetation Simulator Conference**; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 234 p.

Abstract

The Forest Vegetation Simulator (FVS) is a suite of computer modeling tools for predicting the long-term effects of alternative forest management actions. FVS was developed in the early 1980s and is used throughout the United Sates and British Columbia. The Third FVS conference, held February 13–15, 2007, in Fort Collins Colorado, contains 20 papers. They describe the use of FVS on the stand and landscape scale, and to analyze fuels management in the presence of insects and fire. Several papers compare FVS predictions of the effects of insects and disease to field measurements. FVS is continually evolving and improving in technology and capability to meet the needs of its ever increasing user community. Papers describe new methods for data acquisition and preparation for input to FVS, new economic analysis capabilities within FVS, new methods for simulating forest regeneration, new developments in calculating growth and mortality, and future plans for incorporating the effects of climate change in model simulations.

Keywords: forest management, forest planning, growth and yield, vegetation dynamics, habitat modeling, carbon inventory, prognosis model, landscape dynamics, fire, fuels, climate change, economics, forest health

The Compilers

Robert N. Havis is a Systems Analyst with the USDA Forest Service, Forest Management Service Center (FMSC) in Fort Collins, CO. A Civil and Environmental Engineer by training, Dr. Havis has developed natural resource simulation tools, including models for mine waste management, agricultural water quality, eutrophic lake management, stream bed load transport and gravel quality, and contaminant dispersion around dredging operations. He has been involved in software development and support for the FVS base model and extensions since 1998. The FMSC is the technology transfer center for the FVS model system. It distributes software to the public, provides user training and hotline support, and develops new geographic variants and enhancements to the base model system.

Nicholas L. Crookston is an Operations Research Analyst with the USDA Forest Service, Rocky Mountain Research Station in Moscow, ID. He has spent his career working on the base FVS system and its extensions. His first contribution to FVS, in the late 1970s, involved creating the first extension—one that represented mountain pine beetle population dynamics in lodgepole pine. Work on the development of the Douglas-fir tussock moth and western spruce budworm extensions followed. These extensions formed a template on which all FVS extensions have been based. Mr. Crookston conceived and built the Event Monitor and, in a collaborative effort with Al Stage, built the Parallel Processing Extension to FVS. His recent efforts have been in building the Suppose user interface, managing the development of the Fire and Fuels Extension and leading the effort to develop a climate-driven version of FVS.

Acknowledgments

Funding for this publication was provided by the Forests and Woodlands Ecosystems Research Program of the Rocky Mountain Research Station (RMRS), the Forest Health Technology Enterprise Team, and the Forest Management Service Center, all part of the USDA Forest Service. The compilers are particularly grateful to Dennis Ferguson, RMRS; Loa Collins, Publications RMRS; and Sheryl Romero, ITX. The conference organizing committee included Robert Havis (chairperson), Judy Adams, Dave Cawrse, Nicholas Crookston, Gary Dixon, Chad Keyser, Stephanie Rebain, Erin Smith-Mateja, and Don Vandendriesche.

You may order additional copies of this publication by sending your mailing information in label form through one of the following media. Please specify the publication title and number.

Fort Collins Service Center

Telephone	(970) 498-1392
FAX	(970) 498-1122
E-mail	rschneider@fs.fed.us
Web site	http://www.fs.fed.us/rm
Mailing Address	Publications Distribution Rocky Mountain Research Station 240 Prospect Road Fort Collins, CO 80526

Third Forest Vegetation Simulator Conference

Fort Collins, CO
February 13–15, 2007

Compilers:
Robert N. Havis
Nicholas L. Crookston

Conference Endorsements

The Society of American Foresters (SAF)
The International Union of Forestry Research Organizations (IUFRO), Division 4, Forest Assessment, Modeling and Management

Sponsoring Organizations

USDA Forest Service, Rocky Mountain Research Station (RMRS)
USDA Forest Service State & Private Forestry
USDA Forest Service Forest Health Protection
USDA Forest Service National Headquarters Forest Management

Citations to Previous Conference Proceedings

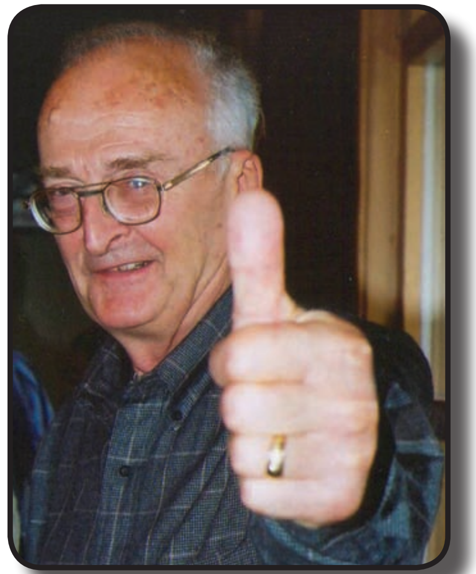
Teck, Richard; Moeur, Melinda; Adams, Judy, comps. 1997. Proceedings: Forest Vegetation Simulator conference; 1997 February 3–7; Fort Collins, CO. Gen. Tech. Rep. INT-GTR-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 222 p.

Crookston, Nicholas L.; Havis, Robert N., comps. 2002. Second Forest Vegetation Simulator Conference; February 12–14, 2002; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 208 p. Online: http://www.fs.fed.us/rm/pubs/rmrs_p025.html

Rocky Mountain Research Station
240 West Prospect
Fort Collins, Colorado 80526

These papers received technical peer review and were edited to a uniform style; however, authors are responsible for content and accuracy of their papers.

Albert R. Stage



Al Stage showing how to use your thumb as an angle guage in variable plot sampling (photo by Kim Iles).

Dedication

These proceedings are dedicated to Al Stage, Emeritus Scientist who passed away July 12, 2008. Al was one of the giants in forest biometrics research and forest growth dynamics modeling in the world. His broad breadth of knowledge, analytical skills, creativity and curiosity, and his sheer love of science, made him a consummate forest scientist. It is noteworthy that his most productive year measured in refereed journal papers was 2007, many years after becoming an Emeritus Scientist. He had more work to do and many more papers planned than his lifetime permitted.

Al was best known for the creation of the Prognosis Model for Stand Development, first published in 1973. This model is the core of what is currently known as the Forest Vegetation Simulator (FVS), the most widely used forest growth model in the world. Al's vision, his quiet but persuasive prodding, and his firm grasp of biophysical, mathematical, and statistical concepts are at the foundation of FVS. Many who had the pleasure of working closely with him stand in awe of his achievements; the fervor and pace with which Al attacked forestry research was exhausting!

Contents

Issues in Forest Management

Forest Disturbance: Fire

Forest Disturbance: Insect and Disease

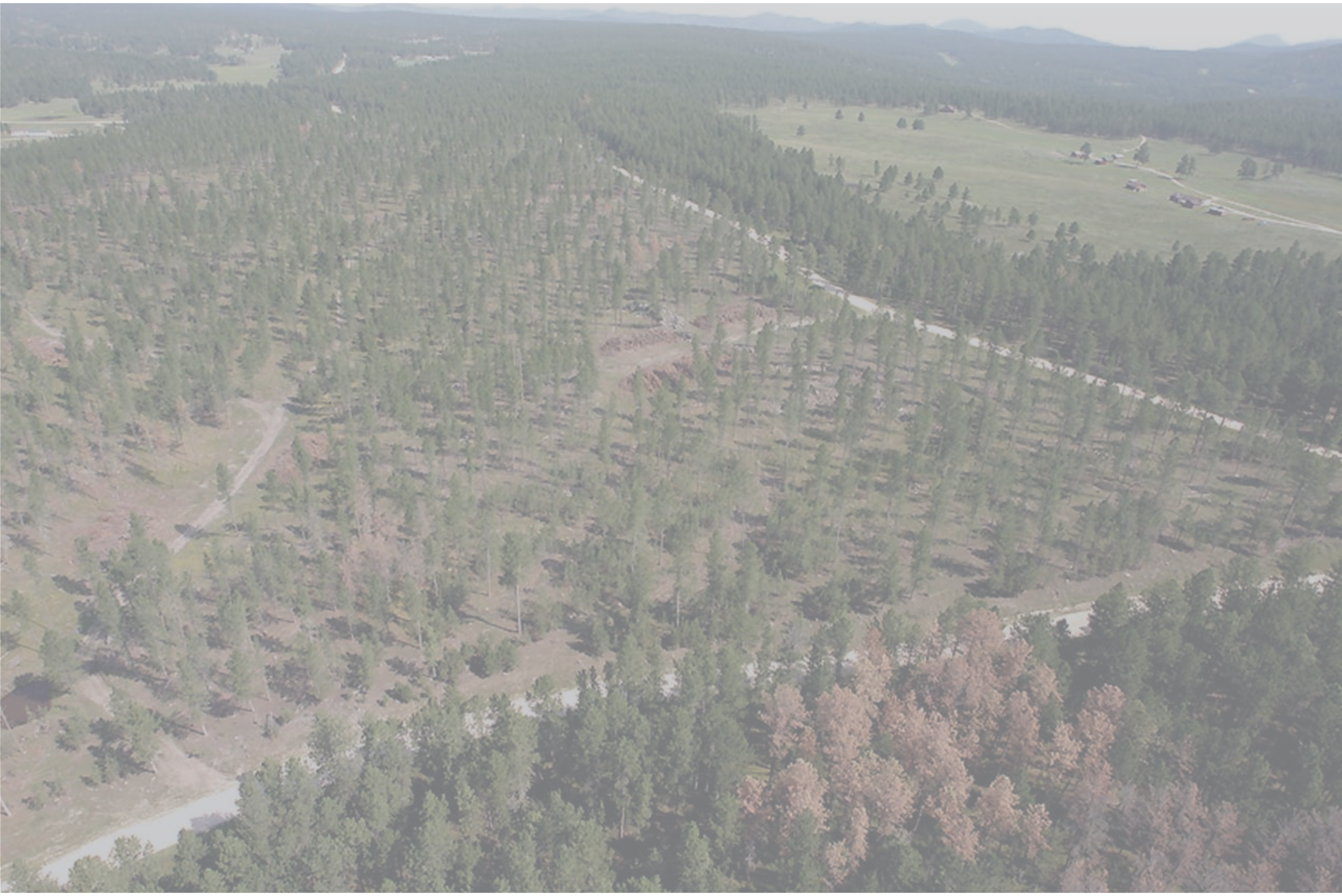
Forest Planning

FVS Data

Model Development I

Model Development II

Issues in Forest Management



Vegetation Simulation and Our Changing World: Keynote Address

Corbin Newman
Director of Forest Management
USDA Forest Service
Washington, DC
Current affiliation, Regional Forester
Southwestern Region
USDA Forest Service

Summary

Prior to the 1990s, a primary focus of vegetation management on National Forest System (NFS) lands was commodity production. While the production of goods is still important, the last 20 years has seen an emphasis in the restoration of ecosystem function and resiliency. This is illustrated by a decline of more than 80% in NFS timber production since the late 1980s. The current Forest Service focus on ecological restoration reflects both changing public values, and the current ecological conditions on NFS lands. Ecological restoration is not restoring land to some predetermined point in time, but to create conditions within the ecosystem that restores its health and resiliency to natural forces and disturbances that affect it while meeting societal needs.

"FVS has grown to meet the needs of field practitioners, and evolved to address the emerging forest management issues such as biomass and carbon sequestration. Most importantly, FVS has remained dedicated to the user."

The shift from commodity production to restoring ecosystem resiliency has occurred in the context of concern for the effects of climate change on forests, a decade-long drought in parts of the West, and a multi-decade increase in forest density. In many parts of the country, increases in forest density have been in progress since the late 19th century. Forest growth greatly exceeds removals on NFS lands in the Interior west. When dense forests combine with extended drought, the ecological stress sets the stage for increased insect epidemics and wildfire. There has been a major shift in fire regime from low to high severity, and the intensity of wildfire has increased. At the same time, there has been an unprecedented expansion of residential development into wild lands.

There has been a compelling political call to action, and key socio-political forces are shifting. There is broader recognition of climate change and the need for action to address it. There is a growing recognition of the need to actively manage NFS lands to restore and protect important ecosystem services such as carbon sequestration and bio-energy. The Forest Service has responded with dramatically increased forest fuels treatments and vegetation treatments focused on density management, and a robust Forest Health Protection program on federal and non-federal lands. A major strategy of National Forest management has been to focus on ecosystem restoration and fuels treatment.

Today, more than ever, FVS is ready to provide the vegetation management tools needed by planners to analyze alternative futures, by decision makers to understand the effects of actions they contemplate, by collaborative groups to explore common ground around treatments, and by land management agencies to understand the consequences of policies they consider. FVS has grown to meet the needs of field practitioners, and evolved to address the emerging forest management issues such as biomass and carbon sequestration. Most importantly, FVS has remained dedicated to the user. The conference and the proceedings document the contemporary uses and state-of-the-art of FVS, and look into the near future applications and model development goals.

Enjoy the conference.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

FVS and Global Warming: A Prospectus for Future Development

Nicholas L. Crookston[1]
Gerald E. Rehfeldt[1]
Dennis E. Ferguson[1]
Marcus Warwell[1]

Abstract—Climate change—global warming and changes in precipitation—will cause changes in tree growth rates, mortality rates, the distribution of tree species, competition, and species interactions. An implicit assumption in FVS is that site quality will remain the same as it was during the time period observations used to calibrate the component models were made and that the site quality will not be affected by climate change. This paper presents evidence of the impacts of climate change on forests and argues that FVS needs to be revised to account for these changes. The changes include modification of the growth, mortality, and regeneration establishment models, all of which need to account for changes in site quality and genetic adaptation. Criteria for modifying the model recognize that the model's applications and uses will not diminish and need to be supported. The new process, climate change, needs to be recognized by the model because it influences all of the processes FVS currently represents. Plans are being made to address this major task.

Introduction

This paper is a call to action. A key use of FVS is to forecast the species and size distribution of forest stands over time, given proposed management regimes. This and other uses are documented by two previous symposium proceedings (Teck and others 1997; Crookston and Havis 2002) and other key documents (Dixon 2003; Crookston and Dixon 2005). Typical applications of FVS are clearly within the time span of predicted significant climate change (Rehfeldt and others 2006; IPCC 2007a).

FVS needs to be modified so that it can be useful in the face of changing climate (Monserud 2003). The key uses of FVS will be in even greater demand as forest managers try to cope with climate change in addition to ever increasing demands for wood, habitat, and other ecosystem services. How to manage forests over the rest of this century and into the next is an open question that cannot be addressed with forest growth models that are both insensitive to climate change and are designed for century long projections.

Necessary changes to FVS touch all aspects of the base model as climate change influences the processes the model represents (Crookston and Dixon 2005; IPCC 2007b). In this paper we present research that shows how one scenario of climate change is predicted to alter the climate for some important species (Rehfeldt and others 2006) and present some recent exploratory work showing how it might influence the carrying capacity of forested lands in the Western United States as measured by stand density index (Reineke 1933), one of the key variables used in FVS to predict mortality. In addition we review recent exploratory work that relates growth increment to precipitation and temperature and discuss the role genetics might play in predicting growth. After the need for modifying FVS is clearly documented and some of the exploratory work is presented, we discuss the design criteria for a new climate-based variant and discuss our ideas on how this model might take shape.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Operations Research Analyst, Geneticist (Retired), Research Forester, and Geneticist, respectively,USDA Forest Service, Rocky Mountain Research Station, Forest and Woodland Ecosystems Program, Moscow, ID; e-mail: ncrookston@fs.fed.us.

Change In Species Distributions

Climate is the major factor controlling species distributions (Holdridge 1947). Rehfeldt and others (2006) published maps of the climate profiles for individual species and plant associations. Figure 1 depicts the current and projected locations of the climate profiles for *Pinus ponderosa*, *Larix occidentalis*, *Pseudotsuga menziesii*, and *Picea engelmannii* for contemporary climate and at three points in the future. A species climate profile is a model that predicts the presence of a species according to climate metrics. The maps were produced by relating current species distributions as recorded in the Forest Inventory and Analysis (FIA) data to the climate variables predicted using a model of the climatic normal period of 1960 to 1990 (Rehfeldt 2006). Future distributions of species' climate profiles were made by predicting the future locations using forecasted climates. The forecasted climates were based on the average of two global circulation models run for a "business as usual" scenario of 1 percent increase in greenhouse gases per year over this century. The two models are from the Hadley Center (HadCM3GGa1) (Gordon and others 2000) and Canadian Center (CGCM2_ghga) (Flato and Boer 2001).

It appears that for some species, for example *P. menziesii*, the future does not seem too bleak (yet likely understated in these figures; see the discussions in Rehfeldt and others 2006), but for others, the forecast is not very positive (*P. engelmannii*, for example). The point is that the locations of the climate profiles change, some more than others, and that the change is clearly within the period of typical one-century long FVS projections. We conclude that species composition is likely to be influenced in ways not contemplated with the current FVS model formulation and that the magnitude of the change is likely to be large and widespread.

Carrying Capacity, Maximum Stand Density Index

As part of our preliminary work on modifying FVS, we worked out a model of maximum stand density index (MaxSDI) (Reineke 1933) computed using the Western U.S. FIA data as a function of two climate measures, mean annual precipitation (MAP) and the number of degree days above 5 °C (DD5). SDI is the equivalent trees per acre (TPA) at a quadratic mean diameter (QMD) of 10 inches (there is a metric version as well that does not have an exact linear conversion), expressed as follows: $SDI = TPA\,(QMD/10)^{1.605}$. SDI is used in the mortality models in some FVS variants. As the tree density reaches a proportion of the maximum tabulated in the model for a site, the model increases the mortality rate so that the established upper limits of SDI are not exceeded. In this context, MaxSDI is used as a measure of the site carrying capacity. The climate-derived MaxSDI equation is:

$$MaxSDI = b_0\ (1\text{-}\exp(\text{-}(b_1\ MAP)^{b_2}))\ \ DD5\ \ \exp(b_3\ DD5) \qquad (1)$$

where $b_0 = 1.901$, $b_1 = 0.003489$, $b_2 = 1.861$, $b_3 = -0.000775$, with a residual standard error of 181.5 where all coefficients are significant with $P < 0.01$. Observations used to fit this model are those subplots (from the FIA data) that carry the highest SDI measurements across several climate gradients. Briefly, the procedure for one climate variable was to create 300 bins of observations corresponding to 300 fixed intervals along a climate gradient (MAP, for example). In each bin, the identity of the 99th percentile observation of SDI was recorded. This procedure was completed independently for each of 35 climate variables used by Rehfeldt and others (2006). The lists of subplot identities were then combined and all duplicates were removed.

Figure 2 illustrates the equation's response surface. At the lower end of the precipitation gradient, MaxSDI increases with increased precipitation, but at the upper end there is no increase in carrying capacity. In fact, there is some evidence that at the highest precipitations, MaxSDI falls as precipitation increases. This can be seen by inspecting the residual plot that shows that MaxSDI is over predicted at high levels of precipitation. For the purposes of this paper, we left the equation form as shown with an upper asymptote on precipitation. The response of MaxSDI to heat is different in that higher heat results in higher MaxSDI until an optimum is reached and then additional heat causes decreases in MaxSDI. The equation captures some important components of climate and plant interactions.

The quotient of DD5 divided by MAP is sometimes called annual moisture index (Rehfeldt and others 2006), but may be better referred to as an annual dryness index (ADI) because as the amount of heat increases for a fixed amount of moisture, the numeric

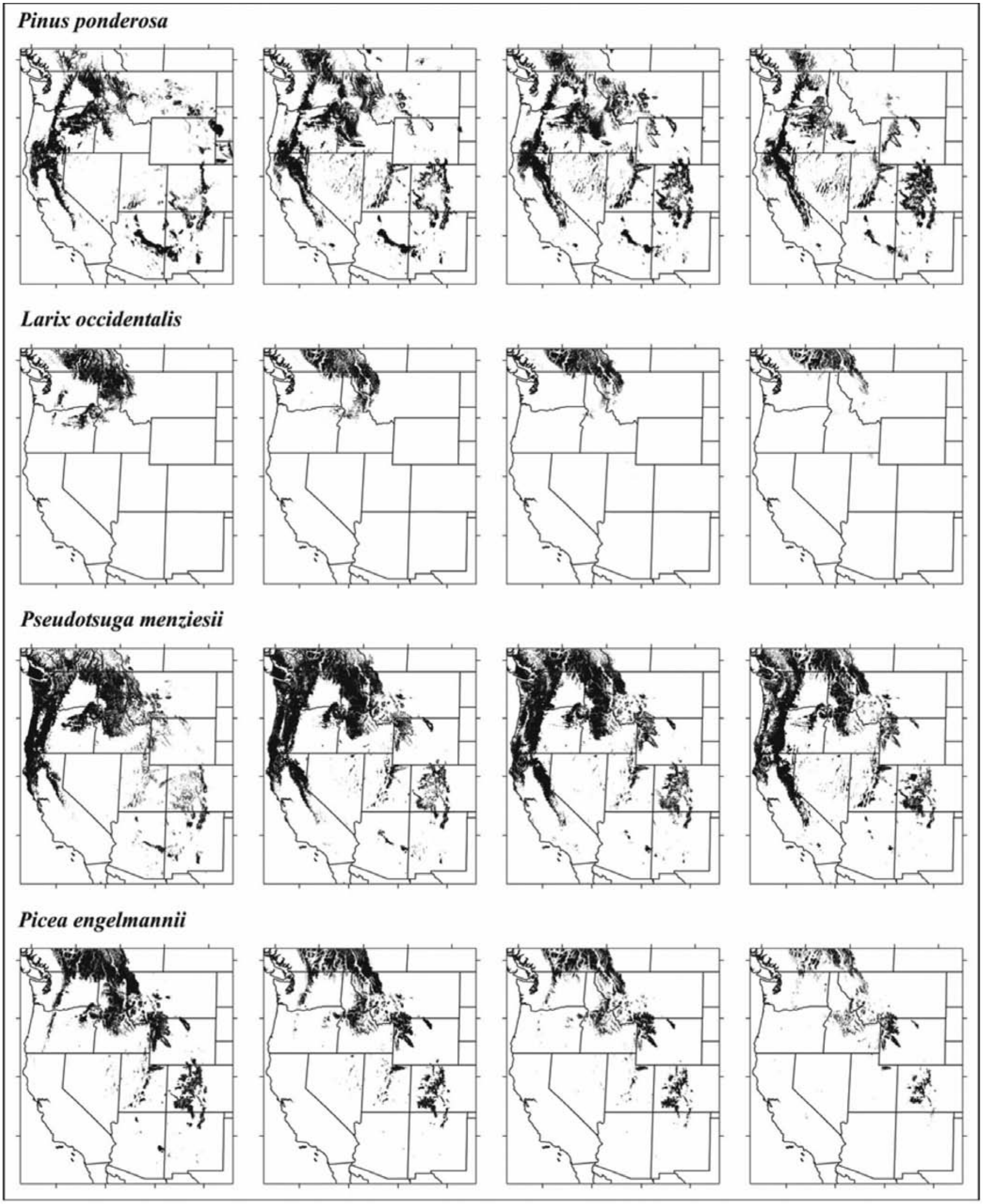


Figure 1—Modeled climate profiles of four forest tree species for the contemporary climate and for the decades beginning in 2030, 2060, and 2090 (left to right) (reprinted from Rehfeldt and others 2006, p. 1146).

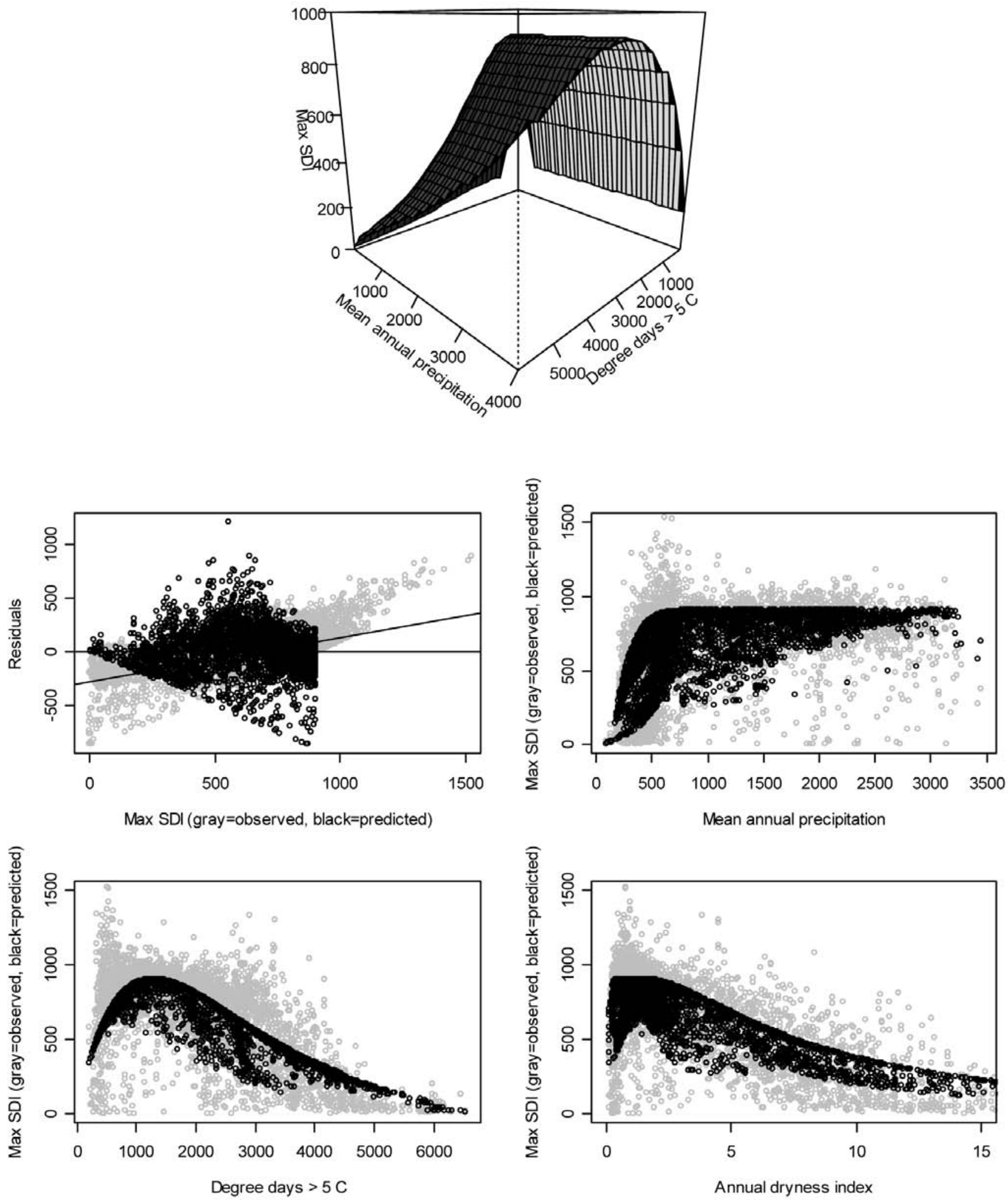


Figure 2—The top graphs predicted values of MaxSDI (Equation 1) plotted over mean annual precipitation (MAP) and degree days >5 °C (DD5). In the rest of the panels, gray is the observed data and black is the predicted. The middle row left panel displays the residuals with a flat reference line and a diagonal line that illustrates bias. The predicted values are plotted over the predictor variables in the middle right and lower left panels. The last plot (lower right) is predicted plotted over annual dryness index (ADI) even though that variable was not included in the regression.

value of the index increases. We plotted MaxSDI over ADI to illustrate the relationship (fig. 2, lower right), but we did not directly include this ratio as a predictor.

Figure 3 maps the predicted change in MaxSDI for areas currently considered forested or woodlands (Brown and others 1998) in the Western United States using Equation 1. The period of change is from climate normal period (1961 to 1990), to the year 2060 as predicted by the climate model of Rehfeldt (2006). The projected changes are quite large and beg a question regarding how much the equation is being used to extrapolate into future climates. Figure 4 (left) is a scatter plot of the observations used to calibrate Equation 1 designed to show the range of MAP and DD5 measurements. Four example locations were picked to illustrate that in some cases, for example, in the Olympic Mountains of western Washington State the current climate is quite unique in the Western United States, with very high precipitation and low heat. Increases in DD5 and MAP indicated by the short vector do indeed suggest that the model is being used to extrapolate beyond contemporary experience. But the other three locations are within the range of data and exemplify a large percentage of the mapped changes. The right side of figure 4 charts the MaxSDI values for all four locations now and in the future. In general, increases in MaxSDI are consistent with areas that are currently cold and wet that will become warmer and still have enough precipitation to support forests. Decreases in MaxSDI are generally consistent with places that are already hot, are projected to become hotter, and any increase in precipitation will not significantly offset the increase in heat. This work does not account for changes in species composition that may be necessary to actually see any gains in MaxSDI or that might result from loses.

MaxSDI is not used in every variant of FVS as some use basal area maximum (Crookston and Dixon 2005). Note that while these two measures are not identical, they are strongly related and there is little doubt that conclusions reached by studying MaxSDI apply to maximum basal area as well.

Change in Growth Rates

Growth increment in FVS is a function of three basic factors: tree size (represented by diameter, height, age, or these in some combinations), competition (measured by stand density and basal area in larger trees), and site quality (measured as site index or habitat type, slope, elevation, and other factors). The model formulations are designed to predict increment as tree size, competition, or both change, but not designed to allow for site quality to change assuming that it will remain constant over time. As we have shown, that assumption under climate change is not defensible. Crookston and others (2007) did a preliminary analysis of the diameter increment of *P. menziesii*. They refit the increment equation in FVS (Wykoff 1990; Stage and Wykoff 1998) by replacing the static site quality measurements with mean annual temperature and precipitation. Although preliminary, plots made using the equation provide some insights (fig. 5). First, the FIA data used to calibrate the equation did not support the notion that growth will decline with temperature increases, although it will increase with increased precipitation. This result defies growth theory. Surely, as temperature increases beyond the limits of a tree to cope, the result will be lower growth. Furthermore, the adaptive response of individual trees, measured by the response for individual genotypes, determines the individual growth response to climate change (Langlet 1936; Rehfeldt and others 1999; 2002, 2003). Genetics research supports a bell-shaped curve for growth response on a temperature gradient, with different maxima for each genotype.

We conclude that a combination of information from genetics research, growth theory, and observations like those from FIA will need to be combined to realistically model growth. Proper modeling of mortality is also necessary. The growth rates of trees that recently died are normally not recorded and are therefore observations of growth for dying trees are rare in the data used to calibrate the growth model. Statistical analyses of these data lead to model parameterizations that do not reflect slowing of growth as trees die. The mortality model, therefore, also needs to be adjusted so that trees are predicted to die as conditions change from those that support growth to conditions that do not support growth.

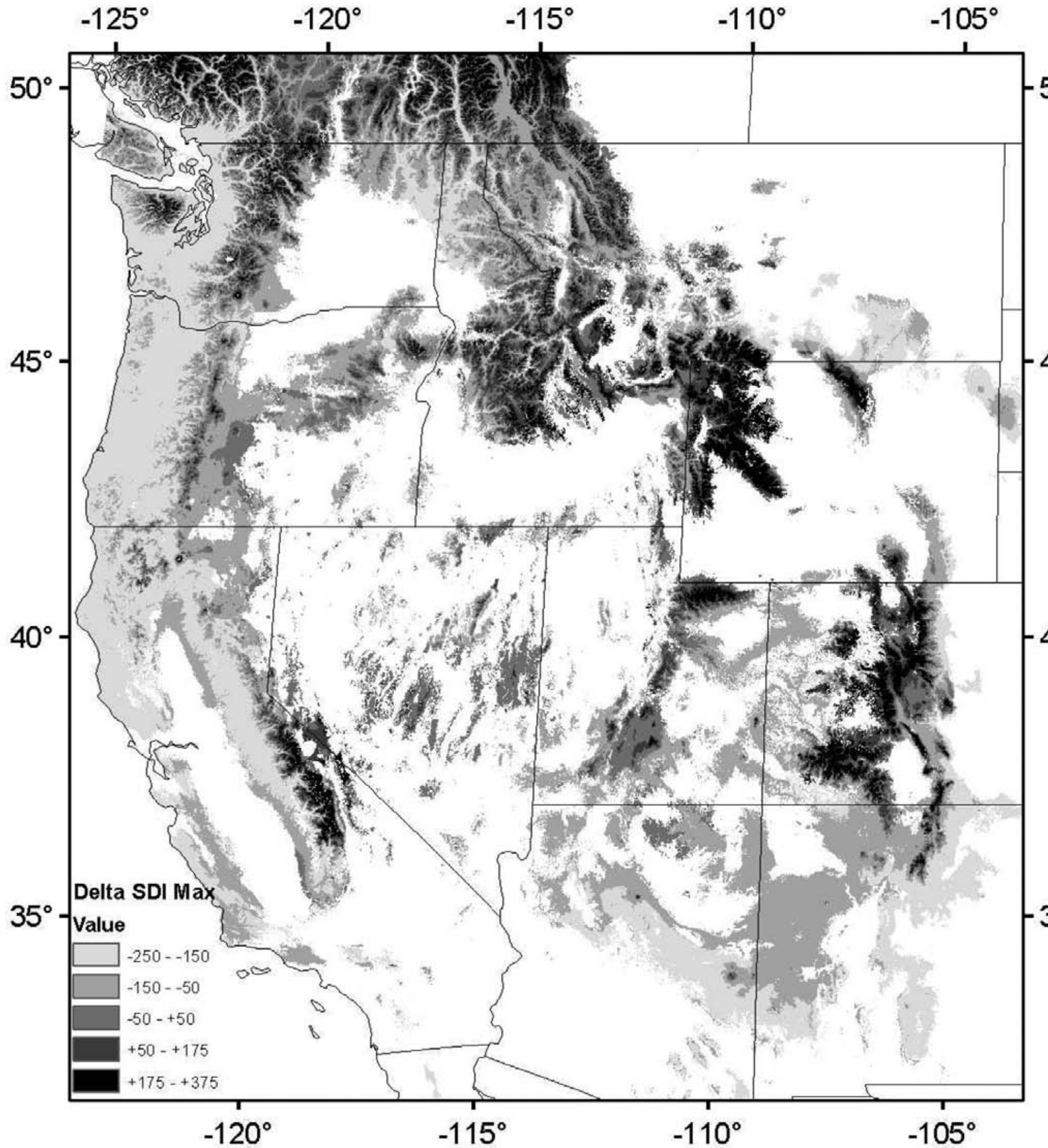


Figure 3—Predicted change in the MaxSDI for areas currently considered forest or woodlands for the 1960–1990 climate normal period to the year 2060, using the spline model of Rehfeldt (2006) and the average of the predictions of two global circulation models run under a "business as usual" scenario.

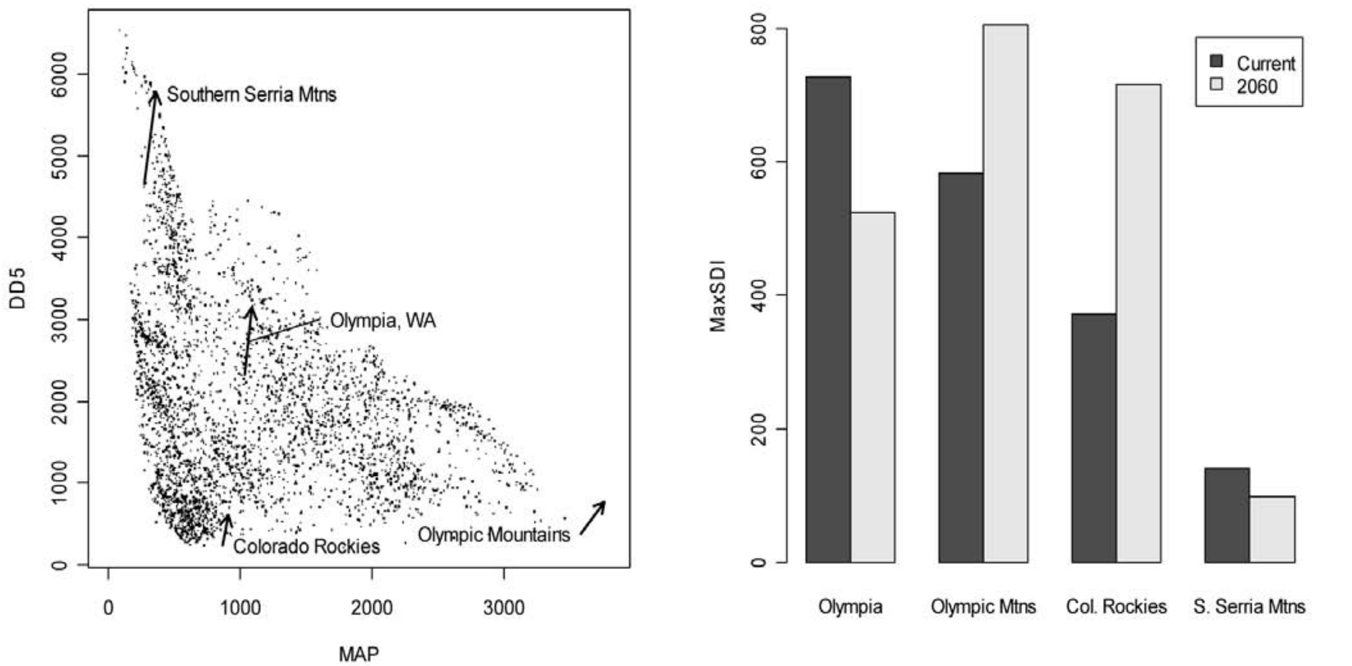


Figure 4—The left side is a scatter plot of the observations used to calibrate Equation 1 with the predicted change in MAP and DD5 from current climate to 2060 indicated with short vectors for four example locations. The bar chart on the right shows the predicted change in MaxSDI for the four locations. Changes predicted for the Olympic Mountains are slightly beyond the range of the data while the others are within the range of observations.

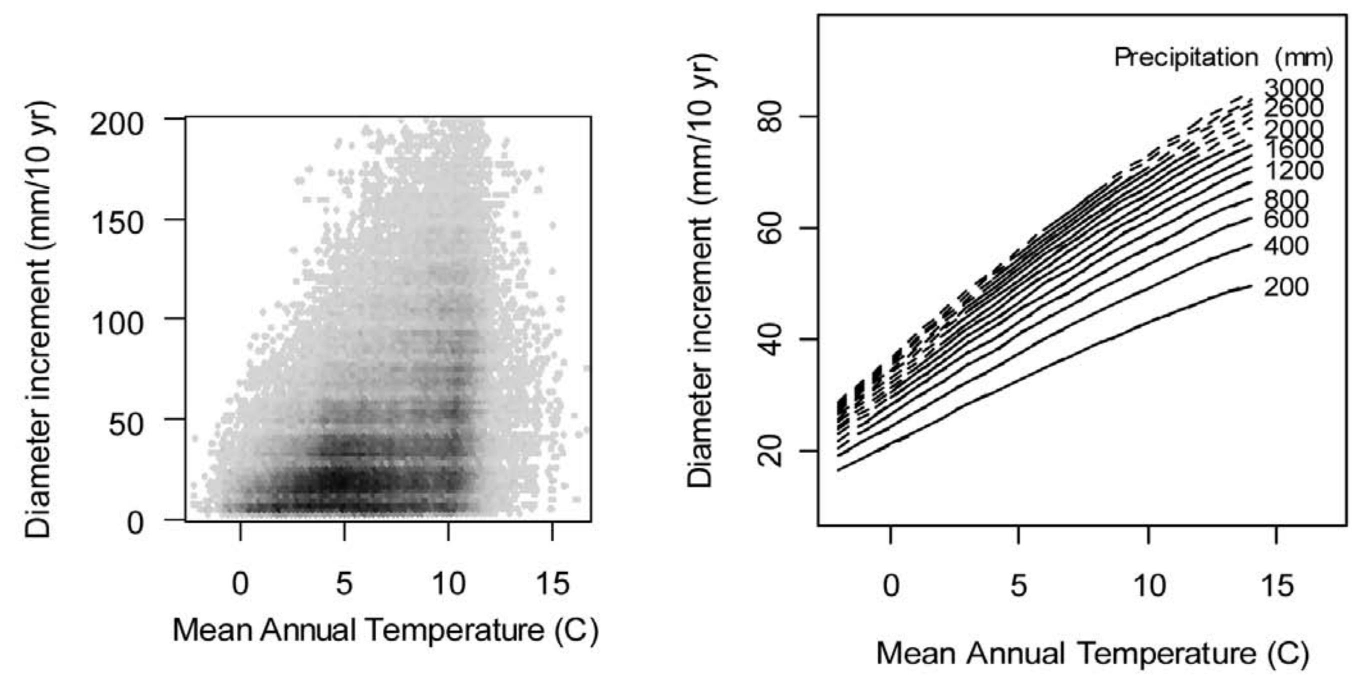


Figure 5—The left side is a scatter plot of the observations used to calibrate a diameter increment equation and the right side is the response of increment to mean annual temperature (MAT) and MAP (from Crookston and others, in press).

FVS Components and Ideas for Change

Design Criteria

In contemplating the design of a new FVS methodology that is sensitive to climate change, several factors come to mind.

- The overall needs met by current FVS variants will remain; sensitivity to climate change must be added.
- There should be no "built in" climate change scenario. FVS must be programmed to use the outputs produced by these models and users need the ability to choose the climate change scenario they wish to run.
- The model should be consistent with current variants when run under a no climate change scenario. While this is an important goal, it will be hard to reach as differences in predictions are inevitable.
- Research indicates that genetics play a major role in determining the growth of trees when site conditions change. Some species, for example *P. menziesii*, are genetic specialists where sub populations of the species are closely tuned to the climatic regime to which they are adapted. FVS will need to take into account the climate associated with the sub-population of a species; it will not be sufficient to account for climate at the species level.
- There are several extensions to FVS that represent insect pests, pathogens, and notably fire and fuels (for an overview, see Crookston and Dixon 2005, p. 64). These extensions make use of many of the same static measures of site quality, notably habitat type/plant association and forest type, used by the base model. Any changes in the base model that represent changing site quality should be made in a way that the extensions can use the results.

Meeting these design criteria is a tall order and likely beyond the scope of first versions. Here are our speculative ideas on how to proceed.

Diameter and Height Increment

The preliminary analysis of increment presented above offers suitable direction to take for every species in FVS, however, it is likely that different climate variables will be important among species. We plan to compile and analyze contemporary observations of growth on individual trees using currently known methods to represent competition and size while introducing new methods to represent site through climate. (see Froese 2003 for a first attempt at this work). While this approach promises to capture the effect of climate on increment, it will not capture the effect of changing CO_2 or other resources that control tree growth.

Some species have strong genotypic adaptation to narrow portions of the environmental range evident for the species as a whole and that this variation is directly related to growth (Monserud and Rehfeldt 1990). Almost all of the available observations of growth record the species of the tree, not the genotype. Crookston and others (2007) addressed this issue and offered a possible solution for *P. menziesii* that would work for other species where sufficient data are available from common garden experiments. While a structure that accommodates these kinds of relationships can be included, data to calibrate the relationships are not generally available for many species. Including what is known about these relationships must be an objective of this work.

Mortality

Many current mortality models in FVS use MaxSDI as a key driver. The preliminary analysis described above holds some promise that climate can be used to predict MaxSDI. Warming temperatures and changes in precipitation can then have direct influences on mortality rates. In addition, the recent work of Rehfeldt and others (2006), plus some as yet unpublished results, indicate that species' realized niche space can be predicted using climate. We believe that climate changes can be translated into changes in the likelihood that a species can exist at a given location. Reductions in the probability that a species exists would increase the probability of mortality, and *visa versa*. This approach leaves unanswered the role of interspecific competition. Currently growing trees (trees that provide us with contemporary evidence) generally have potential niche spaces that are significantly larger than those evident in inventory data. An empirically calibrated model like the one we envision would miss this factor. We see no solution to this issue other than to press on and push for the installation of the necessary field studies that would allow us to measure the difference between realized and potential niche. In cases where the relationships are already known, they can be taken into account in the model. Other cases will need to wait for the necessary evidence.

Regeneration Establishment

This model component predicts the number and species of newly established trees on a site. A model that purports to appropriately represent climate change in forecasts of forest species and size composition must contain a reasonable establishment model. We intend to use the same general information used to model mortality, but in a complimentary way. Stands that are under stocked will be restocked with species that have high probability of existing in the climate regime. The current methods used in FVS to model establishment contain two approaches. In the so called "full establishment" model, the model predicts the number, size, and species of trees one would expect to find at a given time past a disturbance of know character. In the other, users specify this information thereby simulating what they expect to occur. Our first step will be to include the partial model but our longer term plan is to provide a full establishment model. An important assumption of this effort is that when trees of a given species are established, they will be of proper genetic characteristics for the climate to which they are established.

Conclusions

Climate is changing (IPCC 2007a); climate affects birth, growth, and mortality of trees; FVS represents those processes, and therefore FVS must be adapted to use climate measures as predictor variables. Otherwise, FVS will lack relevance to forest managers that it has had in the past. The lack of relevance will be directly tied to the fact that FVS will be ignoring a key process (climate change) that directly influences key processes the model is designed to represent. Furthermore, we understand this to be the case, so modification of the model is essential if FVS is to be viewed as containing the scientific evidence relevant to its purposes and uses. Therefore, plans are being made to rebuild FVS so that forest managers will continue to have this important tool for aiding their management planning and activities. It will help inform foresters and other natural resource managers about the implications climate change will have on the ecosystems they are charged with managing.

References

Brown, D.E.; Reichenbacher, F.; Franson, S.E. 1998. A classification of North American biotic communities. Salt Lake City, UT: University of Utah Press. 141 p.

Crookston, N.L.; Dixon, G.E. 2005. The forest vegetation simulator: A review of its structure, content, and applications. Computers and Electronics in Agriculture. 49:60–80.

Crookston, N.L.; Havis, R.N., comps. 2002. Second Forest Vegetation Simulator conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 208 p.

Crookston, N.L.; Rehfeldt, G.E.; Warwell, M.V. 2007. Using Forest Inventory and Analysis Data to Model Plant-Climate Relationships. In: Proceedings of the seventh annual forest inventory and analysis symposium; 2005 October 3–6; Portland, ME. Gen. Tech. Rep. WO-77. Washington, DC: U.S. Department of Agriculture, Forest Service: 243–250.

Dixon, Gary E., comp. 2003. *Essential FVS: A User's Guide to the Forest Vegetation Simulator*. Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.

Flato, G.M.; Boer, G.J. 2001. Warming asymmetry in climate change simulations. Geophysical Research Letters. 28:195–198.

Froese, R.E. 2003. Re-engineering the prognosis basal area increment model for the Inland Empire. Moscow: University of Idaho. 113 p. Dissertation.

Gordon, C.; Cooper, C.; Senior, C.A.; Banks, H.; Gregory, J.M.; Johns, T.C.; Mitchell, J.F.B.; Wood, R.A. 2000. The simulation of SST, sea-ice extents and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustments. Climate Dynamics. 16:147–168.

Holdridge, L.R. 1947. Determination of world plant formations from simple climatic data. Science. 105:367–368.

Intergovernmental Panel on Climate Change. 2007a. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Summary for Policymakers. http://www.ipcc.ch/WG1_SPM_17Apr07.pdf

Intergovernmental Panel on Climate Change. 2007b. Climate change 2007: Impacts, Adaptation and Vulnerability Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report Summary for Policymakers. http://www.ipcc.ch/SPM13apr07.pdf

Langlet, O. 1936. Studies on the physiologic variability and their relationship with the climate. Meddelelser Statens Skogsförsöksanstalt. 29:217–470. [In Swedish].

Monserud, R.A. 2003. Evaluating forest models in a sustainable forest management context. FBMIS 1:35-47. Online: http://www.fbmis.info/A/3_1_MonserudR_1

Monserud, R.A.; Rehfeldt, G.E. 1990. Genetic and environmental components of variation of site index in Inland Douglas-fir. Forest Science. 36(1):1–9.

Rehfeldt, G.E. 2006. A spline model of climate for western United States. Gen. Tech. Rep. RMRS-GTR-165. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research. 21 p.

Rehfeldt, G.E.; Crookston, N.L.; Warwell, M.V.; Evans, J.S. 2006. Empirical analyses of plant-climate relationships for the Western United States. International Journal of Plant Science. 167(6):1123–1150.

Rehfeldt, G.E.; Tchebakova, N.M. ; Milyutin, L.I.; Parfenova, E.I.; Wykoff, W.R.; Kouzmina, N.A. 2003. Assessing population responses to climate in *Pinus sylvestris* and *Larix* spp. of Eurasia with climate-transfer models. Eurasian Journal of Forest Research. 6(2):83–98.

Rehfeldt, G.E.; Tchebakova, N.M.; Parfenova, Y.I.; Wykoff, W.R.; Kuzmina, N.A.; Milyutin, L.I. 2002. Intraspecific responses to climate in *Pinus sylvestris*. Global Change Biology. 8:912–929.

Rehfeldt, G.E.; Ying, C.C.; Spittlehouse, D.L.; Hamilton, D.A. 1999. Genetic responses to climate in *Pinus contorta*: niche breadth, climate change, and reforestation. Ecological Monographs. 69(3):375–407.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46:627–638.

Stage, A.R.; Wykoff, W.R. 1998. Adapting distance-independent forest growth models to represent spatial variability: effects of sampling design on model coefficients. Forest Science. 44(2):224–238.

Teck, R.; Moeur, M.; Adams, J., comps. 1997. Proceedings: Forest Vegetation Simulator Conference; February 3–7, 1997; Fort Collins, CO. Gen. Tech. Report INT-GTR-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 222 p.

Wykoff, W.R. 1990. A basal area increment model for individual conifers in the Northern Rocky Mountains. Forest Science. 36(4):1077–1104.

The Kane Experimental Forest Carbon Inventory: Carbon Reporting with FVS

Coeli Hoover[1]
Stephanie Rebain[2]

Abstract—As the number of state and regional climate change agreements grows, so does the need to assess the carbon implications of planned forest management actions. At the operational level, producing detailed stock estimates for the primary carbon pools becomes time-consuming and cumbersome. Carbon reporting functionality has been fully integrated within the Forest Vegetation Simulator (FVS), allowing users to produce carbon reports along with traditional FVS output. This added capability can be easily used by managers familiar with FVS and requires just a few additional keywords. All methodologies and computations are consistent with Intergovernmental Panel on Climate Change and U.S. standards. In this paper we present a current carbon inventory for the Kane Experimental Forest, an Allegheny hardwood forest located in northwestern Pennsylvania. Future carbon stocks are also projected using the new carbon budgeting capabilities of FVS.

Overview

Quantification of forest carbon stocks became an important research issue with the advent of the Kyoto Protocol, which permits some carbon uptake from afforestation and reforestation to be counted against a country's carbon emissions. Although the United States did not ratify the protocol, the nation's forest carbon stocks are reported as part of the overall carbon accounting under the U.N. Framework Convention on Climate Change. The United States also has a voluntary greenhouse gas reporting program covered under section 1605(b) of the Energy Policy Act. Under this program, business entities may report their overall emissions budgets; forest carbon sequestration is also reported. The program has carbon accounting rules and guidelines (available at http://www.eia.doe.gov/oiaf/1605/aboutcurrent.html) that are consistent with IPCC (Penman and others 2003) good practice guidance for carbon accounting.

Recently, the increasing number of climate change agreements and action plans at scales ranging from local to international has led to a greater need for information on forest carbon stocks now and in the future. While estimates and tools (Proctor and others 2005; Smith and others 2004; U.S. EPA 2006) are available at the county, state and national level, developing carbon estimates from inventory data for multiple forest stands or entire forests is generally a lengthy and unwieldy process. As forest carbon markets continue to emerge, the question of how forest management practices positively or negatively affect carbon storage becomes increasingly important to answer. Assessing the probable carbon consequences of forest management alternatives, while not difficult in a technical sense, is time consuming and cumbersome and so is often impractical for landowners and managers. The difficulty in accounting for the carbon in harvested wood presents an additional challenge.

Because of this increased demand for forest carbon information, a tool was needed to calculate forest carbon stocks at smaller scales. The following criteria were established: the tool should be accessible to managers and allow the flexibility to assess the carbon outcomes of forest management treatments, and the estimates produced must meet current U.S. carbon accounting rules and guidelines.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Research Ecologist, USDA Forest Service, Northern Research Station, Durham, NH; e-mail choover@fs.fed.us.

[2] Forester, USDA Forest Service, Forest Management Service Center, Fort Collins, CO.

Development History

The development of carbon accounting capabilities within FVS first began in 2003 when Nick Crookston and Dennis Gammel created a prototype to examine the prospect of using the model's output to predict forest carbon storage. They found that using the Fire and Fuels Extension (FFE) to FVS for carbon accounting was promising, but their prototype brought up questions as to how carbon reporting should be added to the model. A few years later in 2005, development of carbon accounting capabilities within FVS took off quickly once a collaboration was established between scientists at the Northern Research Station and the staff at the Forest Management Service Center. Initial consultations to determine the broad outlines of the project included Coeli Hoover, Stephanie Rebain, Rich Birdsey, Nick Crookston, Gary Dixon, Linda Heath, and Jim Smith. It was agreed that many of the necessary components of a stand-level carbon estimate were already being tracked and reported through the Fire and Fuels Extension (Reinhardt and Crookston 2003), and so rather than creating a post-processor the carbon reporting functions would be contained within the FFE and requested using keywords. In the summer of 2005, Rebain met with Hoover, Heath, and Smith to work out the specifics of which variables would be reported and which computation methods would be used, locate documentation for default assumptions, and finalize report design. All methodologies are consistent with U.S. carbon accounting rules and guidelines and the Intergovernmental Panel on Climate Change (IPCC) Good Practice Guidance for Land Use, Land Use Change, and Forestry. Don Robinson and Sarah Beukema of ESSA Technologies completed the necessary programming for the carbon reports. The new FVS carbon reports were available in the fall of 2006. Complete documentation of the carbon reporting methods and assumptions is provided in the Fire and Fuels Extension Addendum document (http://www.fs.fed.us/fmsc/fvs/documents/gtrs_ffeaddendum.php).

Report Structure and Options

There are two reports that can be requested: the Stand Carbon Report and the Harvested Carbon Report. The ***Stand Carbon Report*** includes the major carbon pools as defined by the U.S. Carbon Accounting Rules and Guidelines and the IPCC Good Practice Guidance: aboveground live tree, belowground live tree (coarse roots), belowground dead tree, standing dead trees, down dead wood, forest floor, and understory (shrubs/herbs). In addition, the merchantable portion of live tree carbon is reported, as well as total stand carbon, total carbon removed and carbon released from fire (if harvests or fires are simulated). The user has a choice of measurement units: pool sizes can be reported in tons per acre or metric tons per hectare. Biomass is assumed to be 50% carbon for all pools except forest floor, which is 37% carbon (Smith and Heath 2002). Carbon pools in the Stand Carbon Report are defined and calculated as follows:

- Total Aboveground Live: carbon in live trees, including stems, branches, and foliage but excluding roots. Choice of calculation methods: either default FVS-FFE methods or Jenkins and others (2003).
- Merchantable Aboveground Live: carbon in the merchantable portion of live trees; choice of calculation method as above.
- Belowground Live: carbon in coarse roots of live trees; carbon in fine roots is assumed to be part of the soil pool, not currently reported in FVS. Computed from Jenkins and others (2003).
- Belowground Dead: carbon in coarse roots of dead or cut trees. Computed from Jenkins and others (2003); default root decay rate can be adjusted by the user.
- Standing Dead: carbon in dead trees, including stems and any branches or foliage still present, but excluding roots. Calculated with FVS-FFE methods.
- Down Dead Wood: all woody surface material regardless of size; FVS-FFE method.
- Forest Floor: all surface organic material excluding wood (litter and duff); FVS-FFE method.
- Herbs and Shrubs: FVS-FFE method.

Other categories reported are Total Removed Carbon including carbon removed through cutting live or dead trees and hauling away surface fuel, and Carbon Released from Fire, which includes carbon in fuel consumed by simulated wildfires, prescribed burns, and pile-burns. An example of the Stand Carbon Report is shown in figure 1.

****** CARBON REPORT VERSION 1.0 ******
STAND CARBON REPORT
STAND ID: 2010 MGMT ID: NONE

	Aboveground Live		Belowground			Forest			Total	Total	Carbon
YEAR	Total	Merch	Live	Dead	Stand Dead	DDW	Floor	Shb/Hrb	Stand Carbon	Removed Carbon	Released from Fire
	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA
2006	133.1	81.1	25.9	3.0	12.0	4.9	14.6	0.7	194.3	0.0	0.0
2011	145.2	88.4	28.3	2.7	10.6	7.9	16.6	0.7	212.0	0.0	0.0
2016	81.0	50.5	16.1	16.9	14.2	33.7	16.9	0.7	179.6	47.4	0.0
2021	87.9	55.6	19.7	13.6	7.5	26.2	15.3	0.7	170.9	0.0	0.0
2026	95.0	59.6	19.7	11.0	3.8	21.8	15.7	0.7	167.7	0.0	0.0
2031	103.7	64.5	20.9	9.0	1.9	19.8	16.5	0.7	172.3	0.0	0.0

Figure 1—Screen shot of sample *Stand Carbon Report* (units are metric tons/hectare).

The ***Harvested Carbon Report*** tracks the fate of carbon in harvested merchantable volume, including salvaged logs (biomass is assumed to be 50% carbon). Carbon in merchantable biomass is allocated into various pools and followed over time; for example, a product in use may be discarded, transferring carbon from the product pool into the landfill pool. Both merchantability specifications and allocation to harvested carbon pools differ by FVS variant; the breakpoints between pulpwood and sawtimber are 9 inches diameter at breast height (dbh) for softwoods and 11 inches dbh for hardwoods by default (these can be adjusted by the user). Carbon in harvested merchantable biomass is allocated following the methods of Smith and others (2006) to the following pools:

- Products in use
- Products in landfills
- Carbon emitted from combustion with energy capture
- Carbon emitted from combustion or decay without energy capture

Carbon in the first two categories of the Harvested Carbon Report is summarized in the Merchantable Carbon Stored column of the report, while the Merchantable Carbon Removed column reflects all of the carbon in merchantable biomass that was removed from the stand. Over time, more of the carbon removed in a particular harvest will shift to one of the emissions categories. An example of the Harvested Carbon Report is given in figure 2. While carbon removed from the stand is reported in the year of harvest in the Stand Carbon Report, the carbon contained in earlier removals is not included, nor is the carbon accounted for once it leaves the stand. If harvesting is simulated, a user must request both reports and add the Merchantable Carbon Stored from the Harvested Carbon Report and Total Stand Carbon from the Stand Carbon Report columns to estimate total carbon sequestered. Both reports may be sent to an external database or spreadsheet using the database extension of FVS.

****** CARBON REPORT VERSION 1.0 ******
HARVESTED PRODUCTS REPORT
STAND ID: 2849 MGMT ID: NONE

					Merch Carbon	
YEAR	Prducts	Lndfill	Energy	Emissns	Stored	Removed
	T/HA	T/HA	T/HA	T/HA	T/HA	T/HA
2006	25.6	0.0	9.4	6.4	25.6	41.4
2011	18.2	3.9	11.3	8.1	22.1	41.4
2016	13.7	6.1	12.5	9.1	19.8	41.4
2021	10.9	7.4	13.2	9.9	18.4	41.4
2026	9.1	8.2	13.7	10.4	17.3	41.4
2031	7.9	8.7	14.1	10.8	16.6	41.4

Figure 2—Screen shot of sample *Harvested Carbon Report* (units are metric tons/hectare).

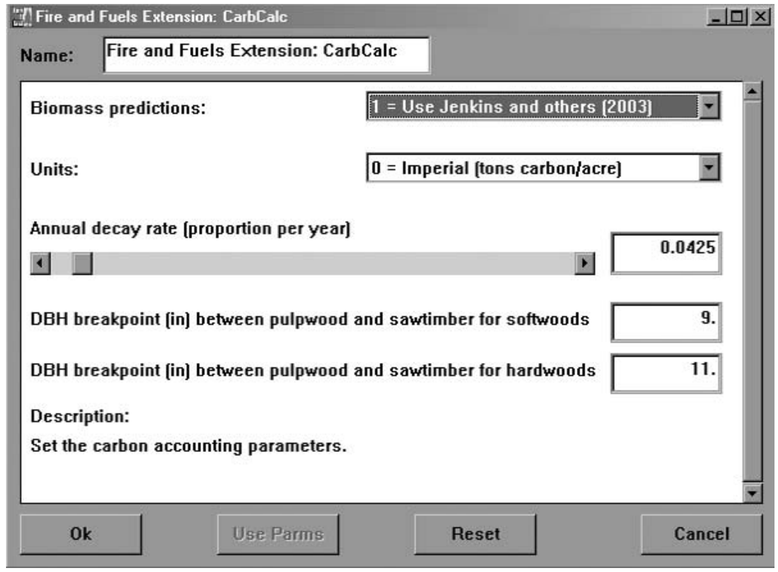


Figure 3—Screen shot of CarbCalc dialog box in Suppose.

Getting There from Here—Carbon Keywords

The keywords needed to generate carbon reports can be found in the FFE menu in Suppose. Three main keywords relate to the carbon accounting functionality. CarbRept requests the Stand Carbon Report and CarbCut requests the Harvested Carbon Report. As with other reports, the user needs to specify the year the report should start, the duration of the reporting period, and the reporting interval. The CarbCalc keyword is used to select the biomass prediction method, reporting units, annual decay rate of coarse roots, and dbh breakpoints for sawtimber and pulpwood. Figure 3 shows the CarbCalc window in Suppose. Both reports can be sent to an external database or spreadsheet using the CarbRpts keyword in the database extension menu in Suppose. Carbon reports can be generated during any simulation and the effects of management actions are reflected in the carbon pool estimates. For example, when the YardLoss keyword is used to adjust the amount of slash left after a thinning or harvest, the amount of carbon in the down dead wood pool is also adjusted. Similarly, a salvage harvest changes the estimates of carbon in the harvested and standing dead pools. The down dead wood and forest floor carbon stocks are derived from variant-specific FFE default values, but can be replaced with inventory data.

The Kane Experimental Forest Carbon Inventory

The Kane Experimental Forest (KEF) is an Allegheny hardwood (cherry-maple) forest of approximately 1,700 acres, located in northwestern Pennsylvania. During the summer of 2006, the forest was the site of a systematic inventory that replicated the original forest survey conducted in 1932. Plots 1/10th acre in size were located 10 chains (660 ft) apart on a grid covering the entire forest; all live and dead trees 1 inch dbh and over were measured. Down dead wood was tallied on transects through the center of each plot, and forest floor samples were collected on each plot. Additional data not related to the carbon inventory were also taken. In total, 153 plots were tallied. The inventory provided an opportunity to assess the feasibility of collecting the additional data required for a full carbon accounting as well as testing the carbon reporting capabilities of FVS. Current carbon stocks for KEF are given in table 1. All estimates are based on inventory data with the exception of the forest floor carbon stocks (these estimates will be updated when the data are available). The data were easily converted into FVS-ready files using the database extension. Without the carbon reporting capability of the FFE, the baseline carbon stock estimates shown in table 1 would have been produced by using allometric equations to compute the aboveground biomass of each sample tree in a plot, repeating the process for the belowground biomass, producing per acre estimates for each plot,

Table 1—Carbon stocks on the Kane Experimental Forest in 2006.

Pool	Tons C/acre	Tons C forest-wide
Live tree [a]	60.2	42,147
Dead tree [b]	5.8	4,059
Down dead wood	2.2	1,561
Forest floor	6.2	4,371
Total	74.5	52,137

[a] All live biomass including coarse roots.
[b] All dead biomass including coarse roots and standing dead trees.

then aggregating to compartment estimates to produce a forest-wide average. Separate computations would be required for the down dead wood and forest floor pools. While feasible for a small number of plots, producing the current carbon estimates for KEF would have taken several weeks using this approach. For a user with FVS-ready data files, generating carbon estimates that are consistent with current carbon reporting guidance can now be done quickly and without specialized knowledge.

Increasingly, forest managers are being asked to consider the potential carbon consequences of forest management actions. The possibility of earning income from the sale of carbon credits further highlights the need for information on projections of forest carbon stocks in the future. While there are multiple carbon registries at this time, many require that forest carbon storage be "additional"—that is, above and beyond business as usual, to receive credit as an emission offset. Determining this baseline level of carbon storage can be difficult, but this is another area where the carbon reporting functions can help managers. As an illustration, the data from KEF were used to run projections of carbon stocks over the next 25 years, with and without simulated management. These projections are a test exercise and are not fine-tuned to reflect actual management prescriptions, although they are a general approximation of Allegheny hardwood management. The test version of the revised northeast variant was used "out of the box"; for the growth only scenario no regeneration was added other than that from stump sprouts included in the base model (a main reason for the relatively short projection period). For the management scenario, stands were treated if they were between 85 and 120 years old and fully stocked. Approximately one-third of the basal area was removed (assuming a thinning from below using a ThinBBA keyword in FVS) and regeneration was added after thinning; seedling numbers were based on data from regeneration surveys conducted during the inventory. Stands that were untreated were grown as in the base projection; two compartments that are described as probable old growth were reserved from harvest. Table 2 shows the carbon stocks from these projections; the estimates from the management projection include the carbon in wood products and landfills. By default in the eastern FVS variants, branches and tops of cut stems are left in the stand and transferred to the down dead wood pool. Modifications to this setting using the YardLoss keyword will alter the distribution of carbon among pools accordingly. This is a short-term simulation; the same management practice may have different carbon outcomes over different time frames, depending on stand growth patterns and product types. If the model is carefully calibrated for local conditions, then long-term simulations may be run to investigate these tradeoffs.

Table 2—Projected carbon stocks on the Kane Experimental Forest. Simulation was for testing purposes; model was not calibrated to site conditions.

Year	Growth only (tons C/acre)	With management (tons C/acre)
2006	75	73
2011	81	77
2016	87	81
2021	94	85
2026	99	88
2031	104	91

Summary

By building on the existing capabilities of the FFE, we were able to integrate easy-to-use, comprehensive carbon accounting capabilities into FVS. Managers familiar with the model are now able to quantify carbon stocks and assess the carbon implications of different management practices alongside more management objectives by using just a few additional keywords. The estimates produced by the model are consistent with U.S. carbon accounting rules and guidelines and cover all pools except for soil carbon. Users can also track carbon in harvested wood products or carbon released in fuels consumed by fire. A test of the new carbon reports was conducted utilizing recent inventory data from the Kane Experimental Forest. Current carbon stocks on the Forest are estimated to be 74.5 tons/acre and are projected to increase to 104 tons/acre by 2031.

Acknowledgments

We thank Rich Birdsey, Nick Crookston, Gary Dixon, Linda Heath, and Jim Smith for valuable input during the development process. Special thanks to Susan Stout, Cori Weldon, Harry Steele and the KEF Inventory Crew for providing the inventory data and supporting information. Susan Stout and Linda Heath provided helpful suggestions on the manuscript. Thanks also to Don Robinson and Sarah Beukema for programming the reports.

References

Jenkins, J.C.; Chojnacky, D.C.; Heath, L.S.; Birdsey, R.A. 2003. National-scale biomass estimators for United States tree species. Forest Science. 49:12–35.

Penman, J.; Gytarsky, M.; Hiraishi, T.; Krug, T.; Kruger, D.; Pipatti, R.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K.; Wagner, F., eds. 2003. Good practice guidance for land use, land-use change and forestry. Intergovernmental panel on climate change, technical support unit. Hayama, Kanagawa, Japan: Institute for Global Environmental Strategies. [Online]. Available: http://www.ipcc-nggip.iges.or.jp

Proctor, P.; Heath, L.S.; Van Deusen, P.C.; Gove, J. H.; Smith, J. E. 2005. COLE: A web-based tool for interfacing with forest inventory data. In: McRoberts, R. E.; [et al.], eds. Proceedings of the fourth annual forest inventory and analysis symposium; 2002 November 19–21; New Orleans, LA. Gen Tech Rep NC-252. St Paul, MN; U.S. Department of Agriculture, Forest Service, North Central Research Station: 167–172.

Reinhardt, E.; Crookston, N. L., tech. eds. 2003. The fire and fuels extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Reinhardt, E.; Crookston, N. L.; Rebain, S.A., tech. eds. 2007. Addendum to the fire and fuels extension to the Forest Vegetation Simulator. [Online]. Available: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_ffeaddendum.php

Smith, J.E.; Heath, L.S. 2002. A model of forest floor carbon mass for United States forest types. Res. Pap. NE-722. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 37p.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.

Smith, J.E.; Heath, L.S.; Woodbury, P.B. 2004. Forest carbon sequestration and products storage & Appendix C. In: U.S. Agriculture and forestry greenhouse gas inventory: 1990–2001. Tech. Bull. No. 1907. Washington, DC: U.S. Department of Agriculture, Global Change Program Office: 80-93, C1-C7. Chapter 4.

U.S. Environmental Protection Agency. 2006. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2004. EPA 430-R-06-002. Washington, DC: United States Environmental Protection Agency, Office of Atmospheric Programs.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Effects of Using Visualization and Animation in Presentations to Communities About Forest Succession and Fire Behavior Potential

Jane Kapler Smith[1]
Donald E. Zimmerman[2]
Carol Akerelrea[3]
Garrett O'Keefe[2]

Abstract—Natural resource managers use a variety of computer-mediated presentation methods to communicate management practices to the public. We explored the effects of using the Stand Visualization System to visualize and animate predictions from the Forest Vegetation Simulator-Fire and Fuels Extension in presentations explaining forest succession (forest growth and change over time), fire behavior, and management options. We used an experimental design with purposive samples of three populations: rural mountain residents, town residents, and student groups. We compared participants' knowledge gain and attitudes after a visualized, animated presentation to knowledge gain and attitudes after a non-visualized, non-animated presentation. Participants gained substantial information (statistically significant) from both visualized and nonvisualized presentations. Mountain residents gained significantly more information from the visualized, animated presentation than from the non-visualized, non-animated presentation. While not statistically significant, mountain residents tended to score slightly higher than town residents and students on all knowledge topics. The groups viewing the visualized, animated presentations rated the visuals significantly more attractive and the presentations easier to follow than did the groups viewing the non-visualized, non-animated presentations. We found no significant differences within or between groups in perception of the USDA Forest Service, and no significant differences in agreement that models, such as FVS-FFE, added to the credibility of the Forest Service.

This research was published in a refereed journal in 2006. The citation is Zimmerman, Donald E.; Akerelrea, Carol; Smith, Jane Kapler; O'Keefe, Garrett. 2006. *Communicating Forest Management Science and Practices Through Visualized and Animated Media Approaches to Community Presentations: An Exploration and Assessment*. Science Communication. 27(4): 514–539. It is available online at: http://www.fs.fed.us/fmi/products/zimmerman_et_al_2006.pdf.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. The content of this paper reflects the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

[1] Ecologist, USDA Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory, Missoula, MT; e-mail: jsmith09@fs.fed.us.

[2] Professors, Department of Journalism & Technical Communication, Colorado State University, Fort Collins, CO.

[3] Program Analyst, USDI Bureau of Land Management, Alaska State Office, Anchorage, AK.

Forest Disturbance: Fire

Incorporating Landscape Fuel Treatment Modeling into the Forest Vegetation Simulator

Robert C. Seli[1]
Alan A. Ager[2]
Nicholas L. Crookston[3]
Mark A. Finney[1]
Berni Bahro[4]
James K. Agee[5]
Charles W. McHugh[1]

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 several command line programs linked together: (1) FVS with the Parallel Processor (PPE) and Fire and Fuels (FFE) extensions that pauses the simulation during each cycle and transfers data to and from other system components; (2) a component to create the spatial landscape file with fuel model logic to select fuel models not available in FFE; and (3) a command line version of FlamMap utilizing the Minimum Travel Time fire growth method and Treatment Optimization Model to identify treatments, simulate wildfires, and evaluate the performance of the fuel treatments. 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 utilizing the Inland Empire, Western Sierra, and Blue Mountain FVS variants. Several limitations of FVS were identified during the project. Understory vegetation important for fuel modeling is not simulated in FVS, and the cap of 10,000 stands in PPE limited the size of the analysis areas. This simulation system required a large time commitment for data development, multiprocessor computer hardware to perform the simulations, and a range of technical expertise that is more specialized than land management agencies are currently staffed to handle. The system was successful in meeting the project's requirements. The research nature of this simulation system suggests it is probably not practical to run in most places for operational planning uses.

Introduction

Local or stand level changes in fire behavior resulting from fuel treatments are well documented (Agee and Skinner 2005; Cram and others 2006; Graham 2003; Graham and others 2004; Pollet and Omi 2002; Raymond and Peterson 2005;). Designing fuel treatments for landscapes (essentially a collection of stands composed of a variety of fuels and topography) creates additional challenges (Finney and others 2007), especially if there are constraints to the proportion of the landscape that can be treated. Finney (2007) has reported an algorithm to apply a mathematically derived treatment pattern to realistic complex landscapes. Additionally the effects and scheduling of treatments through time further complicates the issues. Testing these concepts with real fires on real landscapes is not feasible. So we developed computer simulations for modeling fires and fuel treatments at the landscape level through a period of time that would allow forest dynamics to modify treatments and dynamically schedule retreating stands as necessary.

Modeling forest fuel changes over time within a stand requires first modeling the dynamics of vegetation growth and death as well as the derivation of dead and live fuel components from the vegetation. The Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003) to the Forest Vegetation Simulator (FVS) (Wykoff and others 1982) allows the effects on surface and aerial fuels for stand level treatments to be modeled over time. This extension explicitly represents:

- Dead fuel production from live vegetation components (litterfall, branchwood)
- Deterioration of dead fuels
- Dynamics of live fuel components (regeneration, canopy fuels).

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forester, Research Forester, and Forester, respectively, USDA Forest Service, Missoula Fire Sciences Laboratory, Missoula, MT; e-mail: rseli@fs.fed.us.

[2] Operations Research Analyst, USDA Forest Service, Western Wildland Environmental, Threat Assessment Center, Prineville, OR; e-mail: aager@fs.fed.us.

[3] Operations Research Analyst, USDA Forest Service, Forestry Sciences Laboratory, Moscow, ID.

[4] Assistant Regional Fuels Specialist, USDA Forest Service, Pacific Southwest Region—FAMSAC, McClellan, CA.

[5] Professor, University of Washington, College of Forest Resources, Seattle, WA.

Here we report on the methods, tools, limitations, and assumptions of using FFE to simulate stand level fuel changes and fuel treatments and the interactions with landscape level fire behavior over five decades. We used FVS with FFE and Parallel Processor Extension (PPE) (Crookston and Stage 1991) to simulate forest stand dynamics, and linked with external methods to select and schedule treatments and simulate wildfires. The results illustrate that the rate of fuel treatment (percentage of land area treated per decade) competes against the rates of fuel recovery to determine how fuel treatments contribute to multi-decade cumulative impacts on fire behavior. Using fuel treatment prescriptions that involve thinning and prescribed burning, fuel treatment arrangements that are optimal in disrupting the growth of large fires require at least 1 to 2 percent of the landscape to be treated each year. Randomly arranged units with the same treatment prescriptions require about twice that rate to produce the same fire growth reduction. The results also show that the topological fuel treatment optimization tends to balance maintenance of previously treated units with treatment of new units. Complete results of the study are presented in Finney and others (2007).

Methods and Assumptions

The overall system flow diagram is shown in figure 1. This system consisted of FVS with a modified version of PPE which controlled the system by calling various other components as command line programs. Some of these command line programs are also available as features in version 3 of FlamMap (Finney 2006) while others were specifically developed for this simulation system. In general, data were transferred between components with files written to the computer's hard drive. The components shown in figure 1 are explained in detail below.

Data Preparation and Study Sites

Simulations were done at three study sites using the FVS variants described in table 1. While the study was designed to investigate landscape level fire behavior, the methods dictated a need for stand level detail. Relatively small, homogeneous polygons were used as stands to eliminate the need to divide polygons with treatments. Nearest neighbor techniques, such as Crookston and others (2002) which was used in the Blue Mountains, were used to assign forest inventory FVS tree lists to individual forested stands. Non-

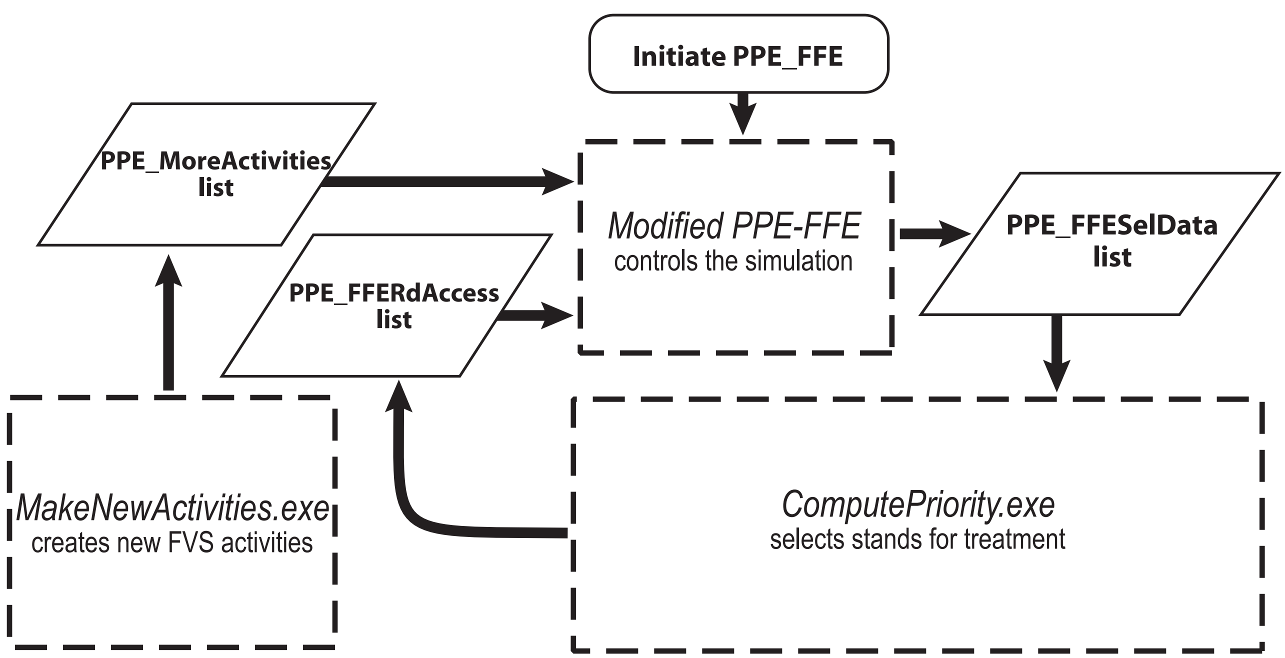


Figure 1—General flow of simulation system. Dashed boxes are the major components, parallelograms are data files used to transfer data between components.

Table 1—Study sites.

Site	Area	Number of FVS polygons	FVS variant
Blue Mountains, WA	54,600 ha	5,752	Blue Mountain. (BM)
Sanders County, MT	51,700 ha	9,699	Inland Empire (IE)
Stanislaus NF, CA	40,500 ha	7,754	Western Sierra (WS)

burnable (rock, water), grass, and shrub polygons were not assigned tree lists and were assumed to be static surface fuel models. A rasterized polygon/stand theme (StandID grid) was developed as an index for stand parameters when developing the landscape (LCP) files (Stratton 2006) from FVS outputs.

Modifying the Parallel Processor Extension

PPE (Crookston and Stage 1991) extends FVS to allow a list of stands in a landscape to be processed one cycle at a time. PPE can model dynamic interactions between adjacent stands, and place landscape-level constraints and goals on management activities. However, PPE has very limited ability to relate stands topologically, and FFE functionality was not available within PPE.

For this study PPE was modified (PPE-FFE) as follows (fig. 2):

1. FFE was added;
2. PPE changed to pause after implementing trial treatments for every stand and
    a. Output a table of stand and fuel conditions with and without treatment (PPE_FFESelData in figs. 1, 2, and 3),
    b. Call a generic program (user developed) named "ComputePriority.exe" which selects which stands to treat,
    c. Wait for ComputePriority.exe to complete and produce a list of stands selected for treatment(PPE_FFERdAccess in figs. 1, 2, and 3);
3. When ComputePriority.exe terminates, PPE implements the stand-level treatments;
4. PPE changed to call an optional generic program (user developed) named "MakeNewActivities.exe" which accepts any new FVS activities before finishing the cycle (for example, wildfires).

For ComputePriority.exe to evaluate trial treatments, prescriptions must be identified for every stand where the potential for treatment exists. In other words, a treatment must be specified for every stand that could possibly receive a treatment. We used a series of If/Then statements to develop a FVS keyword file (an example is found in appendix A) to deal with a wide variety of possible stand conditions that would affect the choice of treatment prescription. While treatments were designed to modify surface and aerial fuels, they had to be silviculturally feasible.

FFE functions were modified as follows:

The CANCALC keyword with the minimum tree height parameter set to 0.6 m (2 ft) was used for all variants, defaults were used for the other CANCALC fields;

The default fuel pool initialization was used for the Montana study site, while initialization values were developed for the Stanislaus N.F. and Blue Mountains study sites using the FUELINIT keyword.

No FVS growth/mortality multipliers or insect and disease extensions were invoked for these simulations. The modifications made for this study have since been incorporated into the production versions of these programs.

ComputePriority.exe

ComputePriority.exe is a command line executable that must be developed by the user. The program must use this name so that PPE-FFE can interact with it. The only requirements for ComputePriority.exe are to pass a list of stands to treat to PPE-FFE and terminate after each trial cycle so flow control returns to PPE-FFE and finishes the current FVS cycle (fig. 3). In our system, ComputePriority.exe first reads a text file that contains arguments for other programs required to prioritize treatments and manipulate files as described below.

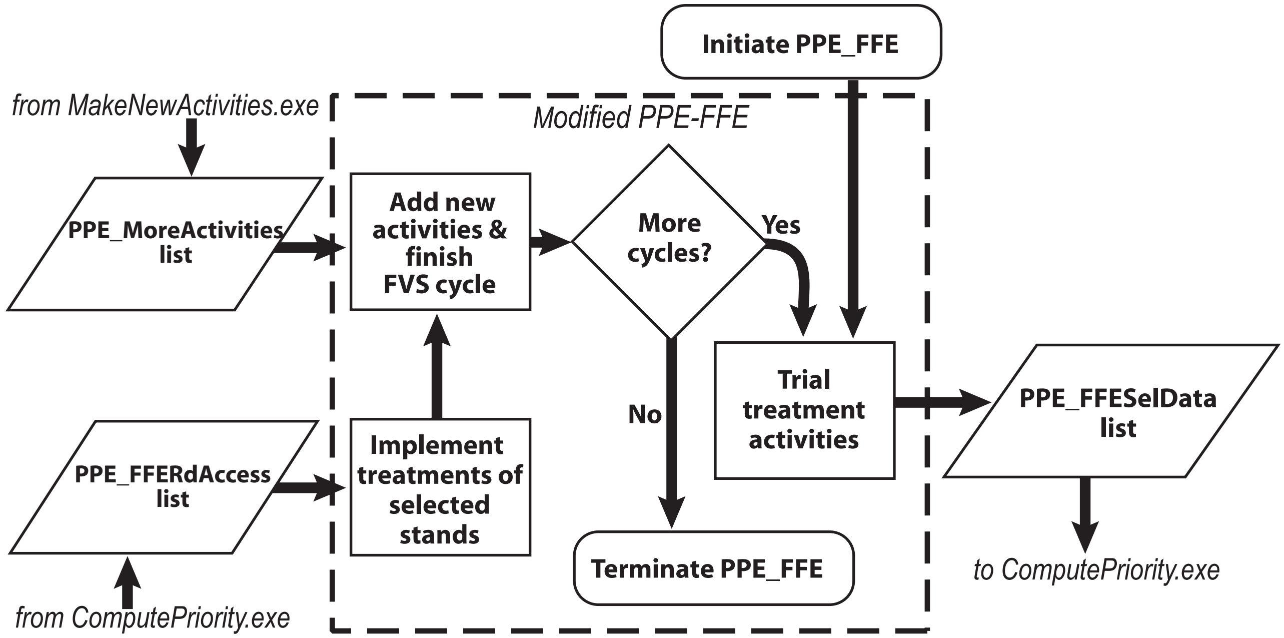


Figure 2—Details of modified PPE-FFE component. Solid boxes are processes within the major component, diamonds are branch points.

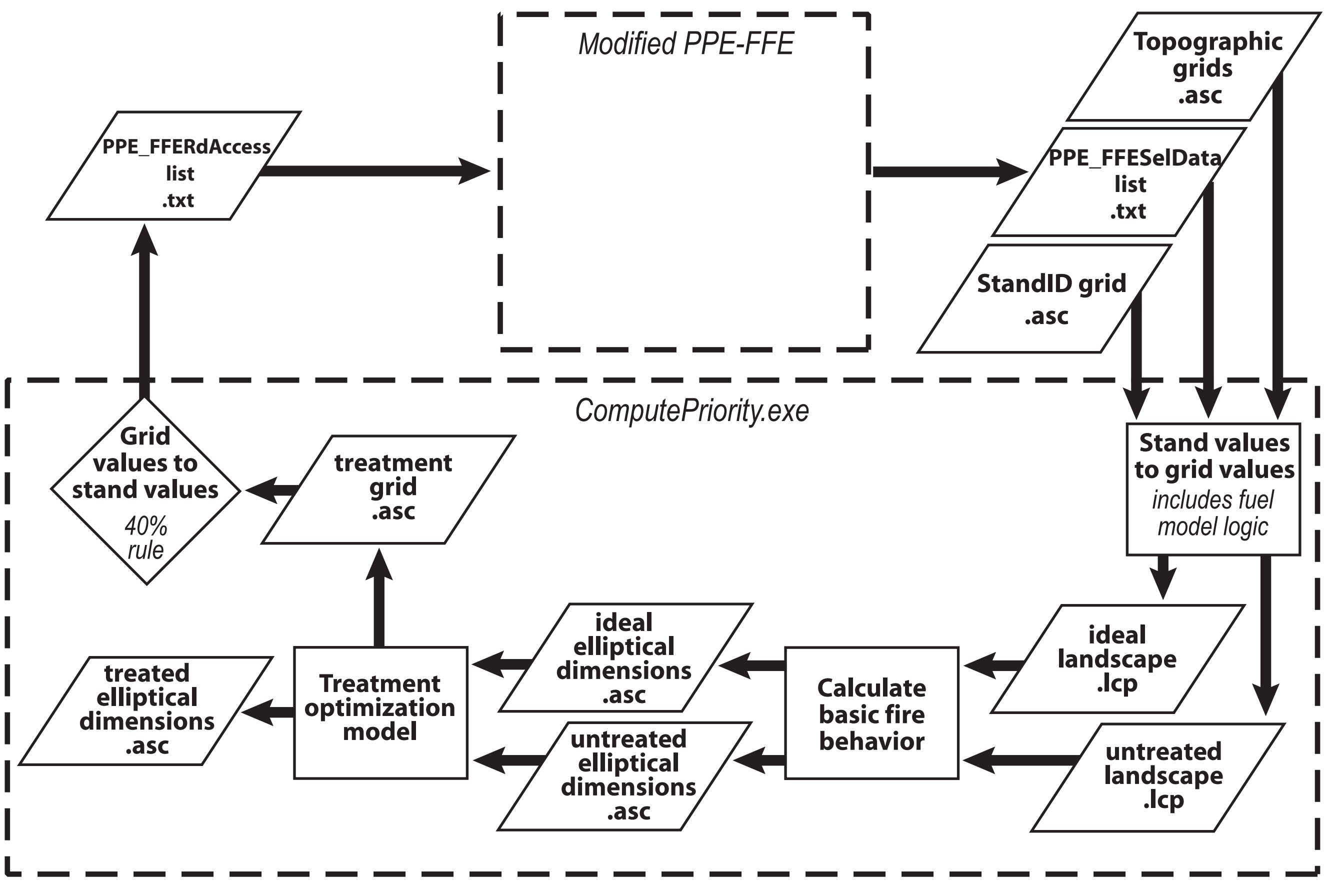


Figure 3—Details of the ComputePriority.exe component and its relation to PPE-FFE.

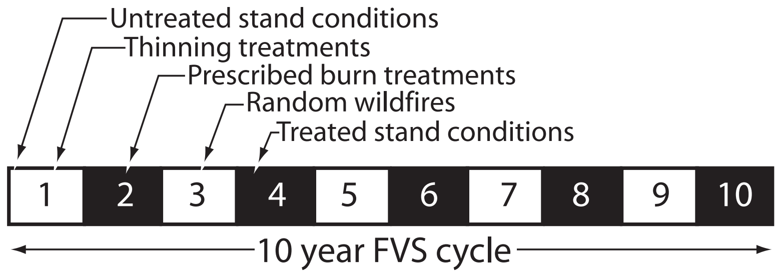


Figure 4—Timeline of PPE-FFE activities within one FVS cycle.

Convert Stands to Spatial Grids—FVS stand level output is converted to a raster LCP file using the program fvs2lcp.exe (fig. 3). Topographic features remain static through the simulation and user supplied slope, aspect, and elevation grids are read into fvs2lcp.exe to be included in the final LCP files. For each FVS cycle two LCP files are created, an untreated LCP file and an ideal LCP file, in which every stand was treated according to the FVS prescription. Both LCP files reflect treatments and forest dynamics from previous cycles. The ideal LCP file reflected the results of the FVS trial treatments at year 4 of the FVS 10 year cycle. This allowed for all activities to be completed and enough simulation time to pass so that short-term consequences of activities (for example, thinning causing temporary increases in fine fuel loading) would not unduly influence results. The untreated LCP used year 1 stand conditions with changes only due to FVS growth and mortality functions from the previous cycle (fig. 4).

Stand values from PPE-FFE for both treated and untreated conditions are passed to fvs2lcp.exe via a text file, PPE-FFESelData.txt (table 2). This file contains a table of stand-polygon values for canopy cover, stand height, canopy bulk density, and canopy base height that fvs2lcp.exe assigns to raster cells by cross referencing the polygon index identification with a raster representation of the polygon locations (StandID grid) containing the index values. A single fuel model was selected for the stand as described below and assigned to the landscape.

Our program deviated from the FFE surface fuel model logic because the fuel models assigned to stands by FFE were found to be inadequate for the treatment optimization. The original 13 Fire Behavior Prediction System fuel models (Anderson 1982) used in FFE do not adequately describe natural variability in surface fuels across large landscapes, or realistically describe a treatment's effect on live and dead surface fuels. (Scott and Burgan 2005)

Table 2—Variables from PPE_FFESelData.txt.

Stand value	FVS event monitor name	Purpose
Stand ID	n/a	Link to StandID grid
Year	n/a	Used in fuel model logic
SelCode	SELECTED	Trial treatment or untreated values
CBH	CRBASEHT	Directly applied to LCP
CBD	CRBULKDN	Directly applied to LCP
Canopy cover	ACANCOV	Directly applied to LCP
Stand height	ATOPHT	Directly applied to LCP
1hrLoad	FUELLOAD(1,1)+FUELLOAD(7,7)	Used in fuel model logic
10hrLoad	FUELLOAD(2,2)	Used in fuel model logic
100hrLoad	FUELLOAD(3,3)	Used in fuel model logic
1000hrLoad	FUELLOAD(4,6)	Used in fuel model logic
Habitat type	HABTYP	Used in fuel model logic (IE variant only)
Forest type	FORTYP	Used in fuel model logic
RTPA	RTPA	Used in fuel model logic
Fire flag	FIRE	Used in fuel model logic
Last treatment	FIREYEAR	Used in fuel model logic

The Scott and Burgan (2005) fuel models realistically place more weight on live fuels, both herbaceous (grasses, herbs) and woody (shrubs). Since FVS does not provide growth models for non-tree vegetation, surrogates for live woody fuels were used. Basic live fuel parameters, including live woody loading and fuel bed depth, were developed using habitat type as the surrogate for the IE variant, elevation and aspect for the WS variant, and forest type for the BM variant. These live fuel parameters were reduced in stands where canopy covers exceeded 50 percent and following fuel treatment. After treatment, the live fuel parameters followed a straight line recovery to pretreatment values 20 years after treatment. An example of the fuel model logic for the IE variant is shown in appendix B.

Fire Behavior—Fire behavior was calculated with a command line version of FlamMap for each LCP file cell under the target fuel moisture and wind conditions. Fire behavior was calculated for both LCP files in order to contrast fire behavior produced in each stand with and without treatment. Fire behavior output is stored as ASCII grid files for further use in treatment selection and wildfire simulation (Finney 2002). The fire behavior is represented as elliptical dimensions of fires in each cell that capture the orientation and shapes of fires needed for computing fire growth.

Treatment Optimization Model—The treatment optimization model (TOM) identifies optimal treatment locations as described in Finney (2007) given the constraints of maximum treatment linear dimension and the total proportion of the landscape desired for treating. Extreme target weather conditions were used so that potential crown fire activity was considered when identifying treatment locations. The treatment optimization outputs an ASCII grid file of the treated cells. Because of the similar fire behavior of all cells in a stand and the optimization method, the treated cells tend to clump into logical treatment units (fig. 5). The treatments were not a fixed size, only the user supplied maximum linear dimension constrained their size.

Convert Treatment Grid to Stands—Further processing by ComputePriority.exe converts the treatment grid into a list of treated stands for PPE-FFE to implement. The treatment ASCII grid is compared to the StandID grid and the stand is considered treated if more than a specified percentage of the cells in a stand are indicated as treated in the treatment output grid. After trial and error, the threshold value of 40 percent was found to produce a polygon map that closely approximated the gridded representation of the treatment units (for example, if 40 percent or more of the cells in a polygon were selected for treatment, the entire polygon was identified for treatment). These results are passed to PPE-FFE in the file PPE_FFERdAccess.txt, a list of all stands with a flag specifying which stands were selected for treatment (figs. 1, 2, and 3).

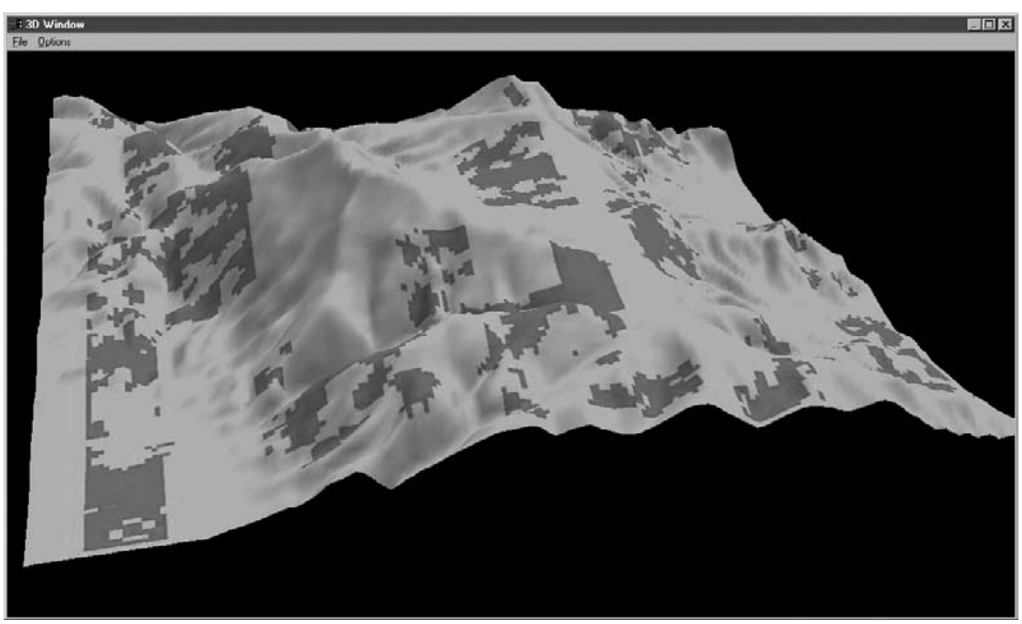


Figure 5—3-D display of treated cells identified by the treatment optimization model.

MakeNewActivities.exe

Once the stands are selected for treatment, PPE-FFE simulates the scheduled activities, models the consequential stand growth, fire and fuel dynamics, and fire effects. However, before it starts this loop over stands, it calls another external generic program called MakeNewActivities.exe (fig. 6). Like ComputePriority.exe, MakeNewActivities.exe is a user-defined executable with a static name for PPE-FFE to interact with. From the FFE-FVS point of view, using an external program to simulate wildfire behavior is the functional equivalent of making new activities and entering them into the activity schedules for the appropriate stands.

Simulating Random Wildfires—For our simulation system we used MakeNewActivities.exe to model random wildfires on the treated landscape. MakeNewActivities.exe then creates SIMFIRE and FLAMADJ keywords for burned stands so PPE-FFE could model stand level fire effects. The treated landscape is created by overlaying the ideal elliptical dimension values on the untreated elliptical dimension grids where stands were selected for treatment. Since both the ideal and untreated elliptical dimension values were generated once with FlamMap, these simulated wildfires burn under the same extreme wind and fuel moisture conditions that the treatments were designed to be effective with.

Random wildfires are simulated using a command line version of the Minimum Travel Time fire growth model found in version 3 of FlamMap (Finney 2006). The number of wildfire simulations is calculated from a user-supplied annual fire probability from the script.txt file. Random ignition locations are placed on the treated landscape for each year in the FVS cycle. A fire duration value, also from script.txt, is used with the treated landscape elliptical dimension grids to establish a fire perimeter for each ignition. The 40 percent rule described previously was used to select which stand polygons were burned in the simulated wildfires (for example, a stand was indicated as "burned" if 40 percent or more of the cells were within the wildfire area). All burned stands are identified in a

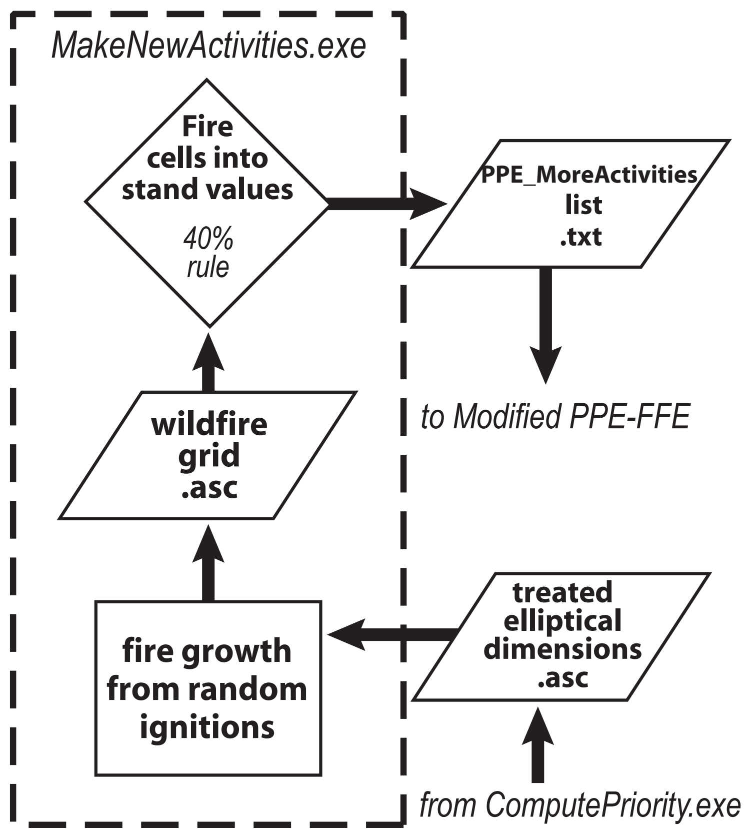


Figure 6—Details of the MakeNewActivities.exe component and its relation to PPE-FFE.

table written to an output file PPE_MoreActivities.txt; two FVS keywords are used to indicate the fire behavior that occurred. The SIMFIRE keyword was for year 3 of the cycle, after treatments have been completed in PPE-FFE (fig. 4). Even though the post treatment conditions contained in the file PPE_FFESelData.txt are for year 4 of the cycle, these stand conditions do not include the random wildfire effects since the treated LCP file is created before the random wildfires are scheduled. Parameters for FLAMADJ keyword (flame length, percent crowning, and scorch height) are also calculated for each stand burned by wildfires.

Other Processes

Several other applications were used after the simulation to evaluate response variables for the simulated treatments. One of those applications calculated what we called the endtime value. The endtime value is the average fire arrival time for the leeward row of cells in the landscape. In effect this measured the time it took for a simulated fire to burn the entire landscape from a line ignition along the windward landscape border. Dividing the treated landscape endtime value by the untreated landscape endtime value provide a relative average spread rate, which was used to compare results.

Results

Our simulation system was successful in meeting the goals of the project, we utilized an spatially explicit method (TOM) to select stands for treatment over multiple FVS cycles. We used a 16-processor shared memory computer to meet the needs of the multi-threaded treatment optimization and wildfire models. Simulations spanning five FVS cycles, 10 years each, required between six hours and several days depending on maximum treatment size and number of cells in the landscapes. Except during development, we excluded the random wildfire simulations from MakeNewActivities.exe because it added too much variability to the results of the treatment effects, which was the primary objective of the study. Effectiveness of the treatments varied by study site and several examples of the Montana study site results are given below. Full results of the project are documented in Finney and others (2007).

Figure 7 shows the effects of treatment size compared to randomly treated stands on the relative average spread rate. The amount of treatment between cycles and treatment sizes was constant. The topological placement of treatments by the treatment optimization algorithm out performed random treatments, especially in the earlier cycles of the simulations. For a given total amount of treated area, the size of the treatments had minimal influence on the relative average spread rate.

As shown in figure 8, the optimal rate of treatment was approximately 20 percent per decade; however, even lower treatment rates were also effective at reducing the relative average spread rate. Treatment rates of 30 percent or more showed small improvements in the early cycles, but matched the 20 percent rate in cycles 3 through 5. Effect of treatment for all the treatment rates was greatest the first decade and leveled out after the second decade.

Discussion

The landscape files describing the fuel conditions are important to acquiring meaningful results. Since the treatment optimization process was used to identify a relatively small proportion of the landscape for treatment, the accuracy of the current fuel conditions and the validity of the treatment effects on fire behavior are paramount to simulating a realistic treatment scenario. This points out the need for quality up-to-date information relevant to the issues for making science based decisions. We found the significance of live fuels in the Scott and Burgan (2005) fuel models and lack of understory vegetation modeling in FVS problematic. We developed simplistic surrogates for shrub cover (appendix B), but did not attempt a systemic evaluation of these surrogates.

In figure 4 it is apparent that FVS activities scheduled in PPE-FFE always occur in a specific year of the cycle. For example, thinnings are always scheduled for year 1 and wildfires for year 3. This is not very realistic as one would expect some random wildfires to occur prior to treatments and logistical considerations usually dictate management

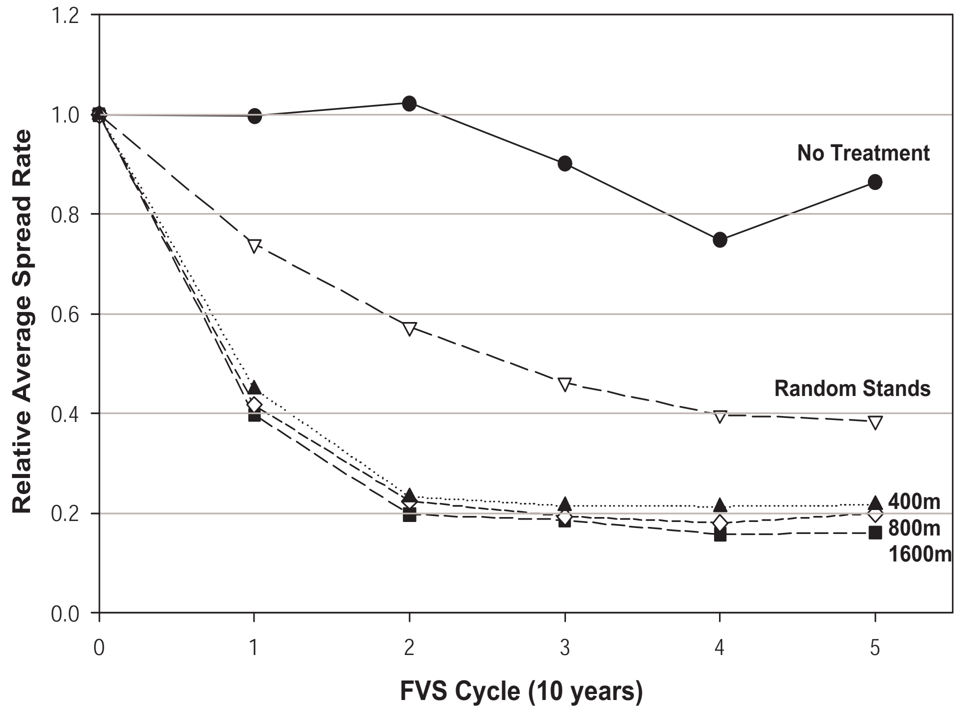


Figure 7—Relative average spread rate across the Prospect Ck. landscape, Sanders Co., MT for five 10-year FVS cycles. All scenarios treated 20 percent of the landscape per cycle. Treatment patterns developed with the treatment optimization methods preformed better than treating random stands, especially in the earlier cycles. Treatment unit size had little effect on the average fire spread rate.

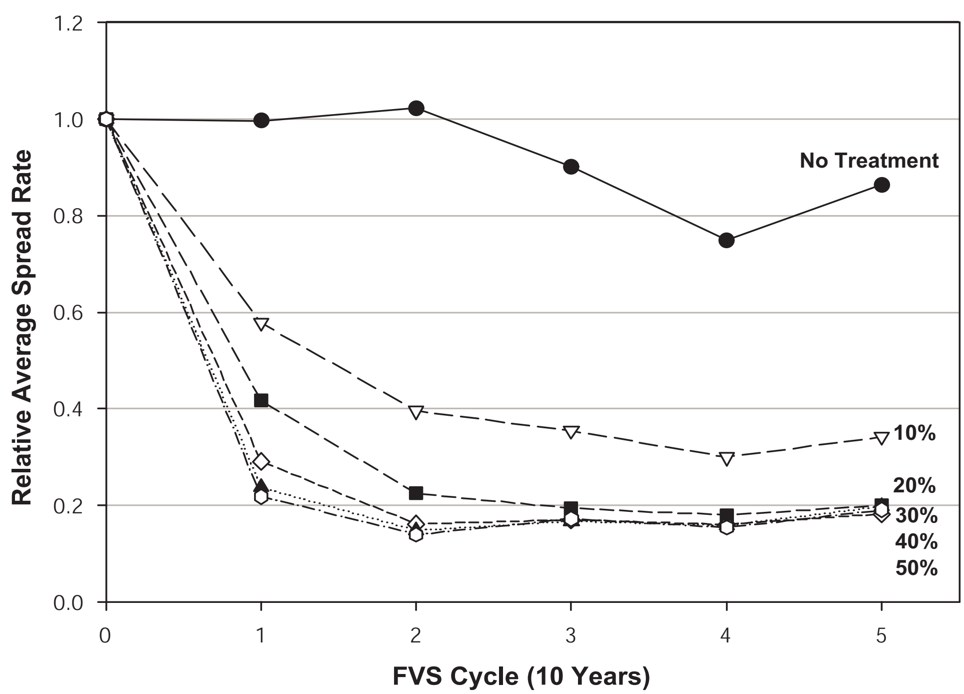


Figure 8—Relative average spread rate across the Prospect Ck. landscape, Sanders Co., MT for five 10-year FVS cycles. All scenarios used a maximum treatment dimension of 800 m. Treatments implemented at a rate of 20 percent per cycle produced overall reductions in average fire spread rate similar to higher treatment rates.

activities be completed over several years. This issue could be minimized by shortening the FVS cycles, exploring more realistic methods of scheduling FVS activities, or both.

Treatment optimization techniques required significant computational capacity when used for these large (50,000 ha) areas. However advances in computer capacity during the life of the project suggested that smaller (25,000 ha) landscapes could be simulated on common multiprocessor desktop computers.

We achieved our results while limiting simulation landscapes to 10,000 stands, the current limit of PPE. While this limit could be increased, FVS is not multi-threaded to take advantage of multiple processors and PPE-FFE portions of the simulation would occupy a larger proportion of the simulation time. On our 16-processor computer, 15 of the processors were idle while PPE-FFE was executing, which was approximately 30 percent of the total simulation time. Recent advances in multi-processor computers would easily allow fast mid-scale simulations or large simulations with 100,000 or more stands if PPE-FFE were multi-threaded. Multi-threading would also allow more detailed simulations with a large number of small stands since the treatment optimization technique selects treatments at the individual raster cell level.

In theory, larger landscapes could be simulated with our existing system by utilizing larger stands, larger LCP grid cells, and larger maximum treatment dimensions since all of these control computational requirements. However, some modifications to the system (the 40 percent rule, for example), larger treatment units, and coarser results should be expected.

Once a landscape was calibrated, prescriptions developed, and otherwise debugged, subsequent runs were easily created by editing the script.txt file for user defined inputs such as maximum treatment size or treatment rate.

The endtime value, and thus relative spread rate, proved an effective measure of landscape fire behavior. As shown in Finney and others (2007), burn probability and fire size distribution would also be equally effective measures. Burn probability, fire sizes, and fire spread rate reflect very similar trends because slower spreading fires are smaller after a fixed period of time, which translates to a smaller probability of burning any part of the landscape within a given time period.

While successful in a research setting, the level of expertise and data availability may limit this type of simulation in operational or project level planning. This project required large efforts in acquiring, preparing, and organizing the data for these simulations. Imputing FVS tree lists into thousands of different stands was adequate for our proof of concept study, but is likely not suitable for planning projects where the accuracy of the individual stand vegetation is important. The suite of expertise required to develop and operate the system is also beyond the capability of most management teams. A variety of ecologists, computer programmers, fire behavior specialists, and geo-spatial analysts were needed to develop and operate the system and evaluate the results. In addition, fire behavior and FVS skills were required to develop and debug the complex interactions between system components and customize prescriptions and fuel logic for individual study sites.

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 Howard Roose with the Bureau of Land Management who also provided funding. We also thank Amber Mahoney, Jim Beekman, and Don Justice on the Umatilla National Forest for their assistance with data collection on the Blue Mountains study site and Sharie McKibben for tackling the nearest neighbor imputations for the western Montana study site.

References

Agee, J.K.; Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management. 211:83–96.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

Cooper, S.V.; Neiman, K.E.; Roberts, D.W. 1991. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 143 p.

Cram, D.; Baker, T.; Boren, J. 2006. Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. Res. Pap. RMRS-RP-55. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 28 p.

Crookston, N.L.; Moeur, M.; Renner, D. 2002. Users guide to the Most Similar Neighbor Imputation Program Version 2. Gen. Tech. Rep. RMRS-GTR-96. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 35 p.

Crookston, N.L.; Stage, A.R. 1991. User's guide to the parallel processing extension of the Prognosis Model. Gen. Tech. Report-INT-281. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 93 p.

Finney, M.A. 2002. Fire growth using minimum travel time methods. Canadian Journal of Forest Research. 32(8):1420–1424.

Finney, M.A. 2006. An overview of FlamMap Fire Modeling Capabilities. In: Andrews, Patricia L.; Butler, Bret W., comps. 2006. Fuels Management—How to measure success: conference proceedings;. 2006 28–30 March; Portland, OR. Proc. RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Finney, M.A. 2007. A computational method for optimizing fuel treatment locations. International Journal of Wildland Fire. 16:702–711.

Finney, M.A.; Seli, R.C.; McHugh, C.W.; Ager, A.A.; Bahro, B.; Agee, J.K. 2007. Simulation of long-term landscape-level fuel treatment effects on large wildfires. International Journal of Wildland Fire.

Graham, R.T. 2003. Hayman fire case study. Gen. Tech. Rep. RMRS-GTR-114. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 396 p.

Graham, R.T.; McCaffrey, S.; Jain, T.B. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.

Pfister, R.D.; Kovalchik, B.L.; Arno, S.F.; Presby, R.C. 1977. Forest habitat types of Montana. Gen. Tech. Rep. INT-34. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 174 p.

Pollet, J.; Omi, P.N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire. 11:1–10.

Raymond, C.L.; Peterson, D.L. 2005. Fuel treatments alter the effects of wildfire in a mixed evergreen forest, Oregon, USA. Canadian Journal of Forest Research. 35: 2981–2995.

Reinhardt, E.; Crookston, N. L. Tech. eds. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Scott, J.H.; Burgan, R.E. 2005. Standard fire behavior fuel models: A comprehensive set of fuel models for use with the Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 72 p.

Stratton, R. D. 2006. Guidance on spatial wildland fire analysis: models, tools, and techniques. Gen. Tech. Rep. RMRS-GTR-183. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 15 p.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

Appendix A: Sample FVS Prescription

Keyword file for western Montana study site showing the prescription logic used for all stands with tree lists. Code explanation:

SizCls (size class)
- 1—sawtimber
- 2—poletimber
- 3—seedling/sapling

ForTyp (forest type)
- 201—Douglas-fir
- 221—ponderosa pine
- 241—western white pine
- 281—lodgepole pine
- 321—western larch

```
IF         0
Selected EQ Yes AND Year GE 2005 AND SizCls EQ 3
Then
ThinBTA      0   640.  0.9500    0.    6.    0.   999.
IF         0
Selected EQ Yes AND Year GE 2005 AND SizCls EQ 3 AND FuelLoad(1,3) GE 2.5
Then
Fmin
PileBurn      0     1    80     5    90     1
End
IF         0
Selected EQ Yes AND Year GE 2005 AND SizCls EQ 2 AND (ForTyp EQ 201 OR ForTyp EQ 221)
Then
ThinBBA      0   130.  1.0000    0.   999.    0.   999.
Fmin
SimFire      1   12.00     2   70.0
End
IF         0
Selected EQ Yes AND Year GE 2005 AND SizCls EQ 2 AND ForTyp GT 221
Then
ThinBBA      0   150.   0.90    0.   999.    0.   999.
Fmin
PileBurn      1     1    70     5    90     3
End
IF         0
Selected EQ Yes AND Year GE 2002 AND SizCls EQ 1 AND (ForTyp EQ 201 OR ForTyp EQ 221 &
OR ForTyp EQ 241 OR ForTyp EQ 321)
Then
ThinBBA      0   140.  0.9000    0.   999.    0.   999.
Fmin
SimFire      1   12.00     2   70.0
End
IF         0
Selected EQ Yes AND Year GE 2002 AND SizCls EQ 1 AND ForTyp EQ 281
Then
ThinBBA      0    0.  0.9000    0.    20.    0.   999.
Fmin
SimFire      1   12.00     2   70.0
End
IF         0
Selected EQ Yes AND Year GE 2002 AND SizCls EQ 1 AND (ForTyp GE 250 AND &
NOT (ForTyp EQ 281 OR ForTyp EQ 321))
Then
ThinBBA      0   150.  .95000    0.   999.    0.   999.
Fmin
PileBurn      1     1    80     5    90     1
End
```

Appendix B: Sample Fuel Model Logic

Logic Used to Select Fuel Models for the Western Montana Study Site.

Variables used for this logic were from the text file PPE-FFESelData.txt described in table 2. Some of both the original 13 (Anderson 1982) and Scott and Burgan (2005) fuel models were used in this method.

First, live woody fuel loading and fuel bed depth were determined from the shrub constancy and average coverage for the stand habitat type (Cooper and others 1991; Pfister and others 1977).

Shrub type	Live woody load, Mg/ha (T/ac)	Fuel bed depth, m (ft)
Tall shrubs	6.6 (3.0)	0.9 (3.0)
Medium shrubs	4.4 (2.0)	0.6 (2.0)
Low shrubs	2.2 (1.0)	0.3 (1.0)
No significant shrubs	0.0 (0.0)	0.1 (0.4)

If more than 40.5 trees/ha (100 trees/acre) were cut (RTPA) and no fuel treatment was accomplished, assign a slash fuel model (11, 12, 13, SB1, SB2, SB3, or SB4) by comparing 1hrLoad, 10hrLoad, and 100hrLoad.

Else–modify live woody fuel loading and fuel bed depth for recent treatments and high canopy cover with one of the following rules:

- If the last treatment is less than 20 years old, reduce live woody fuel loading and fuel bed depth by the ratio (Year–Last Treatment)/20.
- If canopy cover is greater than 70 percent, multiply live woody fuel loading and fuel bed depth by 0.333.
- If canopy cover is between 50 percent and 70 percent, multiply live woody fuel loading and fuel bed depth by 0.666.

If canopy cover is less than 30 percent, assign fuel model as follows:

1. If live woody fuel loading is greater than 0.0 and fuel bed depth is greater than 0.6 m (2.0 ft), assign fuel model GS2.
2. If live woody fuel loading is greater than 0.0 and fuel bed depth is less than or equal to 0.6 m (2.0 ft), assign fuel model GS1.
3. If live woody fuel loading is 0.0, assign fuel model GR1.

Else–If forest type is Ponderosa Pine, assign fuel model as follows:

1. If canopy cover is less than or equal to 50 percent, assign fuel model 2.
2. If canopy cover is greater than 50 percent and 1hrLoad is greater than 9.62 Mg/ha (4.36 T/ac), assign fuel model TL8.
3. If canopy cover is less than or equal to 50 percent and 1hrLoad is less than or equal to 9.62 Mg/ha (4.36 T/ac), assign fuel model 9.
   Else–assign a fuel model (5, 8, 10, GS1, GS2, SR1, SR2, SR5, TU1, TU5, TL1, TL3, TL4, TL5, or TL7) by comparing 1hrLoad, 10hrLoad, 100hrLoad, live woody fuel loading, and fuel bed depth.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Modeling Bark Beetles and Fuels on Landscapes: A Demonstration of ArcFuels and a Discussion of Possible Model Enhancements

Andrew J. McMahan[1]
Alan A. Ager[2]
Helen Maffei[3]
Jane L. Hayes[4]
Eric L. Smith[5]

Abstract—The Westwide Pine Beetle Model and the Fire and Fuels Extension were used to simulate a mountain pine beetle outbreak under different fuel treatment scenarios on a 173,000 acre landscape on the Deschutes National Forest. The goal was to use these models within ArcFuels to analyze the interacting impacts of bark beetles and management activities on landscape fuel dynamics. Issues pertaining to modeling the complex inter-relationships of fire, bark beetles, and fuel dynamics are discussed, including: thinning effects on inter-stand bark beetle migration; relationships between beetle migration and survivorship; tree mortality source (e.g., fire vs. bark beetle) and its relationship to the tree's subsequent fuel deterioration dynamics; fire effects on beetles and beetle behavior in fire-affected landscapes. Ideas for future model development are presented.

Introduction

Bark beetles and wildfire play a major role in determining forest succession patterns in the extensive pine-dominated forests of the Western United States. Historically, many dry pine forest landscapes typically experienced frequent low severity fires that controlled stand densities and surface fuel loads (Graham and others 2004) and thus infrequently experienced large stand-replacing fires. Native bark beetle populations exhibited cyclic patterns of endemic and epidemic activity. During endemic periods (between outbreaks), bark beetles generally kill patches of trees weakened by fire, disease, or other stressors. Bark beetle outbreaks, which occur sporadically when conditions are favorable, cause increased mortality of trees that under endemic conditions would be considered less vulnerable. Silvicultural practices and fire suppression over the past 100+ years has resulted in landscape-scale stand structures that are experiencing an increase in both the frequency and severity of wildfire and bark beetle outbreaks in pine forests of the Western United States (Hessburg and others 1994). Future climate change may foster conditions conducive to wildfire (Meehl and others 2007) and may contribute to future increases in the severity of bark beetle outbreaks (Carroll and others 2006).

In response to concerns over the undesirable impacts of large wildfires, bark beetle outbreaks, and the potential interactions between the two, many land management agencies have adopted strategies calling for stand treatments over wide areas in the Western United States. These treatments include thinning, re-introduction of natural and prescribed fire, and mechanical fuels reductions. Many would agree that such treatments can have beneficial effects, moderating wildfire intensity and extent and, at least in the short-term, reducing within-stand beetle-caused tree mortality. However, it remains unclear what effects these treatments might have on landscape-scale bark beetle dynamics and effects on fuel load and fire behavior. Models such as the Westwide Pine Beetle Model (WWPBM) (Beukema and others 1997; Smith and others 2002, 2005)—a landscape-scale bark beetle contagion and tree-effects model—coupled with the Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003) are useful tools to investigate the landscape-scale fuels treatments and their effects on the dynamics of fire/bark beetle interactions.

Evaluating risks of tree mortality from fire and bark beetles at a landscape scale is a complex problem. Ager and others (2006) discuss many of the issues. The WWPBM and FFE can be used to help analyze possible future scenarios by projecting how, where, and to what extent fire and bark beetle "risk factors"—potential tree mortality, fuel loading, torching index, etc.—might manifest on a landscape under a variety of management scenarios.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Systems Analyst, ITX, Inc., Fort Collins, CO; e-mail: dmcmahan@fs.fed.us.

[2] Operations Research Analyst, Western Wildland Environmental, Threat Assessment Center, Prineville, OR.

[3] Forest Pathologist, Forest Health Protection, Bend, OR; e-mail: hmaffei@fs.fed.us.

[4] Research Biological Scientist, USDA Forest Service, Forest and Range Sciences Laboratory, LaGrande, OR; e-mail: jlhayes@fs.fed.us.

[5] Program Manager, Forest Health Technology, Enterprise Team, Fort Collins, CO; e-mail: elsmith@fs.fed.us.

In this paper, we present an application of the WWPBM and the FFE on a landscape in the Deschutes National Forest on the east side of the Cascades in central Oregon. We used these models to analyze the effects of an aggressive thinning strategy on subsequent dynamics of a simulated bark beetle outbreak. We also examined the effects of these thinning regimes and a simulated beetle outbreak on near-term potential fire behavior and fuel loads. The simulations were conducted and analyzed within ArcFuels (Ager 2005), a customized ESRI ArcMap project, which facilitates the linking of Forest Vegetation Simulator (FVS) inputs and outputs with geographic information systems (GIS) and numerous post-processing applications. Our aims are to (1) foster discussion about how our models simulate the inter-relationships between fire, bark beetles, and fuel dynamics; and (2) demonstrate the types of questions that can be addressed by the models and the types of analyses that are facilitated by ArcFuels. Model strengths and weaknesses are discussed.

Analysis Area

The Five Buttes planning area spans approximately 173,000 acres of predominately forested land (90 percent) located on the Deschutes National Forest in south-central Oregon (fig. 1). The planning area encompasses the Davis Late Successional Reserve (LSR) along with designated wilderness, roadless areas, and general forest that is managed for a number of resources. The Davis LSR was established in the Northwest Forest Plan and is managed to maintain and/or create old-growth habitat for the federally listed northern spotted owl (*Strix occidentalis caurina*) (USDA Forest Service and BLM 1994). The area contains a diverse array of forest types. It is dominated by mixed conifer, lodgepole pine, and ponderosa pine plant association groups (PAG) in its eastern reaches, and dry mountain hemlock PAG in the west. The 2003 Davis fire burned approximately 24,000 acres (~15 percent of forested area) of mostly mixed conifer stands in the northeastern quadrant of the analysis area (fig. 1), destroying approximately 30 percent of the habitat of the northern spotted owl within the Davis LSR.

Simulation Details

The study area contained 5,291 mapped polygons, 135 of which were classified as non-forest (meadows, rock, and water). Polygons within the 2003 Davis fire were assumed to be bare ground. The non-forest and Davis fire polygons were excluded from the fuel treatment scenarios and the WWPBM, leaving 132,340 acres or 76 percent of the entire area being simulated as forested.

We conducted four simulation scenarios by combining a thin or no-thin treatment scenario (TRT, NoTRT) with post-treatment bark beetle outbreak or a no-beetle scenario (+B, –b). Simulations were run using the SORNEC (Southern Oregon, Northeast California) variant of FVS, together with the Parallel Processing Extension (PPE) (Crookston and Stage 1991), the FFE, the WWPBM, and the Database (Crookston and others 2007) extensions. Tree regeneration was not simulated. Simulations were run for seven 3-year cycles with an assumed starting year of 2000[1]. The short cycle length invokes frequent communication between the WWPBM and the FFE, which occurs only at FVS cycle boundaries.

The thinning scenarios treated stands in the mixed conifer type where current stand density index (SDI) exceeded 55 percent of the maximum stand density index (MaxSDI) (Dixon 2007). This threshold SDI (236) (Cochran and others 1994) is generally accepted as a density above which competition can sufficiently weaken trees, causing them to be susceptible to bark beetle attack. We note that this thinning scenario is hypothetical and that operational or other constraints would prohibit treatments on such a large scale. The prescription is compatible with the management goals within and around the Davis LSR to protect large pine and Douglas-fir from bark beetles and wildfire (Maffei and Tandy 2002; USDA 2007). The thinning prescription was simulated in year 2003 and left a residual SDI of 35 percent of the MaxSDI. The prescription favored the retention of large pine and Douglas-fir.

In the beetle outbreak [+B] scenarios, a seven-year long "severe" bark beetle outbreak was imposed during simulation years 2005 through 2011. Tree mortality from endemic-levels of beetles was simulated before and after the outbreak. The no-beetle outbreak scenarios [–b] did not include either outbreak or endemic beetle-caused tree mortality.

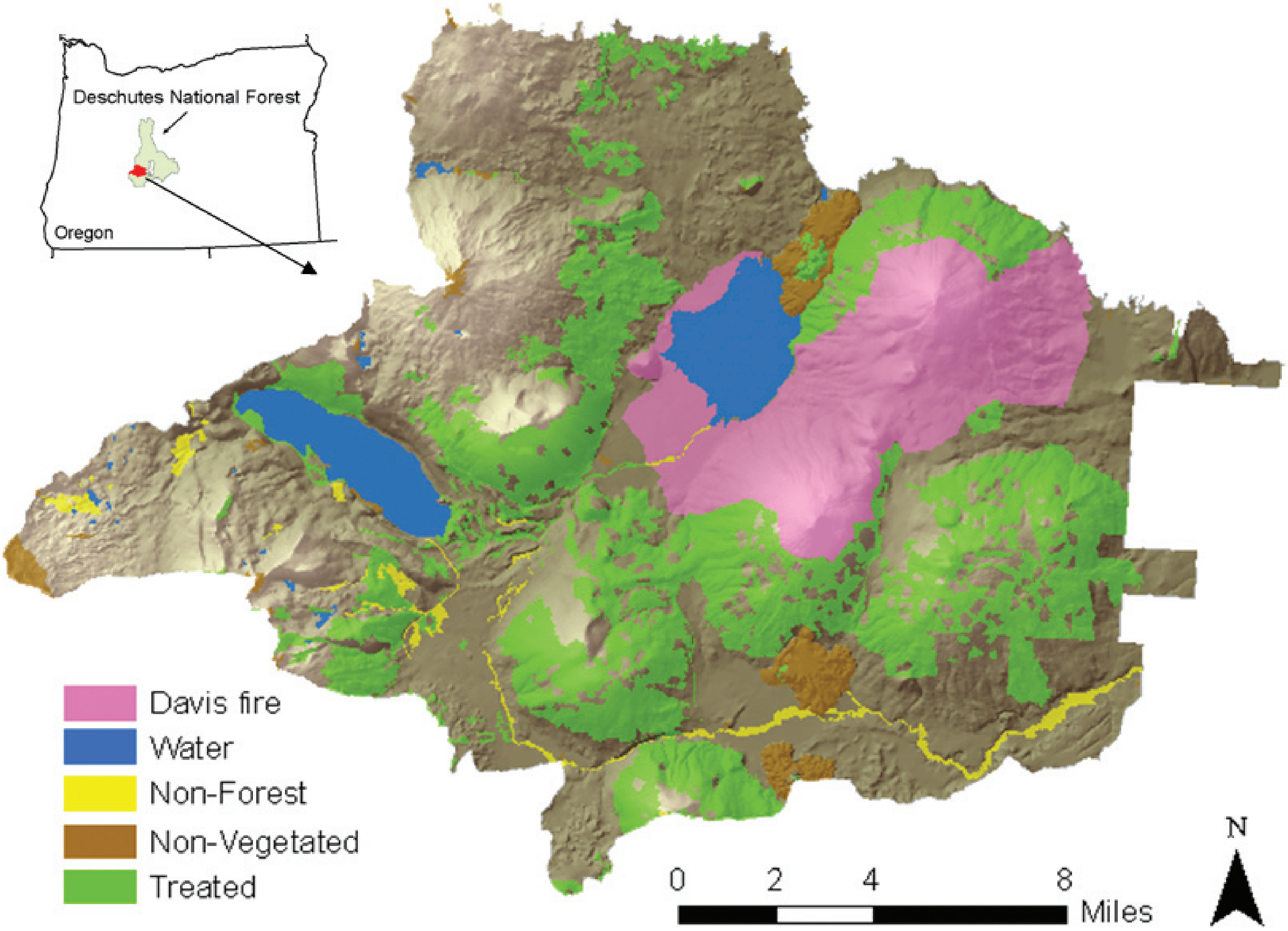


Figure 1—Five Buttes planning area showing land types and the 2003 Davis fire. Stands selected for thinning ("Treated") in the treatment simulations (TRT) are shown in green.

In the [TRT+B] scenario, a sanitation cut (WWPBM keyword SANITIZE) concurrent with the thinning was also imposed in thinned stands to remove all recently beetle-killed trees and their beetles[2].

Beetle populations are simulated in the WWPBM in terms of "beetle kill potential" (BKP), expressed in units of square feet. One unit of BKP is equivalent to an amount of beetles, or "beetle pressure" capable of killing one square foot of host tree basal area. On an annual time step, the WWPBM simulates various BKP dynamics, including its re-allocation among stands ("dispersal"), reductions during dispersal ("in-flight" BKP "mortality"), tree selection and attack, and within-tree increases ("reproduction"). We initialized BKP into the landscape (keyword BMHIST) at the beginning of the simulation by assigning to stands containing significant density of host trees[3] an amount of BKP equal to one percent of the host basal area in the stand. All pines were considered hosts. This BKP initialization rate approximately represents endemic levels of beetles and provides the "seed" BKP for a subsequent simulated outbreak induced via keyword VARYRAIN.

The FFE was used to generate potential fire and fuel reports. No fires were simulated. FVS keyword details are provided in the appendix. Simulations were built and analyzed within ArcFuels. This customized ArcGIS interface was used to build keyword files and to join FVS model outputs to geodatabase layers for rapid and spatial analysis of model outputs.

Results

Thinning

One-third of the forested area met the prescription criteria, resulting in 1,705 stands being treated in simulation year 2003 in the TRT+B and TRT–b scenarios. This set of stands we call the *overstocked mixed conifer* (OMC) stands. They comprise ~87 percent of the unburned mixed conifer PAG. Of these, only 47 stands met the criteria for a sanitation cut (see endnote 2). Nevertheless, sanitation removed 56 percent of landscape total BKP (from 25,656 to 11,204 ft^2). Thinning reduced average stand basal area from 188 to 64 ft^2 $acre^{-1}$ in 2003 in the OMC stands; average stand basal area in all other (non-OMC) stands was 136 ft^2 $acre^{-1}$ in 2003.

Beetle Dynamics

The simulated bark beetle outbreak began in year 2005, peaked in 2010, and was nearly ended by 2012. Thinning reduced landscape average beetle-caused mortality (table 1 and fig. 2). In the TRT+B scenario, beetle-caused tree mortality was nearly eliminated in thinned (OMC) stands (fig. 3). In the NoTRT+B scenario, OMC stands (stands that would have been thinned under the TRT scenario) experienced greater beetle-caused mortality on average than other stands in the landscape (fig. 3). In the TRT+B scenario, unthinned (non-OMC) stands on average experienced beetle-caused mortality greater than they experienced in the NoTRT+B scenario (fig. 3). Over 40 percent of unthinned stands (1,092 stands) in the TRT+B scenario experienced a two percent or more increase in beetle-killed host basal area above what they experience in the NoTRT+B scenario (fig. 4c).

Fire-related Metrics

In simulations without beetles, potential volume mortality from a severe fire was reduced in thinned stands by ~77 percent, from 3,607 to 8,23 ft^3 $acre^{-1}$ in 2003 (data not shown). The landscape average potential volume mortality was reduced in 2003 by 33 percent, from 2,728 to 1,821 ft^3 $acre^{-1}$. Thinning completely eliminated active crown fire and conditional surface fire potential in all treated stands through 2006 (fig. 4b); active crown fire potential returned to only a few treated stands beginning in simulation year 2009. The simulated beetle outbreak caused slight increases in acres projected to have active crown fire in both of the +B scenarios (TRT+B, NoTRT+B) relative to their no-beetle (–b) counter-scenarios (TRT-b, NoTRT–b) (fig. 4a).

FFE estimates of fuel loadings and fuel model change frequently over time in response to thinning treatments and beetle dynamics. These shifts occur as BKP migrates from thinned stand to other stands across the landscape.

Discussion

Overview

In the WWPBM, BKP is dispersed among stands where it "attacks" host trees and "reproduces" in successfully killed trees. Factors controlling how BKP is allocated from one stand to another include: distance between stands, target-stand total basal area, host basal area, and a variety of stand *rating values* representing stresses to tree vigor. In our simulations, only three stressors were invoked: (a) random lightning strikes, set at the default values of two random strikes per 1,000 acres per year (this creates stressed "focus" trees for BKP); (b) dwarf mistletoe severity, provided via input tree lists; and most importantly, (c) the climate-related, outbreak-inducing stress event, invoked via keyword VARYRAIN. Other WWPBM rating values were not invoked. Stands with high total and host basal area and low vigor ratings attract BKP during dispersal; attractiveness diminishes exponentially as the distance between source and target stands increases. All stands are potential sources and targets of BKP each year. Analyses of dwarf mistletoe effects are not presented here.

The imposition of the climate-related stress event occurs landscape-wide; all stands experience the stress event. However, not all stands experience the stress to the same

Table 1—Average cumulative basal area beetle killed per acre (ft[2] acre[–1]) during simulation period 2003–2011 for two suites of stands under two simulation scenarios. The overstocked mixed conifer (OMC) stands are cut in the TRT scenarios and not cut in the NoTRT scenarios. Non-OMC stands are not cut in either scenario.

Scenario	OMC stands	Non-OMC stands
NoTRT+B	24.3	8.9
TRT+B	0.4	13.2

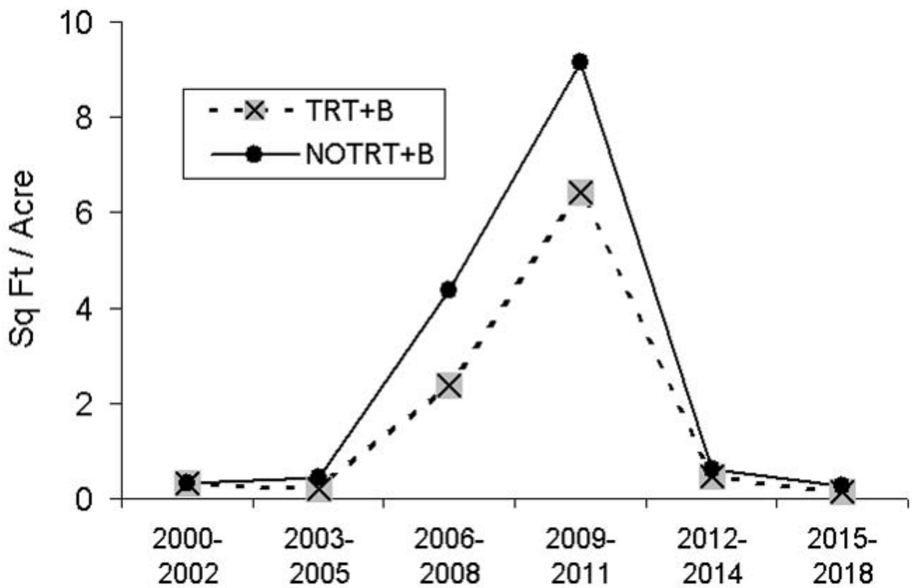


Figure 2—Landscape average basal area mortality from bark beetles during a simulated bark beetle outbreak in two different simulation scenarios. Thinning 1/3 of the landscape (TRT+B scenario) reduced simulated beetle-caused mortality by approximately 36 percent (between 2003 and 2012). Points represent 3-year cumulative basal area mortality through the end of each x-axis period-year.

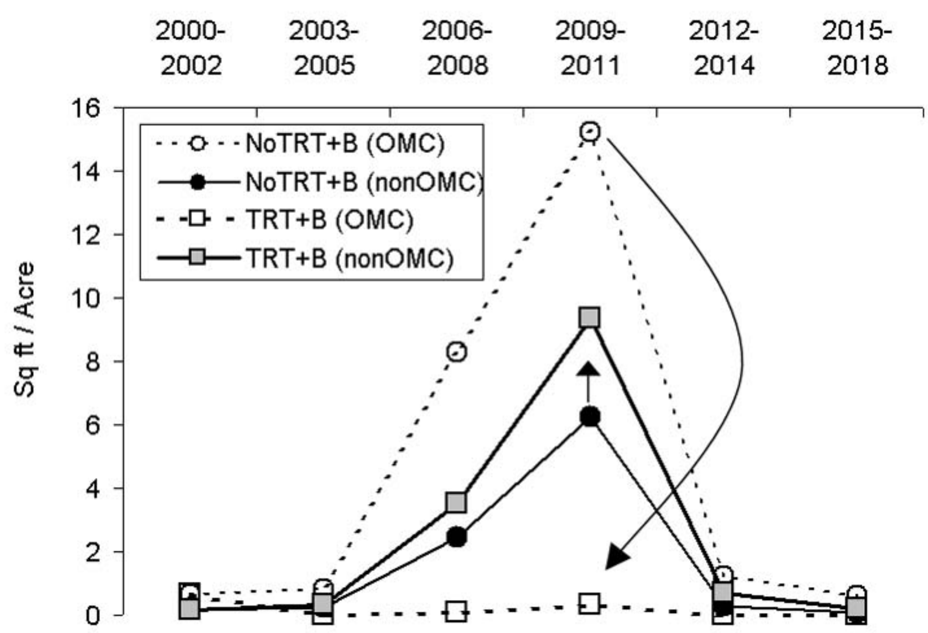


Figure 3—Beetle-killed basal area (ft[2] acre[–1]) for two simulations: NoTRT+B, TRT+B. Results from each simulation are partitioned into two groups of stands: Overstocked Mixed Conifer (OMC) stands and other (non-OMC) stands. All OMC stands (dashed lines) are cut in the TRT+B scenario. Plotted values are stand-area weighted landscape averages. Points on the graph represent 3-year cumulative basal area mortality through the end of each x-axis period-year. OMC stands in the NoTRT+B scenario (open circles) experience significantly more mortality on average than other stands in the NoTRT+B scenario (filled circles). Mortality in OMC stands is reduced to negligible levels upon being thinned (long arrow). Other, non-OMC stands experience on average greater mortality in the thinned (TRT+B) scenario (filled squares) relative to what they experience in the unthinned (NoTRT+B) scenario (short arrow).

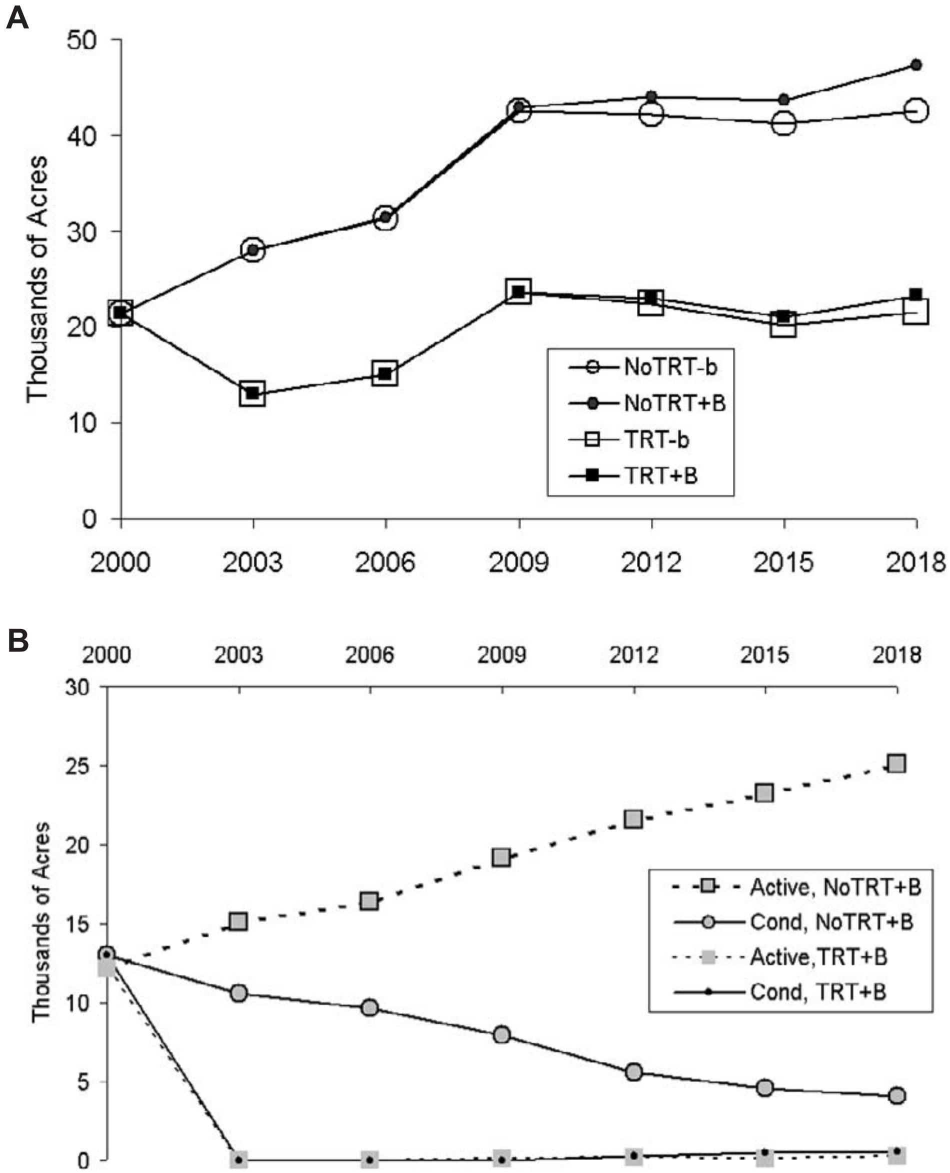


Figure 4—(A) Landscape total acres classed as having “Active” crown fire potential for the four simulation scenarios. Treatments significantly reduce “Active” acreage while beetles slightly increase “Active” acreage. (B) Acres of active crown fire (“Active”) and conditional surface fire (“Cond”) for OMC stands under TRT+B and NoTRT+B scenarios. Trajectory for untreated landscape is for increasing acres categorized as “Active” and decreasing acreage categorized as “Conditional surface.” Thinning treatments reduced both classes to negligible levels.

magnitude—more dense stands experience it more harshly. The event simulates a decrease in tree defense capabilities (the amount of BKP required to kill a tree decreases) and an increase in BKP survivorship (per unit of BKP being dispersed), thereby promoting the outbreak. The factors most strongly controlling where BKP is allocated in the landscape under these conditions are total and host basal area.

Thinning Effects on BKP “Migration”

In our simulations, thinning stands greatly reduces within-stand beetle-caused tree mortality (figs. 3 and 5b). However, because we imposed a “severe” climate-related stress event across the landscape to promote the beetle outbreak, BKP is nevertheless being

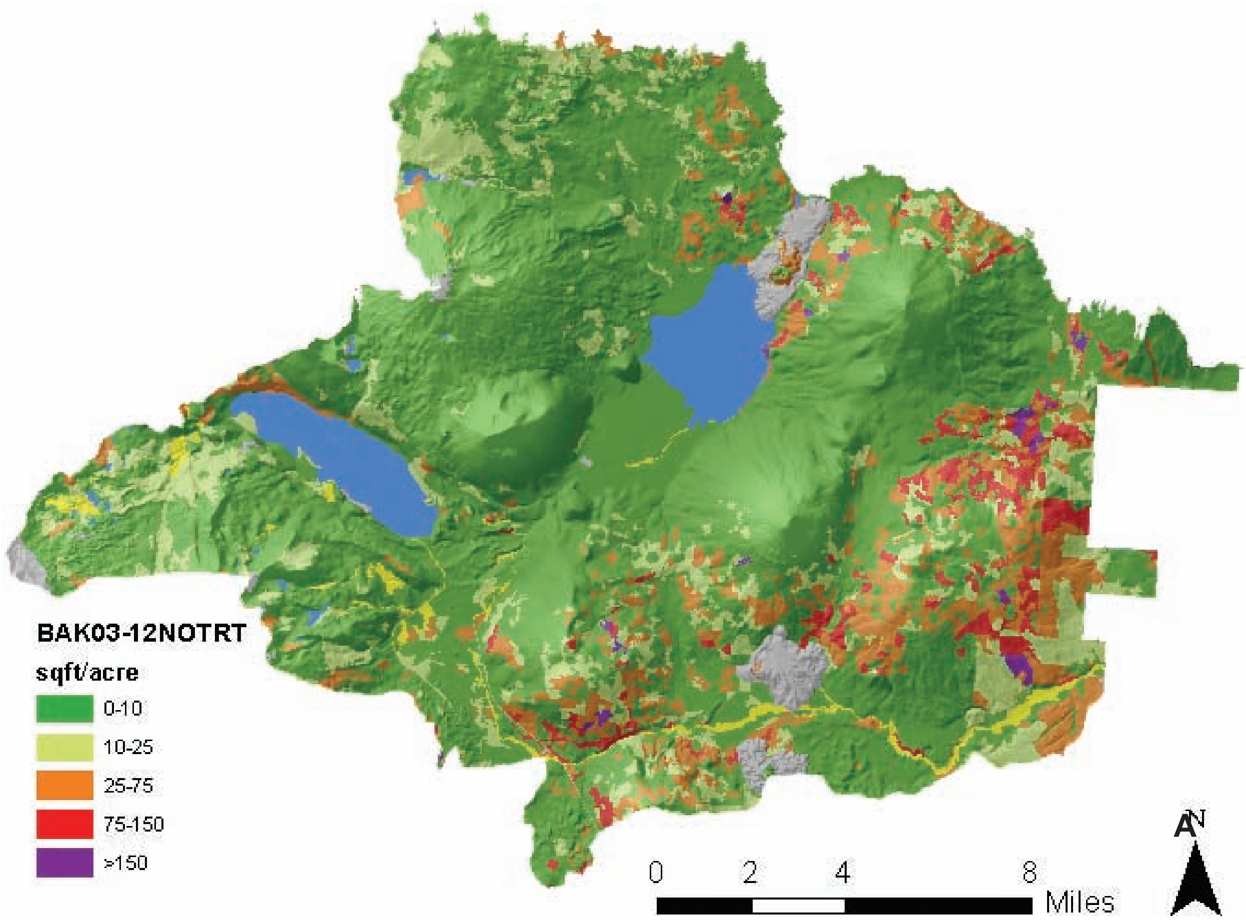
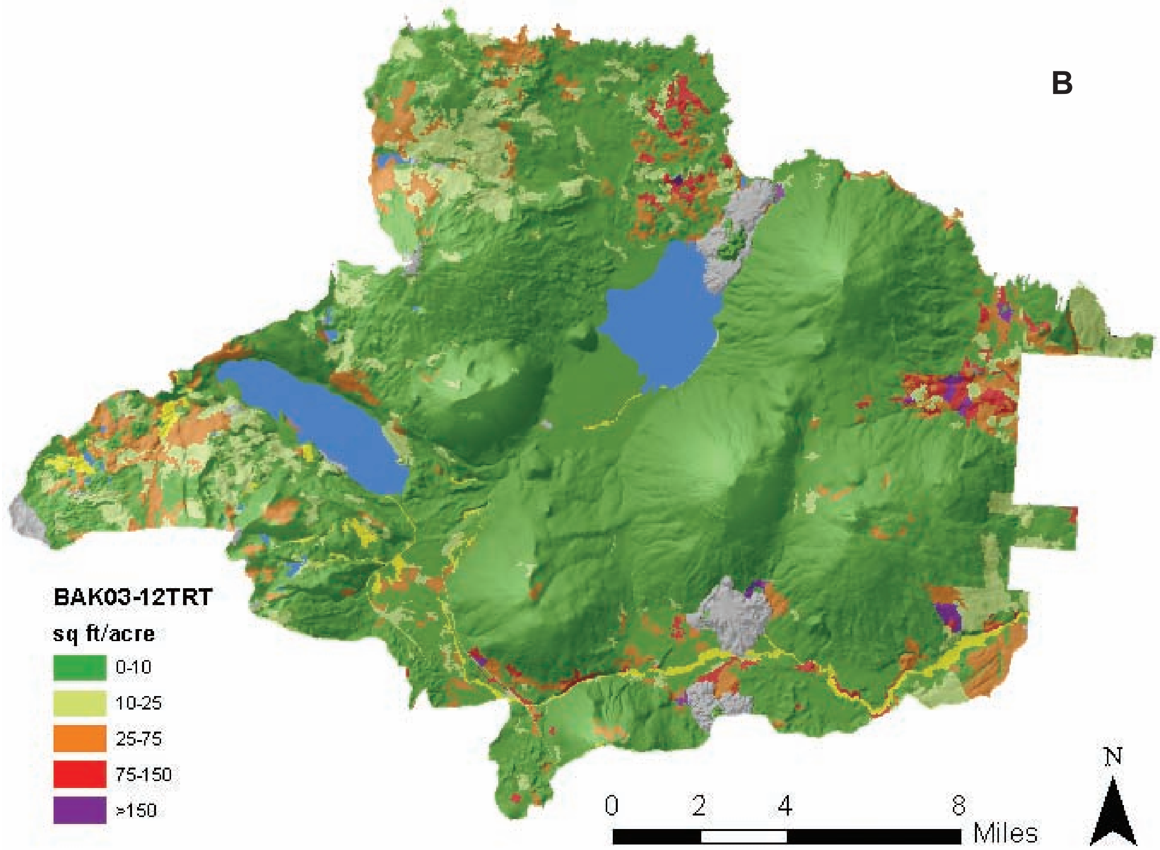


Figure 5—Simulated beetle-killed basal area (BAK, ft^2 acre^{-1}) from simulation years 2003–2011 (inclusive) from two scenarios: (A) NoTRT+B; (B) TRT+B. Image (C) depicts the difference between the NoTRT and the TRT scenarios. In (C), negative values (orange) depict where beetle-killed basal area (2003–2011) has increased post-treatment (versus no treatment) by more than 15 ft^2 acre^{-1}. Green and purple are where beetle-killed basal area has decreased post treatment (versus no treatment). Note: In (C), no color overlay is used to depict BAK values between –15 and +15 (continued on next page).

"encouraged" by the stress event to find and attack remaining host trees, even when the landscape is thinned. A striking conclusion from these simulations is that by thinning a significant portion of the landscape, BKP is effectively "pushed" into other stands where its effect was less under the NoTRT+B scenario (figs. 5a–c). Similar results are presented and discussed in Ager and others (2007).

We know of no published research designed to study the effects of thinning treatments on areas beyond the area thinned. In our simulations, BKP is able to "find" and "attack" remaining host trees in the landscape, and in some cases, at a magnitude greater than that experienced when the landscape is not thinned. Consistent with the design of the WWPBM, simulated BKP is reallocated from thinned stands to other unthinned stands. This is largely the result of the density relationships built into the model's attractiveness algorithms. If a stand were thinned to a low enough total density, BKP would "migrate" from it to denser stands. This model behavior can be exhibited even if the absolute amount and proportion of host in the stand to which it is reallocated is less than in the source stand. What is not clear is the degree this prediction represents real-world behavior. Assuming that conditions instigating an outbreak are primarily exogenous—for example, climate-instigated—and assuming landscapes are intensively managed (our simulation thinned nearly one-third of the forested landscape), then to what degree will beetles in such a landscape find remaining hosts? If, prior to thinning, endemic beetles exist primarily in stands that are scheduled to be thinned, to what degree will remaining "unharvested" beetles remain in the thinned stands versus migrate to other stands when exogenous environmental conditions promote an outbreak? Answers to these questions could help us understand and properly interpret these model results.



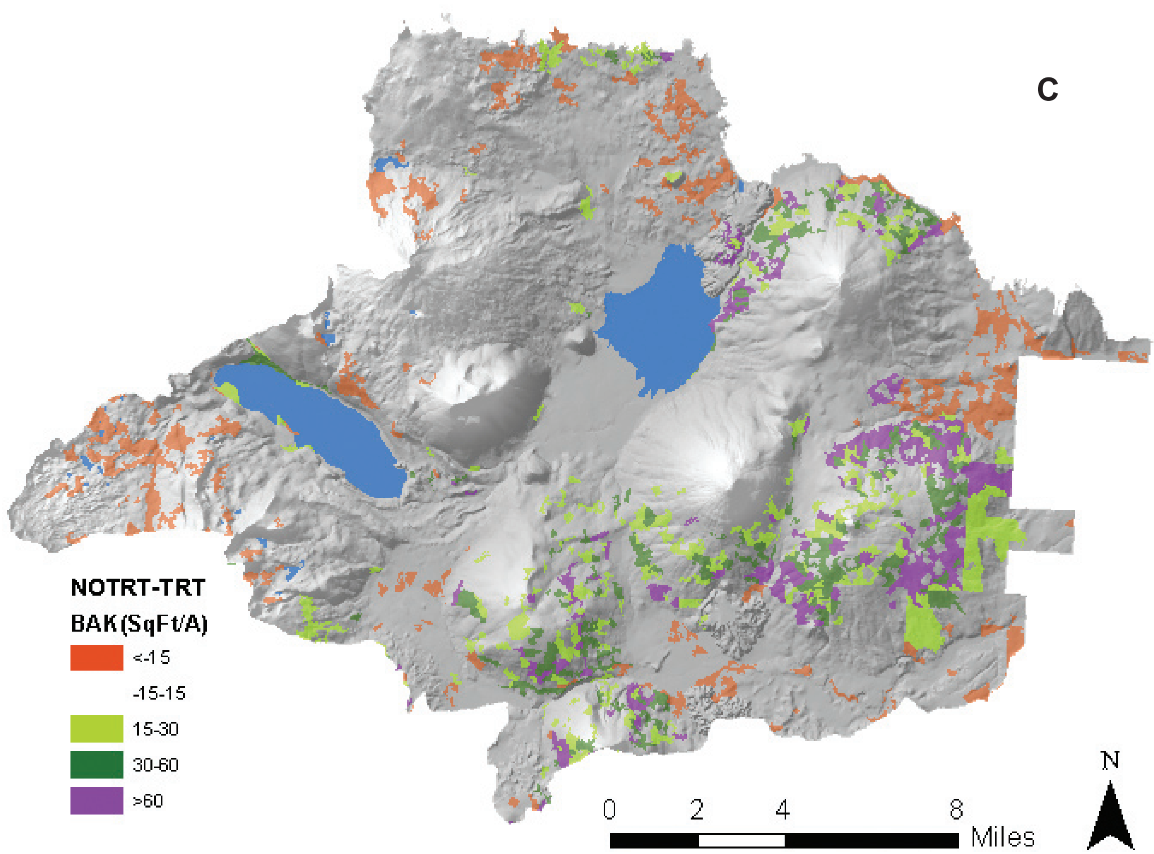


Figure 5—Simulated beetle-killed basal area (continued).

BKP Survivorship in Relation to Migration Distance

During dispersal, BKP is reduced (simulating in-flight BKP mortality). Current WWPBM structure contains algorithms that control BKP survivorship rates as a function of the severity of the VARYRAIN-induced stress event. As the severity of the event increases, BKP survivorship increases (in other words, the amount of BKP "dying" decreases). However, the WWPBM does not adjust BKP mortality as a function of the distance BKP travels as it "migrates" from stand-to-stand. In the model, potentially unlike beetles in a real-world landscape, BKP can just as efficiently "find and attack" a host that is five miles away, for example, as it can a host that is in a neighboring stand[4]. This explains in part why significantly more hosts are beetle-killed in some stands in the treated landscape than those stands experience in an unthinned landscape. Adjusting BKP to mimic beetle survivorship as it migrates long distances is a phenomenon currently not modeled in the WWPBM. Ideally this differential survivorship—assuming it exists at all—should be built into the model, but parameterization is a problem given our limited understanding of beetle survivorship over space and time.

Beetles and Fuel Dynamics

To the degree that the simulated bark beetle dynamics are valid, we found that our simulated, landscape-scale, fire behavior risk factors are significantly affected by bark beetle dynamics. Spatial distribution of standing and surface fuels significantly differs among the simulation scenarios as a result of treatments and simulated beetle activity (figs. 5c and 6). In our simulations, stands experiencing significant beetle mortality (+B scenarios) contain more snags and greater surface fuels, in the short term, than the same stands have in the no-beetle (–B) scenarios, a result of beetle-caused mortality (fig. 6). Further, because of the "redistribution" of BKP, and its concomitant tree mortality resulting from the thinning treatments (fig. 5c), the simulated thinned landscape (TRT+B) experiences significant "shifts" in patterns of beetle-caused snags and fuel loadings relative to the unthinned (NoTRT+B) landscape.

Modeling fuel loads and fuel dynamics in conjunction with disturbance agents (such as bark beetles) compels us to consider relationships between the cause of a tree's demise and its subsequent fuel dynamics. Snag fall-down rate and deterioration has been the subject of considerable research because of the role snags play in fuel dynamics and their value to wildlife (reviewed in Laudenslayer and others 2002). While some studies have focused on deterioration of beetle-killed trees (Hinds and others 1965; Keen 1955; Mielke 1950), few comparative studies of deterioration have been completed for trees killed by other agents. Although some disturbance agents such as root disease or severe fire likely hasten fuel deterioration, there exists few data quantifying such relationships. Thus, with regard to bark beetle effects on snag and fuel dynamics, questions remain: to what degree do the mechanical injuries of attack, larval feeding on phloem, borings from associated beetles and other predators, together with infection from blue stain fungi affect snag fall-down and wood decay rates? Furthermore, other disturbance agents may have different effects on tree and snag deterioration. Incorporating these effects into our landscape projections of fuel dynamics remains a challenge.

Currently in FVS, when the FFE inherits dead trees from the WWPBM (or from any extension, for that matter) it does not "know" the source of the tree's mortality. In the FFE, all dead trees are treated the same. Although it would be possible to build into the FFE recognition of tree mortality sources, the task is not a straightforward one, because the ultimate "cause" of tree mortality often involves more than one agent. For example, suppose a prescribed under burn kills a tree already stressed by root disease and dwarf mistletoe. To what agent is the source of mortality attributable? If mortality is attributable to more than one agent, how should that be accounted for in the FFE? These difficult issues have precluded FFE developers from making such considerations. Nevertheless, various mortality agents can and likely do play a significant role in determining snag and fuel dynamics. Elucidation and elaboration of some of these relationships into the FFE may improve its estimates of snag and fuel dynamics.

In addition to potentially affecting fall-down rates, fuel decay rates, and fuel loading, beetles affect the spatial arrangement of fuels. Stands experiencing a bark beetle infestation exhibit a rapidly changing canopy fuel dynamic, with large proportions of stand canopies (needles) changing from "green" to "red" in a span of one to two years, typically followed by relatively rapid needle fall. The spatial arrangement of fuels is an

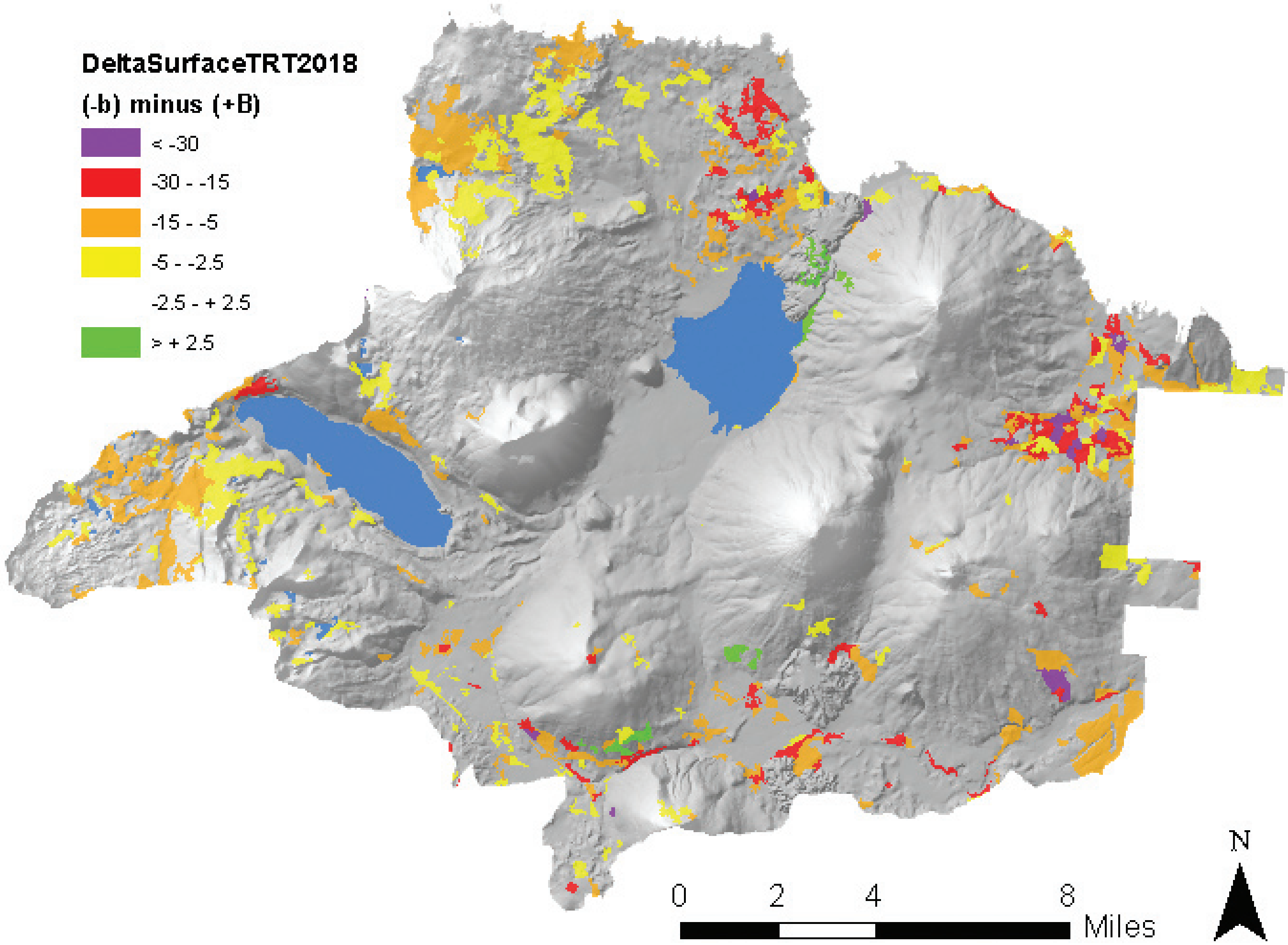


Figure 6—Difference in surface fuel loading (tons per acre) in simulation year 2018 between the TRT–b scenario and the TRT+B scenario. Negative values (yellow, orange, red, and purple) depict where surface fuels have increased due to beetle-caused tree mortality. Note: No color overlay is used to depict values between –2.5 and +2.5 tons per acre.

important component of fire behavior fuel models. Currently used fuel models may or may not be adequate to accurately model fire dynamics associated with beetle-caused canopy fuel changes. These relationships are beginning to be investigated (Page and others 2006). Again, additional studies may help us improve our modeling estimates of beetle-caused tree mortality effects on fire behavior via the development of new or modified fire behavior fuel models.

Fire Effects on Beetles

There are many questions pertaining to potential post-fire effects on beetle dynamics. A number of researchers have investigated post-fire effect relationships (for example, Amman and Ryan 1991; Boyle and others 2004; McHugh and others 2003; Ryan and Amman 1996; Sieg and others 2006; Wallin and others 2003). These effects could be at the tree or stand level. Currently, the WWPBM is designed to account for the stresses experienced by trees surviving a fire. The rating value due to fire is a function of the proportion of crown length scorched. Fire-scorched trees in the WWPBM are more attractive to BKP and are easier for BKP to kill. Although the WWPBM handles this relationship, integration with the FFE is incomplete[5]. Once complete, the relationships will need testing and refinement. A number of questions will need to be addressed, such as: Over what range of conditions will these relationships between fire-damage and beetle-attractiveness hold? Is percent crown scorch the best metric to use to calibrate a tree's rating value? Should fire-caused root damage effects be incorporated into the model? Under what conditions does fire-stress cause trees or stands to be *less* attractive to beetles? How do fire-killed trees contribute toward a stand's attractiveness to bark beetles? How do these relationships vary amongst different tree and beetle species and across forest types? Does the seasonality of fire affect this dynamic (Ganz and others 2003)? How does fire intensity affect bark beetle brood survival (Safranyik and others 2001)? The state of knowledge in these areas is immature. Fowler and Sieg (2004) provide a good review of current research regarding fire-pest mortality relationships in ponderosa pine and Douglas-fir. A detailed discussion of these issues is beyond the scope of this paper. As our knowledge base improves, so will our models.

Concluding Remarks

Landscape scale analyses of management scenarios aimed at ascertaining risks to resources are becoming increasingly important to land managers. To support these analyses, the models and software used for multi-stand level simulation continue to develop and are increasingly accessible. The FVS and its several extensions—the PPE, FFE, Structural Stage model, and WWPBM, to name but a few—continue to evolve and be valuable modeling tools. The PPE, for example, can now be used to "pause" FVS simulations, allowing other programs to run between cycles to provide updated information for use by FVS in the next simulation cycle. The database capabilities of FVS-DB, and geodatabase capabilities of ESRI ArcGIS naturally invite connection. ArcFuels is an application that greatly facilitates the joining of these two data structures. Within ArcFuels, FVS-DB stand and tree tables are easily linked to geospatial data. Data elements such as PPE's AREALOCS[6] supplemental records are easily derived from a GIS and readily imported into FVS via ArcFuels. Microsoft Access database tables can easily be parsed and joined to geodatabases, enabling easy map rendering of FVS model outputs. Although we did not run FLAMMAP[7] simulations in this analysis, ArcFuels streamlines the process of moving data through FVS into FLAMMAP (Finney and others 2004). More importantly, however, are the insights gained by exploring the landscape-scale spatial dynamics of management and modeling estimations, explorations which are becoming evermore important as land managers are increasingly faced with prioritizing management activities across the landscape.

Acknowledgments

The authors wish to thank Stephanie Rebain and Joy Roberts for reviewing drafts of this paper.

References

Agee, J.K. 2003. Historical range of variability in eastern Cascades forests, Washington, USA. Landscape Ecology. 18:725–740.

Ager, A.A. 2005. ArcFuels: forest planning tools for managing wildland fuels. In: Proceedings of the 25th ESRI International users conference; 2005 July 25–29; San Diego, CA: 5. Online: http://gis.esri.com/library/userconf/proc05/papers/pap1296.pdf.

Ager, Alan; Finney, Mark; McMahan, Andrew. 2006. A wildfire risk modeling system for evaluating landscape fuel treatment strategies. In: Andrews, Patricia L.; Butler, Bret W., comps. Fuels management—How to measure success: conference proceedings; 2006 March 28–30; Portland, OR. Proc. RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 149–162.

Ager, Alan A.; McMahan, Andrew J.; Hayes, Jane L.; Smith, Eric L. 2007. Modeling the effects of thinning on bark beetle impacts and wildfire potential in the Blue Mountains of eastern Oregon. Landscape and Urban Planning. 80:301–311.

Amman, Gene D.; Ryan, Kevin C. 1991. Insect infestation of fire-injured trees in the Greater Yellowstone Area. Res. Note RMRS-RN-398. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 9 p.

Beukema, S.J.; Greenough, J.A.; Robinson, D.C.E.; Kurz, W.A.; Smith, E.L.; Eav, B.B. 1997. The Westwide Pine Beetle Model: a spatially-explicit contagion model. In: Teck, R.; Moeur, M.; Adams, J., comps. Proceedings of the Forest Vegetation Simulator Conference. Gen. Tech. Rep. INT-GTR-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 126–130.

Boyle, M. Forbes; Hedden, Roy L.; Waldrop, Thomas, A. 2004. Impact of prescribed fire and thinning on host resistance to the southern pine beetle: preliminary results of the national fire and fire surrogate study. In: Connor, Kristina F., ed. Proceedings of the 12th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS–71. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 60–64.

Carroll, A.L.; Régnière, J.; Logan, J.A.; Taylor, S.W.; Bentz, B.J.; Powell, J.A. 2006. Impacts of climate change on range expansion by the mountain pine beetle. Mountain Pine Beetle Initiative Working Paper 2006-14. Victoria, BC: Canadian Forest Service, Natural Resources Canada, Pacific Forestry Centre, Mountain Pine Beetle Initiative.

Cochran, P.H.; Geist, J.M.; Clemens, D.L.; Clausnitzer, R.R.; Powell, D.C. 1994. Suggested stocking levels for forest stands in northeastern Oregon and southwestern Washington. Res. Note PNW-RN-513. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. 21 p.

Crookston, Nicholas L.; Gammel, Dennis L.; Rebain, Stephanie; Robinson, Donald C.E. 2007. Users guide to the database extension of the Forest Vegetation Simulator Version 2.0. Moscow, ID: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 52 p. Online: http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/DB-FVS-UserGuide.pdf

Crookston, Nicholas L.; Stage, Albert R. 1991. User's guide to the parallel processing extension of the Prognosis model. Gen. Tech. Rep. INT-281. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 88 p. Online: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_parallel.php

Dixon, Gary E., comp. 2007. Essential FVS: A user‘s guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 210 p. Online: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_essentialfvs.php

Finney M.A.; Brittain, S.; Seli, R. 2004. FlamMap: Spatial analysis of fire potential. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Joint Fire Sciences Program. Online: http://www.firemodels.org/content/view/14/28/

Fowler, James F.; Sieg, Carolyn Hull. 2004. Postfire mortality of ponderosa pine and Douglas-fir: a review of methods to predict tree death. Gen. Tech. Rep. RMRS-GTR-132. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 25 p.

Ganz, David J.; Dahlsten, Donald L.; Shea, Patrick J. 2003. The post-burning response of bark beetles to prescribed burning treatments. In: Omi, Philip N.; Joyce, Linda A., tech eds. Fire fuel treatments and ecological restoration: conference proceedings; 2002 April 16–18; Fort Collins, CO. Proc. RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 143–147.

Graham, Russell T.; McCaffrey, Sarah; Jain, Theresa B., tech. eds. 2004. Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p.

Hessburg, P.F.; Mitchell, G.R.; Filip, G.M. 1994. Historical and current roles of insects and pathogens in eastern Oregon and Washington forested landscapes. Gen. Tech. Rep. PNW-GTR-327. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 72 p.

Hinds, Thomas E.; Hawksworth, Frank G.; Davidson, Ross W. 1965. Beetle-killed Engelmann spruce: Its deterioration in Colorado. Journal of Forestry. 63:536–542.

Keen, F.P. 1955. The rate of natural falling of beetle-killed ponderosa pine snags. Journal of Forestry. 27:720–723.

Laudenslayer, W.F., Jr.; Shea, P.J.; Valentine, B.E.; Weatherspoon, C.P.; Lisle, T.E., tech. eds. 2002. Proceedings of the symposium on the ecology and management of dead wood in western forests; 1999 November 2–4; Reno, NV. Gen. Tech. Rep. PSW-GTR-181. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 949 p.

Maffei, H.M.; Tandy, B. 2002. Methodology for modeling the spatial and temporal effects of vegetation management alternatives on late successional habitat in the Pacific Northwest. In: Crookston, Nicholas L.; Havis, Robert N., comps. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 69–77.

McHugh, Charles W.; Kolb, Thomas E.; Wilson, Jill L. 2003. Bark beetle attacks on ponderosa pine following fire in northern Arizona. Environmental Entomology. 32(3):510–522.

Meehl, G.A.; Stocker, T.F.; Collins, W.D.; Friedlingstein, P.; Gaye, A.T.; Gregory, J.M.; Kitoh, A.; Knutti, R.; Murphy, J.M.; Noda, A.; Raper, S.C.B.; Watterson, I.G.; Weaver, A.J.; Zhao, Z.-C. 2007. Global climate projections. In: Solomon, S.; Qin, D.; Manning, M.; Chen, Z.; Marquis, M.; Averyt, K.B.; Tignor, M.; Miller, H.L., eds. Climate change 2007: The physical science basis. contribution of Working Group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: Cambridge University Press: 747–846.

Mielke, James L. 1950. Rate of deterioration of beetle-killed Engelmann spruce. Journal of Forestry. 48:882–888.

Page, Wesley G.; Jenkins, Michael J.; Elizabeth G. Hebertson. 2006. Mountain pine beetle-induced changes in lodgepole pine fuel complexes. Online: http://fhm.fs.fed.us/posters/posters06/mountain_pinebeetle.pdf [Last accessed May 2007]

Reinhardt, E.; Crookston, N.L. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. Fort. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Ryan, Kevin C.; Amman, Gene D. 1996. Bark beetle activity and delayed tree mortality in the Greater Yellowstone Area following the 1988 fires. In: Greenlee, J., ed. Ecological implications of fire in Greater Yellowstone. International Association of Wildland Fire, Fairfield, WA.: 151–158.

Safranyik, Les; Linton, Douglas A.; Shore, Terry L.; Hawkes; Brad C. 2001. The effects of prescribed burning on mountain pine beetle in lodgepole pine. Information Report BC-X-391. Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre. 16 p.

Sieg, Carolyn Hull; McMillin, Joel D.; Fowler, James F.; Allen, Kurt K.; Negron, Jose F.; Wadleigh, Linda L.; Anhold, John A.; Gibson, Ken E. 2006. Best predictors for postfire mortality of ponderosa pine trees in the Intermountain West. Forest Science. 52(6):718–728.

Smith, E.L.; McMahan, A.J.; Eager, T. 2002. Landscape analysis application of the Westwide Pine Beetle FVS extension. In: Crookston, Nicholas L.; Havis, Robert N., comps. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P- 25. Ogden UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 62–67.

Smith, E.L.; McMahan, A.J.; David, L.; Beukema, S.J.; Robinson, D.C. 2005. Westwide Pine Beetle Model Version 2.0: Detailed Description. FHTET 05-06. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Protection, Forest Health Technology Enterprise Team. 101 p.

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management. 1994. Record of decision for amendments to Forest Service and Bureau of Land Management planning departments within the range of the northern spotted owl. Standards and guidelines for management of habitat for late successional and old-growth forest related species within the range of the northern spotted owl. USDA Forest Service, USDI, BLM. April 13, 1994. ROD.

U.S. Department of Agriculture, Forest Service. January 2007. Draft Environmental Impact Statement. Five Buttes Project, Crescent Ranger District, Deschutes National Forest, Deschutes County, Oregon.

Wallin, Kimberly F.; Kolb, Thomas E.; Skov, Kjerstin R.; Wagner, Michael R. 2003. Effects of crown scorch on ponderosa pine resistance to bark beetles in northern Arizona. Environmental Entomology. 32(3):652–661.

Endnotes

1 Our choice of year 2000 to be our beginning-of-simulation year is based on the vintage of the inventory data. Readers should not construe our choice of simulation years to directly correspond to actual years. For example, we simulate that the Davis fire, which occurred in 2003, has already happened in simulation year 2000.

2 Without WWPBM sanitation cuts, BKP in beetle-killed trees would remain in thinned stands, because dead trees are not eligible to be removed via base-FVS thinning keywords. Because actual thinning activities would likely remove at least some beetle-killed trees, we imposed sanitation cuts if stands were thinned. Our sanitation cuts required a minimum sanitation removal volume of 10 cubic feet per acre (in trees greater than or equal to 6 inches DBH), and had a 90 percent removal efficiency. We also ran two additional simulations: a TRT+B *without* sanitation run and a NoTRT+B *with* sanitation, so that we could analyze the effects of the sanitation cut alone. Results from these additional scenarios are not presented here. Note that removal of dead trees via base-FVS keyword SALVAGE will not remove BKP.

3 In this context, "significant" amounts of host means that the stand: (a) had greater than 50 square feet of basal area per acre of host trees *and* greater than 100 square feet per acre of total basal area, if the stand was class as a "mixed conifer" PAG; *or* (b) was not a mixed conifer PAG but met the above criteria *and* had (i) greater than 100 trees per acre in lodgepole pine greater than nine inches DBH *or* (ii) greater than 50 percent of total basal area was composed of host and greater than 50 percent of the host was ponderosa pine.

4 This statement deserves elaboration, because it may seem counter-intuitive or inaccurate to those who understand the attractiveness algorithms built into the WWPBM. This statement is true given that the two stands in question have the same attractiveness scores. Because attractiveness decreases exponentially as distance between "source" and "target" stands increases, a stand farther away must have much more (and/or larger) host than a nearby stand for their attractiveness scores to be equal. But because the BKP survivorship function is independent of the distance over which BKP is allocated, two "target" stands having equal attractiveness scores (relative to the "source" stand) will receive the same amount of BKP regardless of the distance between the source and each of the target stands. Thus, while stand *attractiveness* is highly sensitive to distance between source and target stands, BKP "migration" (its dispersal, once allocated) is uniformly "efficient."

5 Under its current structure, the WWPBM recognizes fire effects only from fires simulated within its own fire subroutines. Currently, the WWPBM does not recognize fires simulated by the FFE.

6 PPE keyword AREALOCS invokes reading of supplemental records containing stand spatial information: x- and y-coordinates of stand centroids and stand area.

7 FLAMMAP is a fire behavior mapping and analysis program that simulates potential fire behavior characteristics (spread rate, flame length, fireline intensity, etc.) over a landscape.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Forest Disturbance: Insect and Disease

Western Root Disease Model Simulation Versus Plot Remeasurement: 11 Years of Change in Stand Structure and Density Induced by Armillaria Root Disease in Central Oregon

Helen M. Maffei[1]
Gregory M. Filip[2]
Kristen L. Chadwick[1]
Lance David[3]

Abstract—The purpose of this analysis was to use long term permanent plots to evaluate the short-term predictive capability of the Western Root Disease Model extension (WRDM) of the Forest Vegetation Simulator (FVS) in central Oregon mixed-conifer forests in project planning situations. Measured (1991–2002) structure and density changes on a 100-acre unmanaged area in south-central Oregon were compared to those predicted by the Southern-Oregon Northern-California variant (SORNEC) of FVS and the WRDM. Within the study area there were 149 variable-radius plots within 12 stands. Predictions were assessed using five variables that were collectively chosen to represent changes in stand density, stand structure, and are commonly used in project planning. For each indicator variable, projections were made using SORNEC alone and then with the WRDM. Projections were made at both the stand and plot level.

Where Armillaria root disease was present, the WRDM better predicted root disease impact than projections using SORNEC alone. Plot projections with the WRDM reduced the unexplained variation an average of 35% over projections made with SORNEC alone. Root disease impacts were generally overestimated using the WRDM as compared to measured changes. The correlations between the predictions and what was measured were much higher and always significant ($p \leq .0.05$) using plots and usually not significant using stands. The level of effort needed to parameterize and troubleshoot the WRDM creates significant barriers to its use as a project planning tool. Improvements that could reduce these barriers and thus, make the WRDM more attractive to project planners would be to provide users with a set of key parameters that are calibrated, offer full automation of the post-run data summaries, and make the root disease distribution and spread more transparent.

Introduction

Armillaria root disease, caused by the pathogen *Armillaria ostoyae*, is common in the mixed-conifer forests throughout western North America and central Oregon. Inventory plot data indicates that it occurs on approximately 25% of the overall acres of mixed-conifer forests in central Oregon (Simpson 2007). Mortality from this disease creates significant gaps in the forest and can change forest successional pathways in affected areas (Fields 2004; Filip and others, in preparation; Shaw and Kile 1991). Additionally, this disease may limit the effectiveness of proposed treatments, reduce productivity, increase susceptibility to bark beetles and other pests, and limit the number of suitable management options (Williams and others 1986).

The Western Root Disease Model (WRDM) extension of the Forest Vegetation Simulator (FVS) was designed to simulate the impact of Armillaria root disease and other root diseases at the stand- or inventory plot-level over time (Frankel and others 1998). The WRDM has been used in several environmental assessments and project planning efforts in central Oregon where root disease is an important disturbance agent. FVS and the WRDM were used to calibrate yield predictions in the mixed-conifer forests for the Deschutes National Forest Land and Resource Management Plan (USDA Forest Service 1990). FVS and the WRDM were also used to analyze how the presence of root disease would affect hazardous fuel accumulation and the development and retention of key structural elements of the Northern Spotted Owl (*Strix occidentalis* var. *caurina*) habitat under

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Plant Pathologists, USDA Forest Service, Forest Health Protection, Region 6, Bend, OR; e-mail: hmaffei@fs.fed.us; klchadwick@fs.fed.us.

[2] Plant Pathologist, USDA Forest Service, Forest Health Protection, Region 6, Portland, OR; e-mail: gmfilip@fs.fed.us.

[3] Systems Analyst, Information Technology eXperts, contracted to USDA Forest Service, Forest Health Technology, Enterprise Team, Fort Collins, CO.

various proposed management scenarios in a late successional reserve on Sisters Ranger District, Deschutes National Forest (Maffei and Tandy 2002). Results from this analysis played an important role in the successful outcome of a legal challenge of the project.

Few analyses have been conducted that evaluate the accuracy of the WRDM predictions using long-term permanent plots and none of these have been located in central Oregon. The most comprehensive comparison has been conducted by Frankel and others (1998) in the mixed-conifer forests of the Stanislaus and Eldorado National Forests in California. They compared predicted changes in stand density (trees per acre and basal area per acre) and mortality (trees per acre and volume per acre) over 13 years to actual measured changes for 26 permanent 0.1-acre fixed-area plots. Comparisons were made using the base FVS model alone and the base FVS model plus the S-type annosus-model subroutines in the WRDM. Frankel and others (1998) found that predictions using the root disease model, on average, corresponded well to the measured values while the base model significantly underestimated the impacts of annosus. Further, initializing root disease from the damage codes resulted in better predictions than initializing using the keyword RRINT. However, correlation coefficients between the measured and predicted plot values were significant but not strongly correlated. They found the Pearson product-moment correlation (r) between the predicted change in basal area and what was measured was r = 0.59 when the root disease model was initialized with the RRTREIN keyword and a correlation of r = 0.14 when the base model was used alone (calculated from results table in Frankel and others 1998). Frankel and others (1998) speculate that this difference could be explained by “the small plot size [which] made the model simulations more variable; one tree killed or not killed on a plot is a high percentage of the volume of a very small plot.”

WRDM Overview

The WRDM provides a dynamic representation of the spatial epidemiology of three types of root diseases: laminated root rot caused by *Phellinus weirii,* annosus root disease caused by *Heterobasidion annosum*, and Armillaria root disease. It is a conceptual spatial model based on a simplified characterization of root disease epidemiology including: the geometry of its spread, root colonization, and impact on susceptible trees. The root disease center is assumed to expand or contract at its perimeter. Root disease spread is modeled based on the assumption that the distribution of root disease in a stand can be characterized as a number of circular root disease centers, each containing both infected and uninfected trees. Host trees become infected within a center when their roots contact the infected portion of the roots of live- or dead-infected trees. Infection spreads at a constant rate throughout the tree’s root system until enough of the root system is infected to kill the tree (assumed default 10%). The root system is also represented as circular. After tree death the model tracks and decays the inoculum level of the dead root system. Everything else being equal, the larger the root system, the longer the inoculum remains.

Critical information when running the root disease model includes:

1. The type of root disease. Only one type may be selected since the WRDM does not simulate multiple root diseases at the same time.
2. The proportion of the plot/stand area in acres to be modeled as being inside the root disease center(s). This must be specified by the user as the model does not infer it.
3. The density of infected trees if the area is to be modeled as one center. This can be either be parameterized by the user or read from damage codes in the tree list file.

Unless damage codes from the tree list file are processed, the model randomly assigns infection to trees within the root disease center. The model also defaults to 25% of the stand area in root disease centers, unless the user defines the proportion of area infected. Stump and dead tree information can be provided to further define the disease simulation environment. However, this additional information is not collected as part of the standard stand exam inventory procedures.

Predicted impacts vary depending on how initial conditions are defined in the model. Sensitivity analysis of the WRDM by a number of investigators (Goheen and Thompson 1998; Marsden 1992a,b; Smith and Zhang 1997) provides the following guidance on critical sensitive variables during model initialization and calibration:

- The model is most sensitive to the type of root disease simulated.
- The size or proportion of the area inside root disease centers has a very significant effect on model results. In general, the greater the area inside the root disease centers, the greater the impact the root disease will have.
- In the WRDM, root disease centers are randomly placed within a stand unless coordinates are provided.
- When root disease occurs in numerous small centers or when the edges of centers are not readily discernible on the ground, the stand should be modeled as one disease center.
- Accuracy of the model run will be further improved if individual tree information regarding root disease infection and severity are obtained in the field and included (via keyword RRTREIN) in the run.
- At least 20 runs with 20 different random seeds (keyword RSEED) should be used for each projection to achieve +/– 4% of the "true" average. Changing some keywords can change the random variates throughout the model, so some variation exists when using the same seed, but different keywords.

The purpose of this analysis was to use local permanent plots in order to evaluate the short-term predictive capability of the WRDM in project planning situations. We evaluated this question by addressing the following questions:

- How accurately does the WRDM predict 11-year changes in stand structure and density compared to measured data when data normally available to project managers are used?
- Does the WRDM allow for better comparisons of alternatives compared to using SORNEC alone?
- How easy is the WRDM to use?
- How easy is managing and interpreting WRDM output?

Methods

Study Area

The data used for this analysis came from a 100-acre unmanaged administrative study area. This area was part of a larger (200-acre) administrative study designed to evaluate and compare silvicultural treatment systems with no management (Filip and others 1995, in preparation). In the portion of the study area being modeled in this analysis, planned treatments were not implemented due to wildlife and recreation restrictions. The study area is about 25 miles NW of Klamath Falls, OR, USA and encompasses some of the most productive sites for white fir (*Abies concolor*), Shasta red fir (*A. magnifica* var. *shastensis*), Douglas-fir (*Pseudotsuga menziesii* var *menziesii*), and ponderosa pine (*Pinus ponderosa*) in south-central Oregon. Elevation ranges from 4,900 to 5,300 ft with an E aspect and 15 to 35% slope. Site index at 50 yr ranges from 65 to 90 for white fir and 59 to 93 for Douglas-fir (Cochran 1979). The plant association is white fir/chinquapin (*Castanopsis chrysophylla*)-boxwood (*Pachistma myrsinites*)-prince's pine (*Chimaphila umbellata*) at the lower slopes and Shasta red fir-white fir/chinquapin-prince's pine/long-stolon sedge (*Carex pensylvanica*) at the upper elevation (Hopkins 1979).

The entire study area is infected with *Armillaria ostoyae* with mortality patches abundant and varying in size from a few scattered trees to several acres (fig. 1). Healthy-appearing groups of trees occur among the mortality patches. The species of *Armillaria* causing mortality has been identified as *A. ostoyae* (NABS I) as determined by genetic testing (Reaves and McWilliams 1991).

The study area encompassed 12 stands (average = 13.8 ac., range = 9-20 ac.) and 147 variable-radius plots. The variable-radius plots were established in 1991 using a 40 BAF and remeasured in 2002. Individual tree measurements included dbh, live crown ratio, and tree condition and were collected according to Pacific Northwest Region stand exam procedures (USDA Forest Service 1991). Trees under 5.0 in. dbh were recorded on a fixed 1/100th acre plot. Plots were remeasured in 2002 for tree dbh and condition. Each plot was also given a root disease severity rating (RDSR) in 1991 (Hagle 1985), which was based on a visual above-ground estimation of the level of canopy reduction caused by root disease. The higher the RDSR, the more severe the impacts of root disease on the

Figure 1—Typical Armillaria root disease center in the study area.

canopy cover of a plot. Thirty-two of the plots had no detectable root disease (RDSR = 0) while the remaining 115 plots had light to severe root disease (RDSR = 1–9) (table1). The percentage of stand area with visible root disease ranged from 14 to 100%, as determined based on the number of plots with RDSR >0. The average plot root disease severity rating was 3.

WRDM Calibration

We were interested in testing the predictive capability of the WRDM when it was parameterized using only data likely to be available to project planners. The WRDM was, therefore, initialized using the standard stand examination data (as described above) we collected in the study, and where necessary, developing initialization logic that could

Table 1—Initial distribution of Armillaria root disease incidence and severity for 147 variable radius plots and 12 stand.

Stand	Root Disease Severity Rating[a]				
	0	2	3-4	5-6	7-9
816	6	7	0	0	0
817	3	7	2	0	1
818	0	2	2	7	2
819	1	2	0	2	2
820	0	3	5	0	1
821	1	4	4	1	0
822	5	6	2	1	2
823	3	10	0	4	2
824	5	8	0	0	0
825	6	8	2	0	0
826	1	5	2	1	0
827	2	2	3	0	2
Total	**33**	**64**	**22**	**16**	**12**

[a]Root Disease Severity Rating (Hagle 1985); higher numbers denote more impact of root disease on the plot.

be fully deduced from the stand exams. No additional stem maps or root disease center maps were provided for the simulations. Using these inferences we parameterized individual plots and stands only when we thought the process could be automated. This was because it is highly unlikely project planners are going to perform hand calibration on the large numbers of stands and plots that are typically modeled in project planning. The keywords and settings we used to initialize and calibrate the WRDM are as follows (Marsden 1992a,b; Smith and Zhang 1997):

- *Armillaria* root disease was identified as the root disease type (keyword RRTYPE = 3)
- The root disease in the stand or plot was assumed to occur as one center since the edges of the centers in the study area were not readily discernible on the ground (typical of root disease centers in mixed-conifer forests in central Oregon).
- For individual variable-radius plot projections, the total size of the area to be modeled was approximated as 1 acre (keyword SAREA).
- For stand projections, the total size of the area to be modeled was approximated as a constant 15 acres (keyword SAREA = 15) to more adequately describe the study units compared to the default of 100 acres.
- For projections, the acres in root disease (keyword RRINT) were assumed to be the stand size (15 acres) multiplied by the proportion of variable-radius plots in the stand where *Armillaria* root disease occurred (RDSR >1). Thus, if half of the plots had a RDSR >1, the area in root disease was set at 7.5 acres compared to the WRDM default of 25%. Thus, the stand acres in root disease were, on average, 7.5 acres in size with a range from 2–15 acres. Since projections are sensitive to the acres in root disease in a stand and there was variation in the incidence of root disease between stands, this adjustment to the default was preferable to setting it to a constant for all stands (e.g., 15 acres).
- For plot level projections, variable-radius plot were assumed to be a single root disease center (keyword RRINT) except when there was no measured root disease on the plot (RDSR = 0 or 1). On plots with RDSR = 0 or 1, some root disease was assumed to occur within the modeled area because root disease was widespread throughout the rest of the stand. Since there was no electronically accessible information (the usual situation for vegetation management projects) with respect to the relative location of infected plots to uninfected plots, the default value of 25% was used.
- The density of infected trees was estimated from the damage codes on individual measured trees (keyword RRTREIN).
- The model was run with default values for bark beetles since preferential bark beetle activity was observed inside the root disease centers.

Model Runs and Post Run Processing

Simulations were made using the Southern Oregon Northern California (SORNEC) version of base FVS along with version 3.1 of the WRDM. Twenty runs were made for each projection (including those that were made using the base model only). In each of these projections only the random seed was changed (keyword RSEED). Outputs from the 20 projections were then averaged in a spreadsheet. Measured data were also summarized in SORNEC so that the algorithms used to compute canopy cover for the measured data would be identical to those computed by the projections. The average 11-year change (measured and predicted) was then calculated for each indicator variable and exported to the SPSS statistical software program for further analysis.

Analysis

Wildlife habitat is a crucial management concern in mixed-conifer forest types on the eastern slopes of the Cascades. Usually, mixed-conifer forests east of the Cascade crest are under the jurisdiction of the Northwest Forest Plan (Thomas and others 1990). Therefore, we evaluated the predictive capability of the model with variables that are useful for demonstrating the effect of root disease in late successional habitat, as well as displaying changes in risk of this habitat to insects, diseases, and wildfire. Because the stands are primarily white fir, variables that collectively represent stand structure and density were chosen as most important and designated as evaluation variables. The indicator variables are calculated as FVS event monitor custom variables from the plot measurements (year 1991 and 2002) and 11-year projections of the 1991 measurements. Indicator variables are as follows:

1. Total canopy cover[2] (TOT) (dbh ≥ 5.0 in.; proportion of total % cc, x = 55, min = 38, max = 81).
2. Canopy cover of pole-size trees (PT) (dbh 5.0–8.9 in.; proportion of total % cc, x = 14 min =0, max = 30).
3. Canopy cover of medium-size trees (MT) (dbh 9.0–20.9 in. proportion of total % cc, x = 49, min = 31, max = 64).
4. Canopy cover of large-size trees (LT) (dbh 21.0 ≥ in.; proportion of total % cc, x = 31 min = 11 max = 52).
5. Stand basal area (ba/acre).
6. Total trees per acre (tpa) ≥5.0 in. dbh.

These diameter class groupings and a fifth grouping consisting of small trees <5.0 in. dbh, are routinely used to describe forest structure and density. Combined with species composition, site productivity, and other factors, they form the building blocks of the assessment process. The process has been adopted and is currently being used to evaluate forest ecosystem health, viable wildlife habitat, and to identify hazardous conditions caused by various disturbance agents. Changes in these variables also indirectly represent changes in other variables of interest including: stand basal area, wood fiber volume, and fuel loads.

For each of the size class groups, 11-year projections (with SORNEC and SORNEC + WRDM) were compared with the measured results and performed in the following formats:

1. Individual inventory plots as the primary modeling unit.
2. Stands as the primary modeling unit.
3. Plots grouped by RDSR measured in 1991

The performance of the model as a predictor of the impact of Armillaria root disease on forest structure and density was based on assessment of both the accuracy and the precision of the WRDM projections of the predictor variables and was based on the following analyses:

1. *The accuracy of the WRDM was assessed in terms of the significance and strength of the positive correlation between the predicted- and the measured-changes for the indicator variables*. The model was considered to have performed well if these correlations were significant, positive, and at least moderate in strength ($r > 0.40$). Pearson's product-moment correlation (r) was used to designate the simple correlation between the measured and predicted variables. The significance of the correlation was tested at the 0.05 level. Correlations would not be expected to be much higher than SORNEC projections for structural components less affected by root disease.
2. *The accuracy of WRDM predictions was based on whether the average value of the predictions is significantly different from the measured value ($p < 0.05$).* As with the correlation coefficients analysis, accuracy would be expected to increase when the WRDM is used, especially for structural components most severely impacted by root disease. A paired sample t-test was used to compare the mean projected value of the indicator variables using the WRDM with the measured values and with projections using SORNEC alone.
3 *The WRDM correctly predicts the impact on structure*. Weighting the strength of the correlation of all the indicator variables equally may not be an appropriate assessment of model performance. Alternatively, it is desirable that WRDM predictions are assigned relative to the amount of potential root disease impact that each structural element within the stand is likely to incur. The greatest positive impact on the correlation coefficient (r) (between the projected and measured

[2] Canopy cover was calculated from algorithms in FVS (SORNEC) for both measured and projected plots.

data), when the WRMD is used over SORNEC alone, is expected to occur in the pole- and mid-sized class structural groups because they are assumed to be more severely impacted by root disease than larger trees (Fields 2004). The assumption that different structural groups will experience different levels of impacts from Armillaria root disease in our study is further supported by the negative significant (at the 0.05 level) correlation between RDSR in the pole and medium sized tree and RDSR together with the lack of a significant correlation for the large tree structure class (fig. 2) in the 1991 data.

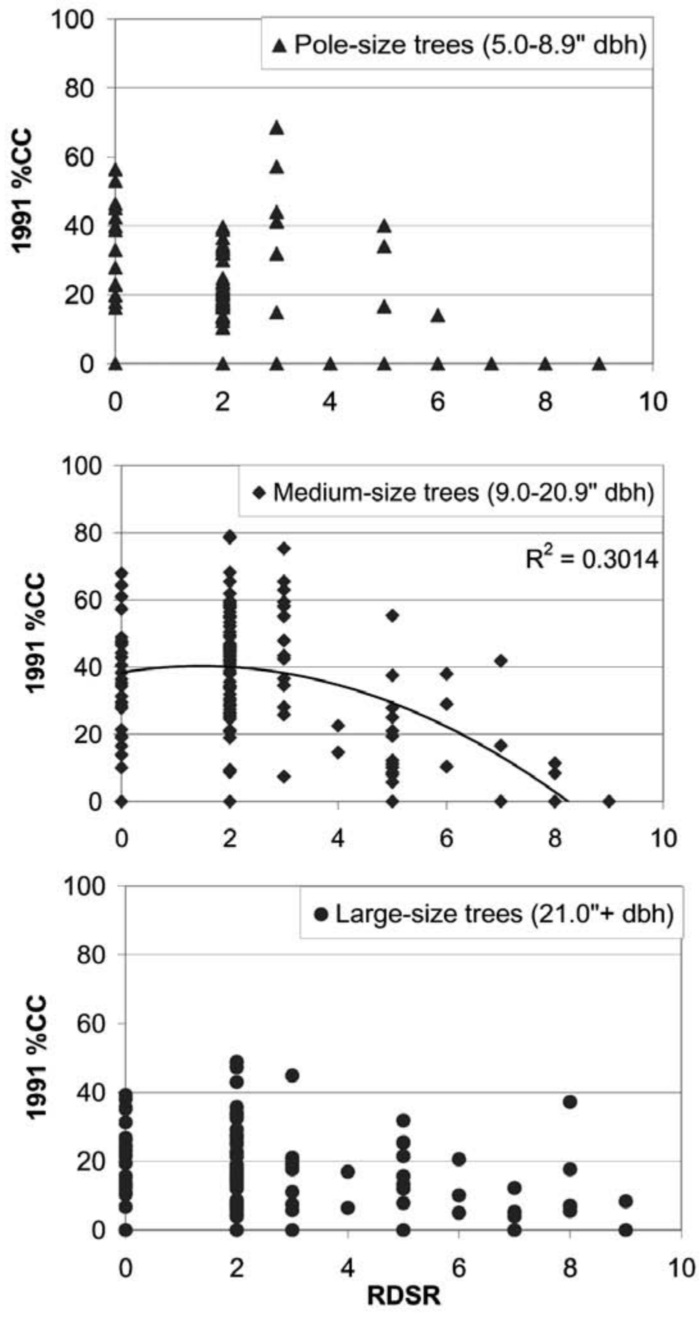


Figure 2—Measured relationship between percent canopy cover and plot root disease severity ratings (RDSR) for the pole sized tree structural class (5.0–8.9” dbh), the medium-sized tree structural class (9.0–20.9” dbh), and the large tree structural class (≥21.0 dbh) in 1991.

Table 2—Averaged 11-year measured changes in % canopy cover and basal area compared with predicted changes (using both variable radius plots and stands as the projection unit) SORNEC alone, and then with the addition of the WRDM. (n = 147 for plot level data; n = 12 for stand level data; TOT = all trees; LT = large trees; MT = medium-size trees; PT = pole-size trees; and BA = basal area ft^2/ac. * indicates that the projection is significantly different from the measured value.)

Size class	Average measured values		Average 11-year change	Projection models[a]	
Projected by plot	**1991**	**2002**	**MEASURED**	**SORNEC**	**WRDM**
Canopy cover by:					
TOT (dbh > 5”)	53	40	–13	–4*	–28*
LT (dbh > 21”)	14	14	0	3*	–6*
MT (9”< dbh <21”)	37	24	–13	–6*	–22*
PT (5”< dbh <9”)	13	8	–5	–2*	–7*
BA (dbh > 5”)	270	200	–70	–18*	–153*
Projected by stand					
Canopy cover by:					
TOT (dbh > 5”)	53	40	–14	–3*	–23*
LT (dbh > 21”)	14	14	0	3*	–3
MT (9”< dbh <21”)	37	24	–14	5*	–18
PT (5”< dbh <9”)	13	8	–5	–3*	–8*
BA (dbh > 5”)	270	200	–72	–10*	–122*

[a] 11-year projections are averages of the 20 runs where only the random seed was changed (keyword RSEED).

Results

On average, root disease caused a decline in stand density as well as caused significant changes in stand structure. Average decline in canopy cover at the plot-level over the 11 year measurement period were 13, 0, 13, and 5%, for TOT (≥5.0 in. dbh), LT (large-size trees ≥21.0 in. dbh), MT (medium-size trees 9.0–20.9 in. dbh), and PT (pole-size trees 5.0–8.9 in. dbh), respectively (table 2). Average decline in basal area was 70 ft^2/ac. The largest proportional decline in the total canopy cover (38%) occurred in MT and PT size classes while the least occurred in the LT size class (0%) (table 2). Irregardless of initial RDSR, the presence of root disease increased the variability in 11 year changes in the indicator variables over what would have been predicted by SORNEC alone. The WRDM projections appeared to reflect this variability (fig. 3).

Precision of WRDM

Projections using WRDM were generally more highly correlated with the measured changes than predictions using SORNEC alone (table 3) though none of the correlations could be considered strong. The strength of the correlation between WRDM predictions and measured changes depended on the primary modeling unit (stand or plot) as well as the size-class group. Plot-level predictions of 11-year changes of the 5 variables representing changes in stand density and structure tended to be more highly correlated with the measured data than the stand level predictions. For example, the average reduction in the unexplained variance was 0.49 and 0.34 for the plot and stand projections, respectively and the one to one correlations between WRDM predicted and measured 11-year change was significant (at the 0.05 level) for all predicted variables at the plot level but for only three variables at the stand level (table 3). On average, plot predictions with the WRDM reduced the unexplained variation by an additional 35% over predictions made with SORNEC alone (table 3). For the plot predictions using the WRDM, Pearson correlation coefficients ranged from r = 0.41 to r = 0.69 with significant, but not strong, one-to-one

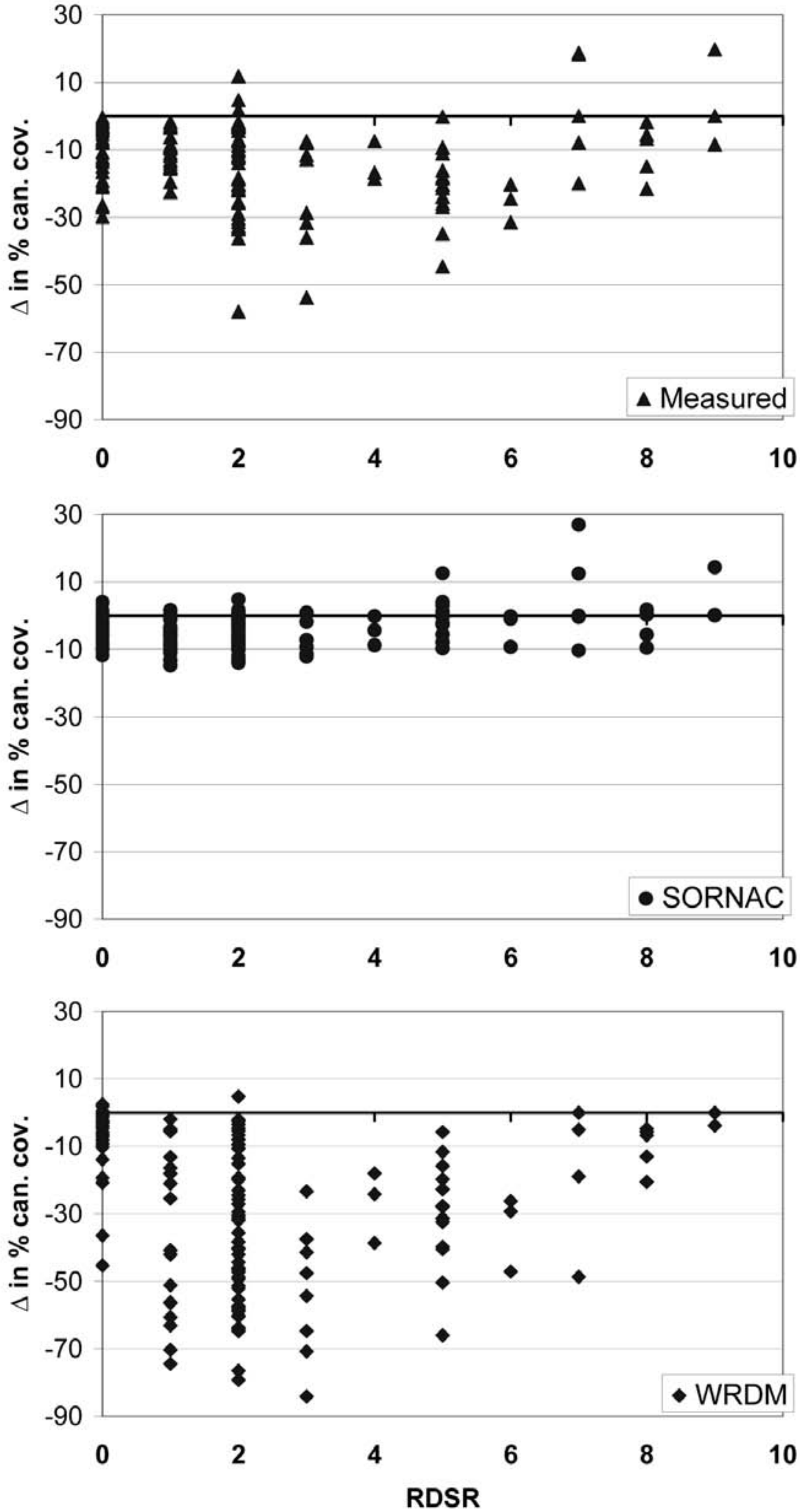


Figure 3—Comparisons of 11-year change in % canopy cover by root disease severity rating (RDSR) for 147 variable radius plots: (1) Measured, (2) SORNEC predictions, and (3) SORNEC + WRDM predictions.

Table 3—Comparison of the positive correlation[a] between 11-year measured and predicted[b] changes in variables representing stand structure and density using SORNEC (base FVS) only, and then adding Western Root Disease Model Extension (WRDM). Both variable-radius plots and stands were used as the projection unit. (Correlations that are significant are in bold. Correlations are significant at the 0.05 level. n = 116 for plot level data; n = 12 for stand level data; plot data are for RDSR > 0; TOT = all trees; LT = large trees; MT = medium-size trees; and PT = pole-size trees.

Size-class group	Projection models SORNEC	SORNEC + WRDM
Projected by plot	**Pearson's correlations**	
Canopy cover by:		
TOT (> 5" dbh)	**0.27**	**0.41**
LT (> 21" dbh)	**0.55**	**0.51**
MT (9–21" dbh)	**0.27**	**0.42**
PT (5–9" dbh)	**0.50**	**0.69**
BA (basal area ft^2/ac)	NS	**0.43**
Projected by stand		
Canopy cover by:		
TOT (> 5" dbh)	0.00	0.21
LT (> 21" dbh)	0.30	**0.74**
MT (9–21" dbh)	–0.84	–0.04
PT (5–9" dbh)	–0.94	0.49
BA (basal area ft^2/ac)	–0.14	0.27

[a] Positive correlations represent the precision of the predictions.
[b] 11-year projections used for correlations are averages of the 20 runs where only the random seed was changed (keyword RSEED).

correspondence between what was predicted and what was measured on individual plots. For infected plots, the initial RDSR appeared to have little, if any, relationship to the correlation between the predicted and measured values indicating a lack of bias. There was no correlation (r = 0) between the predicted and measured change for plots with no initial root disease (RDSR = 0) (measured) for any of the indicator variables.

Accuracy of WRDM Projections

WRDM projections at both the stand and plot level did not meet our criteria as an accurate predictor of 11-year change except in the case of stand projections using the LT and PT structure class variables. Overall, the WRDM tended to over predict the impact of Armillaria root disease while SORNEC did not predict any impact. Paired t-test results were all significant (two-sided p-value <0.05) for comparisons at the plot-level across all size classes for both measured data vs. SORNEC projections and measured data vs. WRDM projections (table 2). At the stand level, paired t-test results were insignificant for the PT and MT (p = 0.123 and 0.159 respectively) size classes, indicating that the WRDM is accurately predicting canopy cover changes in these size classes at the stand level (table 3). Thus, for stands, WRDM projections were acceptably accurate, for the LT and MT size classes; i.e. those most severely impacted by root disease (table 2).

Impact on Stand Structure—WRDM projections were better predictors of the measured 11 year changes in stand structure than projections with SORNEC alone. For size classes (medium (MT) and Pole (PT)) most severely impacted by root disease, the addition of the WRDM decreased the unexplained variation by an average of 32% (table 3). In general, correlations with the measured data were much stronger with WRMD projections than projections with SORNEC alone. The exception to this was seen in the large Tree (LT) structural class where there was no improvement in the correlation (r) (table 3).

Discussion

The use of WRDM simulates changes in stand structure and density better when Armillaria is present, than the use of FVS alone. The WRDM is a more precise and more accurate predictor of the impacts of Armillaria root disease on stand structure and density, especially for variables that represent the structural classes most impacted by the disease. Even when correlations were not significant at the stand level, the addition of the WRDM resulted in trends in the right direction while use of SORNEC drove the projections in the wrong direction in many cases. Given the choice of using the WRDM or SORNEC without the WRDM, we therefore conclude that using the WRDM is preferable in projects where Armillaria root disease is an important management consideration.

While correlation coefficients were similar to the results by Frankel and others (1998), the precision of the projections, on average, is much lower. The lower accuracy in our study could potentially be caused by number of factors including: (1) different inventory methods (fixed plots vs. variable radius plots; plot center located in the middle of the root disease center vs. plot center located on a grid); (2) different root disease (annosus root disease vs. Armillaria root disease); and (3) random chance. The lower precision when projections were made at the stand level vs. projections at the plot level was puzzling since we would have expected the opposite. We hypothesize that the cause might be that the smaller plot sizes impose limitations on variability in the placement of root disease centers as well as the location of infected trees relative to susceptible non-infected trees. Limited variability in these spatial elements might limit potential variability in spread rates.

Although we believe it is preferable to use the WRDM in situations where root disease is an important factor, a number of characteristics are a significant deterrent to its use for routine project planning:

1. *The level of technical expertise required to properly initialize, run the model, and interpret the output is very high*. The WRDM models the process of spread and mortality by individually simulating the many sub-processes thought to be involved. These many processes are governed by numerous random variates and parameters, many of which the user (even those who are advanced) have no way to measure or validate. In addition to the complex parameterization requirements, a fairly extensive knowledge of how the model works is necessary (for example the importance of changing the random seed).
2. *The WRDM is difficult to troubleshoot*. Identifying areas where functions in the model could be better parameterized or improved is difficult because the user cannot see the distribution of centers, infected trees, and spread scenario for an individual run
3. *The predictive capability of the WRDM predictions is disappointing given the model's complexity, especially with respect to the level of precision attained with stand projections and the level of accuracy attained with plot projections*. While the WRDM generally did a better job than SORNEC alone, the performance of the model was not outstanding over the timeframe we evaluated. Whether it is even possible (given the high natural variation in the field and limited available spatial data) to modify the model to achieve consistently better performance remains a question.
4. *Data summarization outside of the model is required for the initialization process and the data output*. For example, we had to export and summarize the results of the 20 runs outside of FVS. While not an overwhelming task, it is another step where errors could occur.

The barriers to using the WRDM raise questions with regard to its routine use in project planning. Some of these include: Does the predictive capability of the WRDM justify the level of proficiency it takes to use it? If not, do we improve the existing model to the point at which it is both easier to run and achieves better predictions? Or, would a simpler model structure be preferable and better serve project planning needs? While providing answers, these questions are outside the scope of this paper, we suggest that mitigated by the following:

1. *Provide users with a set of key parameters calibrated to the mixed-conifer forest communities in central Oregon*. A sensitivity analysis (with this data set and others) may enable us to refine parameterization and better initialize the model for similar mixed-conifer forests in central Oregon. A set of keywords provided to

users specifically tailored to these forests would save time and reduce the amount of expertise required from the user to run the model.

2. *Fully automate post-run data summaries and key parts of the initialization process*. For example, since we know that multiple runs are required to achieve a good average prediction, the WRDM could be modified so that it automatically varies the random seed a set number of times and summarizes the average of all the projections so that the user does not have to perform these operations manually. The area in root disease could also be internally calculated based on the number of plots with root disease damage codes.
3. *Provide the user an option to make root disease distribution and spread transparent*. Perhaps a user-selected option could generate a simple map of the root disease centers and individual infected trees.

Acknowledgments

The authors thank the Forest Health Protection Pest Trend Impact Plot System (PTIPS) program for providing the funds for plot remeasurement, Eric Smith, Ph.D. for statistical guidance and review, Heather Huntley for field work, and the Klamath RD of the Winema NF for supporting this project.

References

Cochran, P.H. 1979. Gross yields for even-aged stands of Douglas-fir and white or grand fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-263. Bend OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Fields, K L. 2004. Impact of Armillaria and annosus root diseases on stand and canopy structure, species diversity, and down woody material in a central Oregon mixed-conifer forest. Corvallis, OR: Oregon State University. 166 p. Thesis.

Filip, G.; Maffei, H.; Torba, L; Jahns, P. 1995. Matching silvicultural treatments to root diseased sites on the Winema National Forest- preliminary report on treatment establishment and baseline data. Unpublished office report on file at U.S. Department of Agriculture, Forest Service, Forest Health Protection, Portland OR. 27p.

Filip, G.; Maffei, H.; Chadwick, K.L; Max, T.M; Torba, L. (In preparation). Matching silvicultural treatments to Armillaria root diseased sites in the Winema National Forest, Oregon:10-year results. Western Journal of Applied Forestry.

Frankel, S.J. 1998. User's guide to the Western Root Disease Model, Version 3.0. Gen. Tech. Rep. PSW-GTR-165. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 166 p.

Frankel, S.J.; Wilson, L.J.; Slaughter, G. 1998. A comparison between western root disease model predictions and real data. In: Frankel, S.J., ed. User's guide to the Western Root Disease Model, Version 3.0 Gen. Tech. Rep. PSW-GTR-165. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 131–138.

Goheen, E.M.; Thompson, M.K. 1998. Pointers for using the western root disease model. In: Frankel, S.J., ed. User's guide to the Western Root Disease Model, Version 3.0. Gen. Tech. Rep. PSW-GTR-165. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 89–98.

Hagle, S.K. 1985. Monitoring root disease mortality: establishment report. Report No. 85-27. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region. 13p.

Hopkins, W.E. 1979. Plant associations of South Chiloquin and Klamath Ranger Districts, Winema National Forest. R6-Ecol-79-005. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 96p.

Maffei, H.; Tandy, B. 2002. Methodology for modeling the spatial and temporal effects of vegetation management alternatives on late successional habitat in the Pacific Northwest. In: Crookston; N.L; Havis, R.N., comps. 2002. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO: Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 69–77.

Marsden, M.A. 1992a. Sensitivity of the Western Root Disease Model to user-specified starting parameters. Res. Pap. 306. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 20 p.

Marsden, M.A. 1992b. Sensitivity of the Western Root Disease Model: Inventory of root disease. Res. Pap. 303. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 6 p.

Reaves, J.L.; McWilliams, M. 1991. *In vitro* fruiting of *Armillaria* Species. Res. Note PNW-RN-505. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 7p.

Shaw, C.G., III; Kile G.A. 1991. Armillaria root disease. Agric. Handb. No. 691. Washington, DC: U.S. Department of Agriculture, Forest Service. 233 p.

Simpson, Michael L. 2007. Forested plant associations of the Oregon East Cascades. R6-NR-ECOL-TP-03-2007. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region.

Smith, E.L.; Zhang, S. 1997. Sensitivity analysis of insect and disease model extensions. In: Tech, R.; Moeur, M; Adams, J., comps. 1997 proceedings; Forest Vegetation Simulator conference; 1997 February 3–7; Fort Collins, CO. Gen Tech. Rep. INT-GTR-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 213–215.

Thomas, J.W.; Forsman, E.D.; Lint, J.B.; Meslow, E.C.: Noon, B.R.; Verner, J. 1990. A conservation strategy for the spotted owl. Washington, DC: U.S. Government Printing Office. 427 p.

U.S. Department of Agriculture, Forest Service 1990. Deschutes National Forest Land and Resource Management Plan. Bend, OR: U.S. Department of Agriculture, Pacific Northwest Region, Deschutes National Forest.

U.S. Department of Agriculture, Forest Service 1991. Field procedures guide Stand Examination Program. Bend, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region.

Williams, R.E.; Shaw C.G., III; Wargo, P.M.; Sites, W.H. 1986. Armillaria root disease. Forest Insect and Disease Leaflet 78. Washington, DC: U.S. Department of Agriculture, Forest Service. 8 p. Online: http:/na.fs.fed.us/spfo/pubs/fidls/Armillaria/armillaria.htm

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Comparison of FVS Projection of Oak Decline on the Mark Twain National Forest to Actual Growth and Mortality as Measured Over Three FIA Inventory Cycles

Don Vandendriesche[1]
Linda Haugen[2]

Abstract—Oak decline has been recorded on oak forests throughout the Ozark Plateau of Missouri since the 1970s, but severe drought in the late 1990s, combined with the advancing age of the Ozark forests, has intensified the levels of crown dieback and mortality beyond historical levels. The purpose of this project was to determine whether the Forest Vegetation Simulator (FVS) model could accurately predict the effect of oak decline on the Mark Twain National Forest (MTNF). Forest Inventory and Analysis (FIA) data were used to benchmark mortality magnitude and to adjust FVS growth projections. Data from inventory cycles 3 (1976–1977), 4 (1986–1987), and 5 (1999–2003) were available for approximately 150 oak stands on the MTNF. These data were translated into FVS-ready format and projected with and without the Oak Decline Event Monitor (ODEM) addfile. Actual growth and mortality versus projected values were compared. In the absence of harvesting or other major disturbance, baseline mortality per size class in a healthy forest is generally constant and departure from this constant may indicate unsustainable forest conditions. We compared current mortality rates to calculated mortality rates between inventory cycles 3 and 4 (i.e. prior to the latest decline events) to indicate whether mortality rates increased between inventory periods. This paper describes the FVS adjustments and methodology used; assesses the usefulness of FIA data and application of the ODEM addfile for this project; and discusses how FVS tools and comparison of baseline mortality rates could be used to predict future trends in Missouri oak forests.

The characteristics of the oak forests that dominate southern Missouri have been largely determined by human activities on the landscape. From 1870 to 1930, most of the natural shortleaf pine (*Pinus echinata* Mill.) and oak-pine woodlands were eliminated by extensive logging followed by annual burning and overgrazing. Around 1930, fire suppression and conservation efforts allowed trees, particularly oaks, to begin to reclaim the land. The resultant forested landscape is much different in composition and structure than the presettlement forest. Many of these stands have a similar time of origin and grow on degraded soils. By the end of the 1900s, a large proportion of the landscape was characterized by aging oak forests, which were predisposed to decline (Law and others 2004; Lawrence and others 2002).

Widespread crown dieback, growth reduction, and mortality in oak forests on the Ozark Plateau of Missouri were documented in the 1970s and 80s, particularly following periods of drought that incited decline (Law and Gott 1987). A severe drought from 1999–2001, combined with the advancing age of the Ozark forests, has intensified the spread and severity of oak decline and mortality (Starkey and others 2004). Although components of the oak decline complex have been present in the Ozark Region for decades, recent mortality has exceeded historic trends. With the unprecedented levels of mortality being observed, land managers in southern Missouri have many questions about the current and future conditions of oak stands affected by decline. The purpose of this project was to use Forest Inventory and Analysis (FIA) data and Forest Vegetation Simulator (FVS) projections to address some of those questions, particularly related to past and current mortality rates and anticipated future conditions.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forester, USDA Forest Service, Forest Management Service Center, Fort Collins, CO; e-mail: dvandendriesche@fs.fed.us.

[2] Plant Pathologist, USDA Forest Service, Northeastern Area State and Private Forestry, St. Paul, MN.

Data and Methods

Source of Data

In Missouri, the 3rd FIA periodic inventory was collected from 1969–1972. Subsequently, data for the Mark Twain National Forest (MTNF) was also gathered in 1976–1977. The 4th FIA periodic inventory cycle for Missouri was completed in 1989 with most of the data on the MTNF collected from 1986–1987. Both the 3rd and 4th inventory data were gathered in accordance with a 10-point sample design distributed over approximately an acre of ground around plot center (NCRS 1969, 1986). All trees 5.0 inches dbh and larger were tallied on a variable radius plot (37.5 basal area factor prism). Trees less than 5.0 inches dbh were tallied on a fixed radius plot (1/300 acre). In 1999, FIA began the 5th inventory cycle for Missouri with a new annualized survey design (NCRS 1999). Under this sampling scheme, four subplots 1/24 acre in size are used to measure trees 5 inches dbh and larger. A microplot 1/300 acre in size was co-located within the major plot, offset from plot center, to gather information on trees less than 5 inches dbh. For the annualized system, 1/5 of all FIA plots are visited each year so that a complete cycle is measured every 5 years.

We acquired FIA data for cycles 4 and 5 in FVS-ready format through the Internet using the Forest Inventory Mapmaker program (Miles 1992). Cycle 3 data was not readily available. It was obtained directly from the North Central Research Station FIA Unit and required subsequent effort to convert to FVS-ready format.

We considered the data from each inventory cycle as unique condition class samples. There were 911 'total' plots assembled and utilized for various aspects of the study. The data were used to: calibrate the FVS model; determine the biological maximums expected for stand density and tree size attainment; and construct regeneration input response files.

North Central FIA also provided a plot number "crosswalk" that enabled us to match center points of sample plots among the 3rd, 4th, and 5th FIA inventory cycles. We restricted our data scope to oak forests of the Mark Twain National Forest residing within the Ozark Plateau in south-central Missouri. This corresponds to forestlands in the Northwest Ozark, Southwest Ozark, and Eastern Ozark FIA Survey Units. Through this screening, we were able to identify 154 'common' plots on the MTNF that were remeasured in FIA cycles 3 (1976–1977), 4 (1986–1987), and 5 (1999–2003). After filtering to exclude disturbed plots, non-oak forest types, small diameter stands, and other anomalous plots (such as cycle 3 plots that were measured during 1969–1971), there were 100 'base' plots available for analysis. For each of these plots, we had field measurements from the same plot center for each of the three inventory cycles spanning a 25-year period.

Adjustments to FVS Base Model

A subset of FIA plots were used for FVS self-calibration procedures. Plots containing trees with repeat measurements of diameter provide an empirical basis to rescale the large-tree diameter increment models within FVS. These data were available from the cycle 3 and 4 periodic inventories. There were 557 'calibration' plots utilized for this purpose. The scaling values derived from these plots are listed in table 1. Given that repeat diameter measurements were not available for some species (e.g. eastern redcedar (*Juniperus virginiana* Lam.)), calibration scale factors were not computed.

Multipliers (i.e. ReadCorD keyword values) less than one indicate that the observed tree growth was less than that predicted by the Central States variant of FVS. Internal algorithms use the multipliers to adjust the predicted large-tree diameter growth to match the rates observed from the calibration data set.

Initially, we pursued comparative analysis based on merchantable tree volume. Soundness factors were needed to compute net volume from gross. This required an estimate of tree defect to be applied to gross tree dimensions. We consulted with the MTNF and other sources to develop an FVS "addfile" (i.e. an auxiliary keyword file) that applied defect deductions to enable determination of net cubic and board foot volume per acre. Upon further evaluation, we chose to display resultant basal area per acre estimates in this paper. We deduced that stand basal area better described overall stand structure.

It was important to set stand density bounds to limit FVS modeled projections to reflect actual growth capacity as exhibited by oak stands on the MTNF. Stocking charts

Table 1—Large-tree diameter growth. Calibration scale factors computed from cycle 3 and cycle 4 FIA data.

Tree species	Total tree records	Mean ReadCorD multiplier
Shortleaf Pine	417	0.511
Pignut Hickory	18	0.851
Black Hickory	10	0.669
Slippery Elm	10	0.566
White Oak	803	0.512
Red Oak	42	0.365
Black Oak	674	0.503
Scarlet Oak	316	0.445
Blackjack Oak	39	0.585
Post Oak	222	0.620
Misc. Hardwood	62	0.499

can be utilized in consort with a growth and yield model such as FVS to display management regimes (Puuri and others 1986). The biological relationship to the average maximum density (AMD) or the effects of density on growth is evident. The upland central hardwoods stocking chart, introduced by Gingrich (1967), has become one the forest manager's most useful tools. The "A" line on the chart was developed from stands of average maximum density, and the "B" line was developed from open-grown trees. The upper extent of the Gingrich chart defines overly dense conditions at 110 stocking percent. Stocking relates the area occupied by an individual tree to the area occupied by a tree of the same size growing in a fully stocked stand of like trees. Visual inspection of the Gingrich chart indicates an approximate basal area maximum of 140 ft^2/acre for larger average diameter stands. An examination of the FIA plots from MTNF reinforced using this value to set the basal area maximum for the projection runs.

The "TreeSzCp" keyword addfile sets the biological limits for maximum diameter and height for a given tree species. The specified diameter acts as a surrogate for age to invoke senescence mortality. Tree size limits were derived using FIA tree measurement data from the total plot set on the MTNF. Adjustments were made based on input from the Forest.

Estimating Natural Regeneration

In order to obtain an accurate FVS prediction of future stand composition, it is necessary to provide FVS with information about the expected regeneration that will occur after long periods of time in the absence of disturbance. An estimation procedure was used that compared measured observations of regeneration as related to stand parameters (i.e. ecological strata, stand size, canopy density) to predict the expected regeneration. For this study, potential tree species for regeneration were divided into nine possible shade tolerance and maximum height attainment groups (e.g. high shade tolerance/mid-story height attainment group, low shade tolerance/overstory height attainment group). The total plot set was used to determine the typical distribution of advance regeneration in each of the nine potential shade tolerance/height attainment groups for four different ecological strata/stand size/canopy density classes. An FVS addfile was created to determine the ecological strata and size/density class of each plot; then, input the target amount of advance regeneration as small saplings from the appropriate shade tolerance/height attainment group.

Assigning Plots to Ecological Strata

Early on, it became readily apparent that in order to make meaningful comparisons, the plots needed to be assigned to distinct strata. Although we had remeasurement data for specific stands, the variable plot design of the periodic inventories prevented valid tree-by-tree or plot-by-plot comparisons over time. Per acre tree expansion factors vary based on changes in tree diameter. Inferences of tree and plot dynamics become obscure as a result. However, given a large enough plot sample size, strata-based conclusions could be drawn.

In brief, the 100 base plots were assigned to strata based on slope exposure (aspect) and productive capacity (site index). Aspect was defined as southerly (113–292 degrees) or northerly (0–112 or 293–360 degrees). High site quality was classified as site index values greater than 70; low was 70 or below. Since black oak was not always the tree species measured for site index, each plot was adjusted to a relative black oak site index as averaged over the three inventory cycles. To simplify tracking the results, sites with northerly aspect and high site quality were designated as "good sites" and sites with southerly aspect with low site quality were designated as "poor sites." Sites with northerly aspect and low site quality responded similarly to sites with southerly aspect and high site quality so they were combined into one stratum designated as "moderate sites".

Additional details regarding model adjustments, regeneration estimates, and ecological stratifications used for this study can be found in an interoffice publication (Vandendriesche 2006).

Assigning Plots to Mortality Groups

Although FIA field crews had gathered information on tree damaging agents and the associated severity, quantifiable measures to identify oak decline events were limited. Another method was needed to determine the threshold between *endemic* levels of tree mortality versus *epidemic*. Endemic implies being constantly present in a particular region and generally considered under control. In contrast, epidemic refers to out of control situations where the vector is spreading rapidly among many individuals. To that end, a process of evaluation presented by Manion and Griffin (2001) that distinguishes between endemic and epidemic conditions was pursued. Their basic tenet for assessing the likelihood of a self-sustaining forest is as follows:

> We propose that healthy forests depend on quantitatively predictable tree death as a continuous process linked to forest structure and growth. Quantifying a baseline mortality value by forest structure analysis using the Law of de Liocourt allows estimation of forest health by comparing the observed mortality to a baseline value.

In quantitative terms, the baseline mortality per dbh class can be used with estimates of dbh growth rates to determine an annual mortality rate needed for stand equilibrium. A given number of trees must die within a dbh class to allow space for the survivors to progress to the next larger dbh class. This number can be transformed into a rate or percentage for all dbh classes.

In application of the Manion and Griffin method, 125 FIA 'mortality' plots were used that were resident from cycle 3 through cycle 5 (i.e. 154 common plots, minus 29 that had experienced disturbance, mainly cutting treatments). Note that for this part of the analysis we were able to use an additional 25 common plots that were of smaller size class or were slightly "off-cycle" from the cycle 3 measurement period. Mortality inferences were based upon the cycle 3 measurements. This period pre-dates the drought years that triggered intensification of oak decline. "Past diameter" and "mortality tree" data is included in each FIA remeasurement dataset; as such, we were able to extrapolate cycle 2 trees per acre values from the cycle 3 data set. The resulting stand table is presented as table 2.

Notice the general trend of approximately twice as many trees per acre from the largest to the next smallest diameter class for cycle 2 data. The computed q-slope across all diameter classes equals a 2.038 factor. Think of this as a survivability factor. Conversely, a mortality factor would equal one minus the inverse of the q-slope. Expressing the baseline relative mortality as a percent equals 50.932 (that is: (1-1/2.038)*100). Thus, approximately one-half of the trees need to die for the survivors to progress to the next larger diameter size class. Knowing the average annual diameter growth rate of the trees allows calculation of the baseline relative mortality. For oak forests on the MTNF, a baseline relative mortality rate of 2.183 percent was computed. The observed mortality rate derived from the data set was 1.582 percent. According to Manion and Griffin, this indicates an evolving forest structure that will trend toward the baseline relative mortality rate.

Applying these same methods to cycles 4 and 5 data rendered the results shown in table 3. The reconstruction of cycle 2 from cycle 3 data represents the 1966 to 1976

Table 2—Stand table displaying trees per acre in each 2-inch dbh size class from FIA cycle 2 to cycle 3 with associated diameter growth, baseline mortality estimates, and observed mortality percent.

DBH Size class (inches)	Trees/Ac Cycle 2	DBH Growth/Yr (inches)	Annual Baseline Mort %[a]	Annual Observed Mort %[b]	Trees/Ac Cycle 3
2	381.953	0.011	0.391	2.286	384.592
4	130.578	0.024	0.851	1.102	118.281
6	59.799	0.040	1.414	0.542	61.196
8	36.070	0.058	2.044	0.355	32.860
10	20.369	0.082	2.877	0.524	22.284
12	12.631	0.097	3.394	0.576	14.359
14	5.900	0.112	3.909	0.802	8.117
16	2.456	0.129	4.489	1.156	3.470
18	1.092	0.143	4.963	1.392	1.485
20	0.551	0.163	5.638	2.595	0.700
22	0.213	0.176	6.073	2.676	0.311
24	0.086	0.203	6.972	4.419	0.124
26	0.058	0.213	7.302	1.552	0.048
28	0.056	0.226	7.730	2.500	0.049
30	0.016	0.243	8.287	1.250	0.037
32	0.006	0.263	8.938	10.000	0.022
Total:	658.552	0.062	2.183	1.582	647.935

[a] Annual Baseline Mortality % = A predictable level of relative mortality caused by biotic and abiotic factors interacting with stocking competition essential for maintenance of a balanced healthy forest. Baseline mortality is linked to forest structure (Law of de Liocourt, Manion and Griffin, 2001) and growth (measured diameter increment).

[b] Annual Observed Mortality % = Sum of the total number of dead trees per diameter size class observed in the field at any point in time divided by the initial live tree stocking, divided by the growth measurement period. Note that mortality is expressed in terms of diameter class rather than years.

Table 3—Calculated mortality rates (baseline versus observed) during the three measurement periods.

Measure period	Annual baseline mortality	Annual observed mortality
	percent	*percent*
1966–1976	2.183	1.582
1976–1986	2.981	3.267
1986–2001	2.974	3.324

growth measurement period. FIA cycle 3 to cycle 4 equates to the 1976 to 1986 growth period. Cycle 4 to cycle 5 spans the 1986 to 2001 measurement interval. Notice that the observed relative mortality exceeds baseline relative mortality during the past two FIA measurement cycles. This correlates well to the observed higher incidence of oak decline.

As a point of comparison, Manion and Griffin reported annual baseline mortality for Adirondack Park, New York, in 1996 at 3.0 percent. Buckman (1985) computed an annual measured mortality rate of 2.7 percent for National Forests in Michigan and Wisconsin. Based on these findings, and specifically on values obtained from the cycle 3 data set, for this study we chose a value of 2.0 percent annual mortality (in terms of trees per acre) from reconstructed cycle 2 to cycle 3 as the threshold to indicate stands of low mortality occurrence versus those of high mortality incidence.

Recall that three ecological strata were identified for this project based on aspect and site index: *poor*, *moderate*, and *good*. Using the 2.0 percent baseline relative mortality threshold to aid in determining low versus high mortality incidence, the plots represented in the FIA data set were distributed as shown in table 4. Thus, six combinations of ecological strata and mortality groups were identified for analysis.

Table 4—Distribution of the base FIA plots among productivity class and mortality group.

Productivity Class	Available number of stands	Number of stands in each mortality group: Low mortality (<2% per yr)	High mortality (>2% per yr)
Good	15	14	1
Moderate	49	34	15
Poor	36	26	10
Total:	100	74	26

Oak Decline Event Monitor

The Oak Decline Event Monitor (ODEM) addfile (Courter 2005) is an auxiliary keyword file that applies the effects of oak decline during FVS simulations of stand growth. Individual plots are evaluated with a probability/risk rating system to determine the susceptibility of the stand to the effects of oak decline. Based on research data from the southeastern United States (including the Missouri Ozarks), the likelihood of an oak decline event depends on many factors including proportion of basal area in the target species groups, condition of the stand, site quality, stand age, and occurrence of previous oak decline events (Oak and others 1996). These factors are used within the ODEM addfile to calculate the probability/risk of a decline event.

An oak decline event is scheduled in the FVS cycle if a drawn random number is less than or equal to the estimated probability in that cycle. If an event is scheduled, oak decline mortality is targeted for the red oak (*Quercus rubra* L.), white oak (*Q. alba* L.), and hickory (*Carya* sp.) species groups at the end of that FVS cycle. Oak decline induced mortality is determined by the stand risk rating with greater mortality and crown reduction scheduled for stands with elevated risk. Within the ODEM addfile, mortality and crown reduction values are applied through use of the "FixMort" and "Prune" keywords.

Analysis Process

After the data were prepared and the various processing components assembled, we were able to use FVS in two ways: (1) to capture static information from the data sets; and, (2) to project the existing data sets into the future. We compared measured changes in basal area and species composition to FVS predicted changes in basal area and species composition over the three periods of remeasurement. We compared different combinations of processing components (i.e., with and without model adjustments and the ODEM addfile) to determine which resulted in stand projection closest to measured trends. We then selected the "best" combination of processing components and used FVS to project poor sites 100 years into the future.

Analysis and Discussion

Static Use from Three Measurement Cycles

FVS was used to summarize various growth parameters for the base plot set from the three ecological strata and two mortality groups. The "good site/high mortality" category had only one stand. Strata based inferences could not be drawn for this site-mortality combination, so it was excluded from further consideration (fig. 1).

For low mortality plots, measured trends indicate that basal area per acre steadily increased from cycle 3 to 4 to 5. For high mortality stands, basal area per acre remained mostly constant from cycle 3 to 4 but then rebounded for cycle 5. On these sites, tree mortality made space for associated species to fill in the gaps over the 25-year period. Recall that we used the reconstructed cycle 2 to cycle 3 mortality rate to distinguish stands of observed high mortality versus those of low mortality occurrence. Thus by our definition of mortality groupings, the "high mortality" sites were already experiencing increased casualty at the beginning of cycle 3

In order to observe how the distribution of species changed over time, we calculated the basal area within seven species groups of particular interest. We considered scarlet

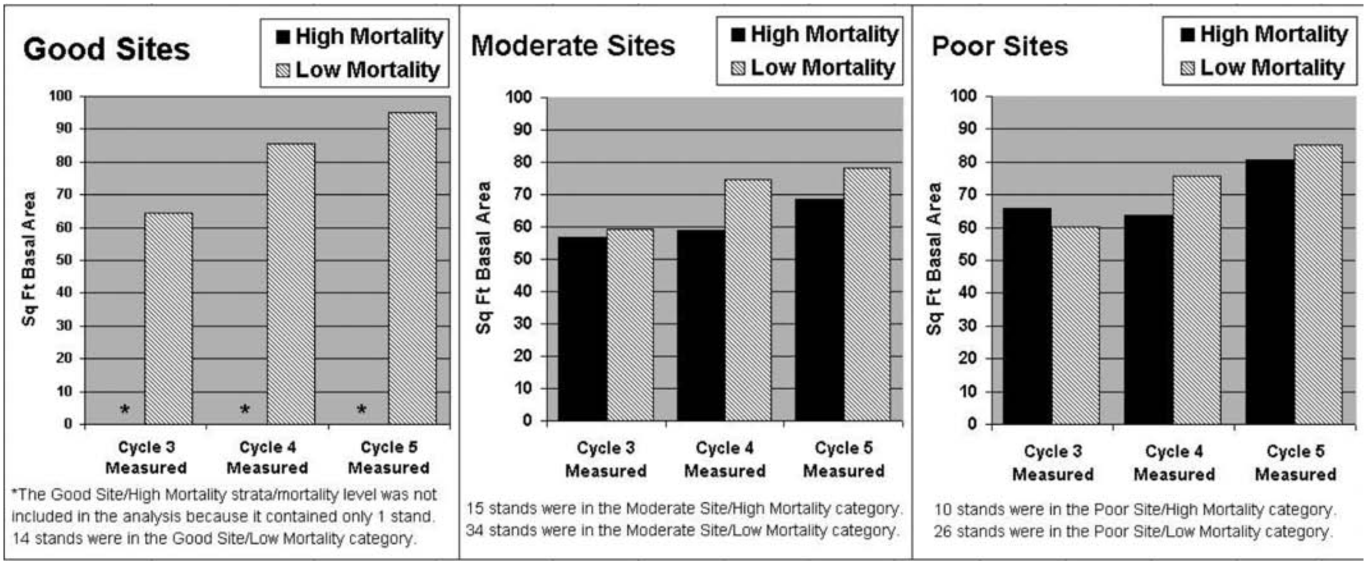


Figure 1—Measured basal area per acre of all trees equal to or greater than 5 inches dbh on good, moderate, and poor sites over three FIA inventory cycles. The bar for sites with high mortality is beside the bar for sites with low mortality for each cycle.

oak (*Q. coccinea* Muenchh.) and black oak (*Q. velutina* L.) as one unique species group, white oak as another species group, and all other oaks (*Quercus* sp.) as a third group. All hickories were considered in the hickory group. All other hardwoods, such as cherry (*Prunus sp.*), ash (*Fraxinus sp.*), dogwood (*Cornus sp.*), etc., were grouped together. Shortleaf pine was the predominant conifer recorded; however, eastern redcedar was observed in cycle 5. Pine and cedar were kept as separate species groups. In figure 2, the proportion of total basal area in each of these species groups is shown for the "poor" sites at each of the three measurement periods.

On poor sites with high mortality, the proportion of basal area in scarlet and black oak decreased in successive measurement cycles. Conversely, the proportion of basal area in white oak increased. This trend is consistent with the silvicultural predictions

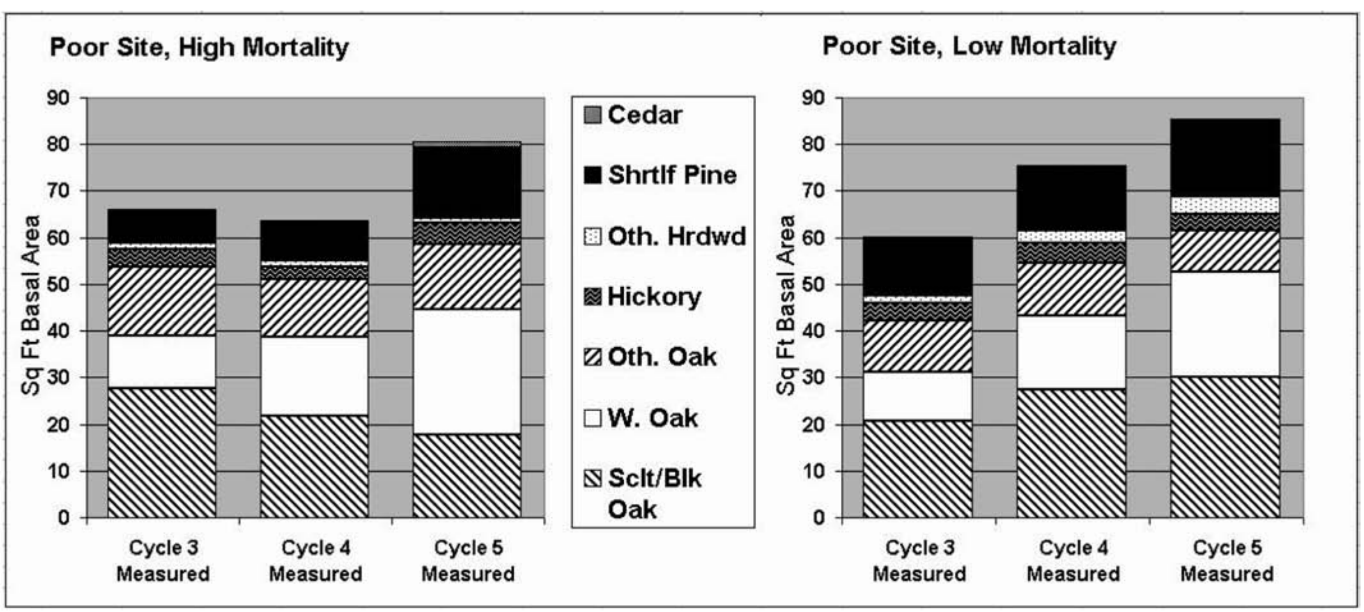


Figure 2—Measured basal area per acre of all trees equal to or greater than 5 inches dbh on poor quality sites over three FIA inventory cycles displayed by tree species representation.

of tree species response to oak decline (Shifley and other 2006). On poor sites with low mortality, basal area in scarlet and black oak increased during each cycle. White oak also increased. The identifiable differences in response pattern between the high and low mortality groups indicate that the criteria we used to distinguish mortality groups were meaningful.

FVS Modeling: Choosing "Best" Combination

Because data were available for the same 100 base plots over a 25-year period, we were able to compare the actual measured basal area per acre values to the predicted basal area estimates when we projected the stands for 25 years under four different combinations of the FVS model. The combinations we compared were:

- FVS without adjustments
- FVS without adjustments, with the Oak Decline Event Monitor (ODEM) addfile
- FVS with adjustments as described in the methods section of this paper
- FVS with adjustments as described in the methods section, with the ODEM addfile

From this comparison (table 5), it was clear that FVS without adjustment consistently resulted in a considerable overestimation of basal area, even after a period as short as 25 years. When the ODEM addfile was applied, predicted values improved as compared to the observed values. For the best prediction of basal area attainment, adjustment alone for low mortality plots and adjustment plus the ODEM addfile for high mortality plots achieved those results. This indicates that even with adjustment, FVS cannot be expected to accurately predict the epidemic levels of mortality that will occur from an oak decline event. Ideally, FVS should be configured to adjust for an inherent level of tree mortality and the ODEM addfile should be used if you want to simulate the potential outcome of an oak decline event. Use of projected values with and without the ODEM addfile could indicate mortality bounds (endemic vs. epidemic). If climatic conditions such as drought exist, you would expect a pending oak decline event.

In order to determine which processing combination provided a better prediction of the future species composition, we compared the predicted basal area of the same species groups previously described to the measured basal area from cycle 5. The predicted basal area was derived from FVS projections of cycle 3 data forward 25 years to cycle 5 under the various adjustments to the base FVS model described above. The results of this comparison for the poor site/high mortality stratum are shown graphically in figure 3. The species composition that was measured in cycle 5 was quite different from the composition projected by any version of the model. Although a 25-year projection by various model configurations predicted different amounts of basal area, the proportion of

Table 5—Measured basal area per acre of all trees equal to or greater than 5 inches dbh in cycle 5 versus predicted basal area from cycle 3 data projected to cycle 5 by various versions of the FVS model.

Site grouping	Number of sites	Cycle 3 measured BA (ft^2/acre)	Cycle 5 measured BA (ft^2/acre)	Cycle 5—FVS without adj.[a] projected BA (ft^2/acre)	Cycle 5—FVS without adj. + ODEM[b] projected BA (ft^2/acre)	Cycle 5—FVS with adj.[c] projected BA (ft^2/acre)	Cycle 5—FVS with adj. + ODEM[d] projected BA (ft^2/acre)
Poor Site, High Mortality	10	66.0	80.5	110.8 (+30.3)[e]	96.6 (+16.1)	90.0 (+9.5)	82.1 (+1.6)
Moderate Site, High Mortality	15	56.8	68.4	94.0 (+25.6)	70.9 (+2.5)	78.5 (+10.1)	64.0 (–4.4)
Poor Site, Low mortality	26	60.3	85.3	104.0 (+18.7)	91.9 (+6.6)	86.4 (+1.1)	71.7 (–13.6)
Moderate Site, Low mortality	34	59.1	78.1	99.3 (+21.2)	89.6 (+11.5)	86.1 (+8.0)	72.5 (–5.6)
Good Site, Low mortality	14	64.6	95.2	108.7 (+13.5)	99.9 (+4.7)	92.2 (–3.0)	72.5 (–22.7)

[a] FVS base model without adjustments.
[b] FVS base model with Oak Decline Event Monitor (ODEM). Note that ODEM has a random component, so values vary from run to run.
[c] FVS base model with adjustments as described in the methods section of the paper.
[d] FVS base model with adjustments, with ODEM included as an addfile.
[e] The figures in parentheses represent the difference between the cycle 5 measured value and the cycle 5 value as predicted by that version of the model.

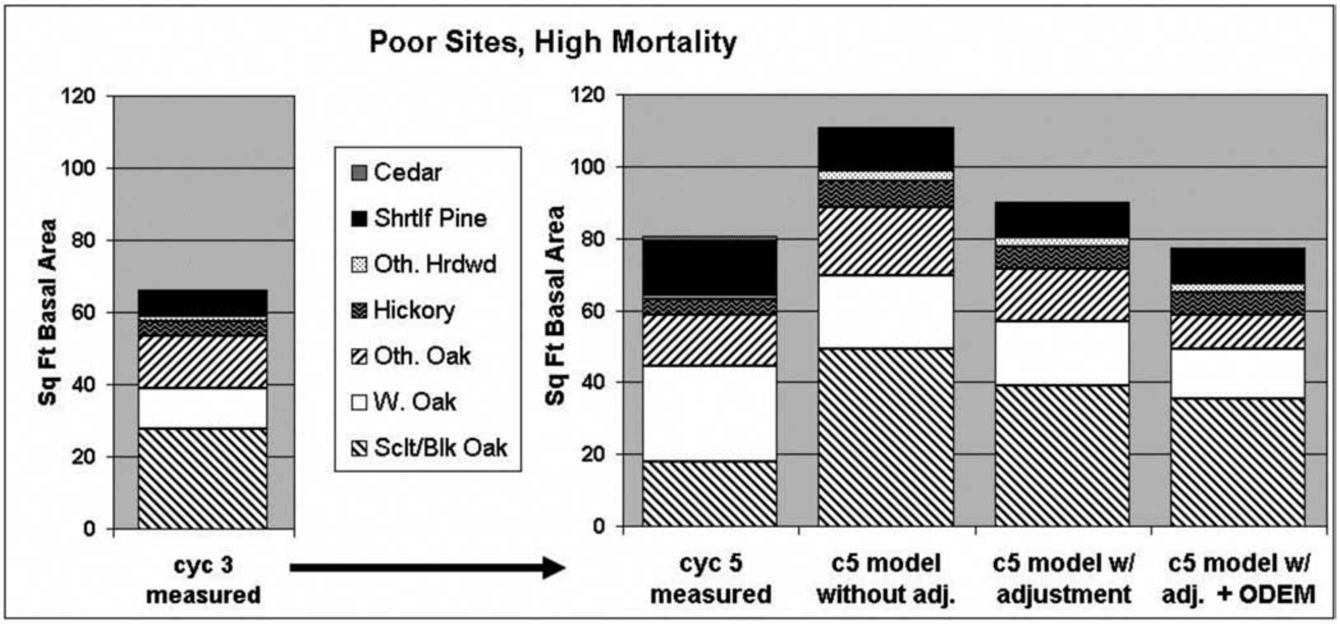


Figure 3—Comparison of measured to projected basal area representation of species distribution on poor quality, high mortality sites. Cycle 3 data was projected 25 years with the base FVS model and also with various versions of the model to compare the affect on the prediction of species composition.

the basal area in any species group was affected very little by the various combinations of the model. Similar results were obtained for the other ecological stratum.

Some of the differences between measured and modeled species composition may be due to the changes in sampling design from cycles 3 and 4 to cycle 5. Since the same center pin was used in all inventories, the trees measured in cycle 5 included some of the same trees measured in cycle 3 and 4. However, not all the trees were the same because the subplot configurations were different between the periodic and annual sampling designs. It is also worth noting that the species composition predicted by all combinations of the model is quite similar to the original composition in cycle 3. Over a 25-year projection, the various FVS combinations did not predict a major shift in species composition because most of the basal area of trees over 5 inches dbh is comprised of the original trees. Over a longer projection, we would expect to see diverging species composition by the various processing combinations of the FVS model due to the application of different mortality rates and regeneration inputs.

Future: Projecting Current Data 100 Years

After determining that the FVS model with adjustments provided reasonable estimates of stand growth, we simulated the development of the poor sites, with both high and low mortality levels, for 100 years into the future. The poor sites with high mortality were projected from cycle 5 for 100 years using the FVS model with adjustments (fig. 4). The Oak Decline Event Monitor addfile was not applied in this case under the assumption that these are "aftermath" stands that have already lost their vulnerable scarlet and black oak component. The adjusted FVS model predicts that these stands would increase in basal area to a maximum slightly above 120 ft^2. It predicts that the white oak and other hardwoods would occupy an increasingly large proportion of the basal area. Projecting data beyond 50 years is suspect, but if pressed to do so, it is encouraging to see that the adjusted model predicts a basal area level and species composition that are similar to measured trends. Note that we also produced an iteration of the FVS model without adjustments to determine what the predicted basal area would be after 100 years of growth. This simulation produced an unrealistically high prediction of basal area.

Poor sites, low mortality were also projected from cycle 5 for 100 years (fig. 5). In this example, we ran the model with and without the ODEM addfile in order to observe the effect of the ODEM addfile on the projection. When the FVS model with adjustments

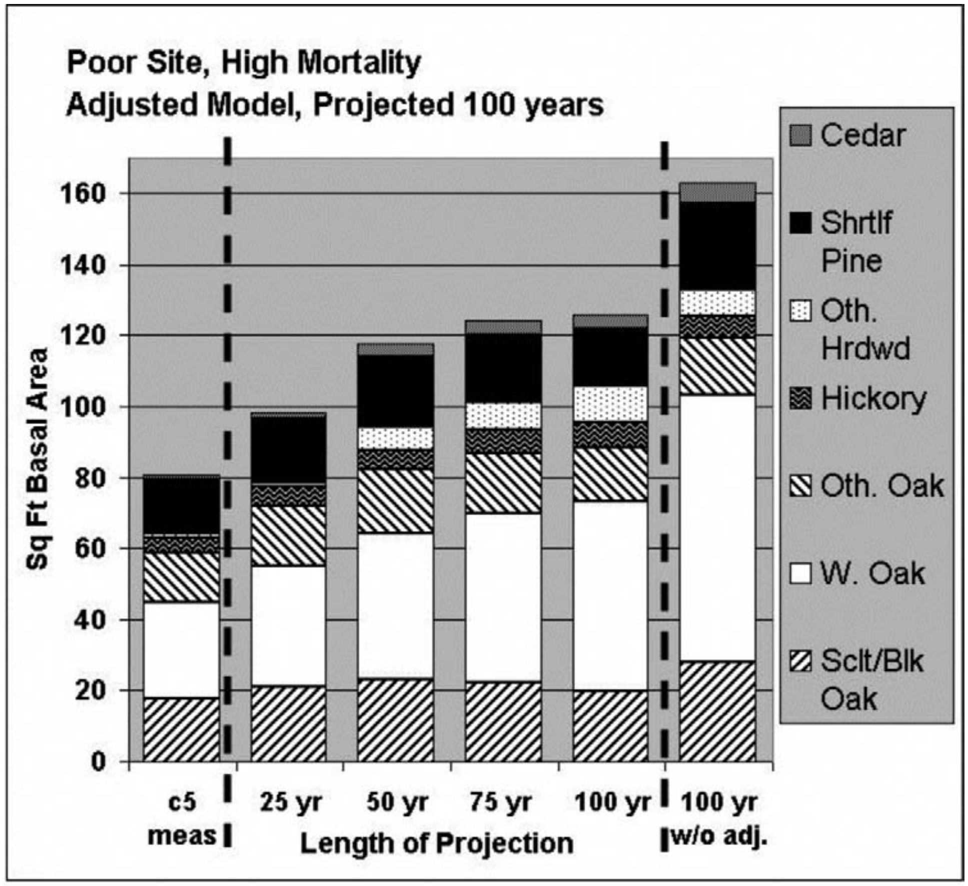


Figure 4—Projected basal area and species composition of poor sites with high mortality from cycle 5 for 100 years into the future, using the adjusted FVS model. Note that the 100-year projected value using FVS without adjustment is also shown for comparison.

was used, the predicted pattern of stand development was very similar to the pattern predicted for the high mortality stands (fig. 4). This is not surprising, since the average basal area of the stands in these two groups was actually quite similar by cycle 5. The interesting result here is the effect of including the ODEM addfile in the projection. Over a 100-year period, adding the ODEM addfile causes a fairly significant shift in species composition. It predicts a much lower proportion of the stand to be composed of either the "scarlet/black oak" or "white oak" species group and a much larger proportion of the stand in "other hardwoods." It also holds the basal area below 100 ft^2/acre throughout the projection. Based on these findings, we recommend that the species related mortality impacts within the ODEM addfile be modified to apply a lower level to the "white oak" and a higher level to the 'other hardwoods' species group.

Summary of Results

A study of this magnitude revealed several important findings. Regarding assembling data sources, access to FIA data has been streamlined in recent years. A simple truth concerning this finding is the more recent the inventory cycle, the more readily available the information. Retrieving past data from older periodic inventories can be challenging. Knowledge of FVS input files and their associated field formats may be required. As with our study, attempting to go back 20 or more years most likely will necessitate a high level of interaction with the raw data to produce FVS-ready files. Also, familiarity with FIA sampling techniques will be mandatory. Syncing inventory procedures is imperative when trying to draw inferences from varying survey designs.

When dealing with data collected from variable plot techniques to glean long-term trends, use aggregated stratum values, not per plot or per tree progressions. With

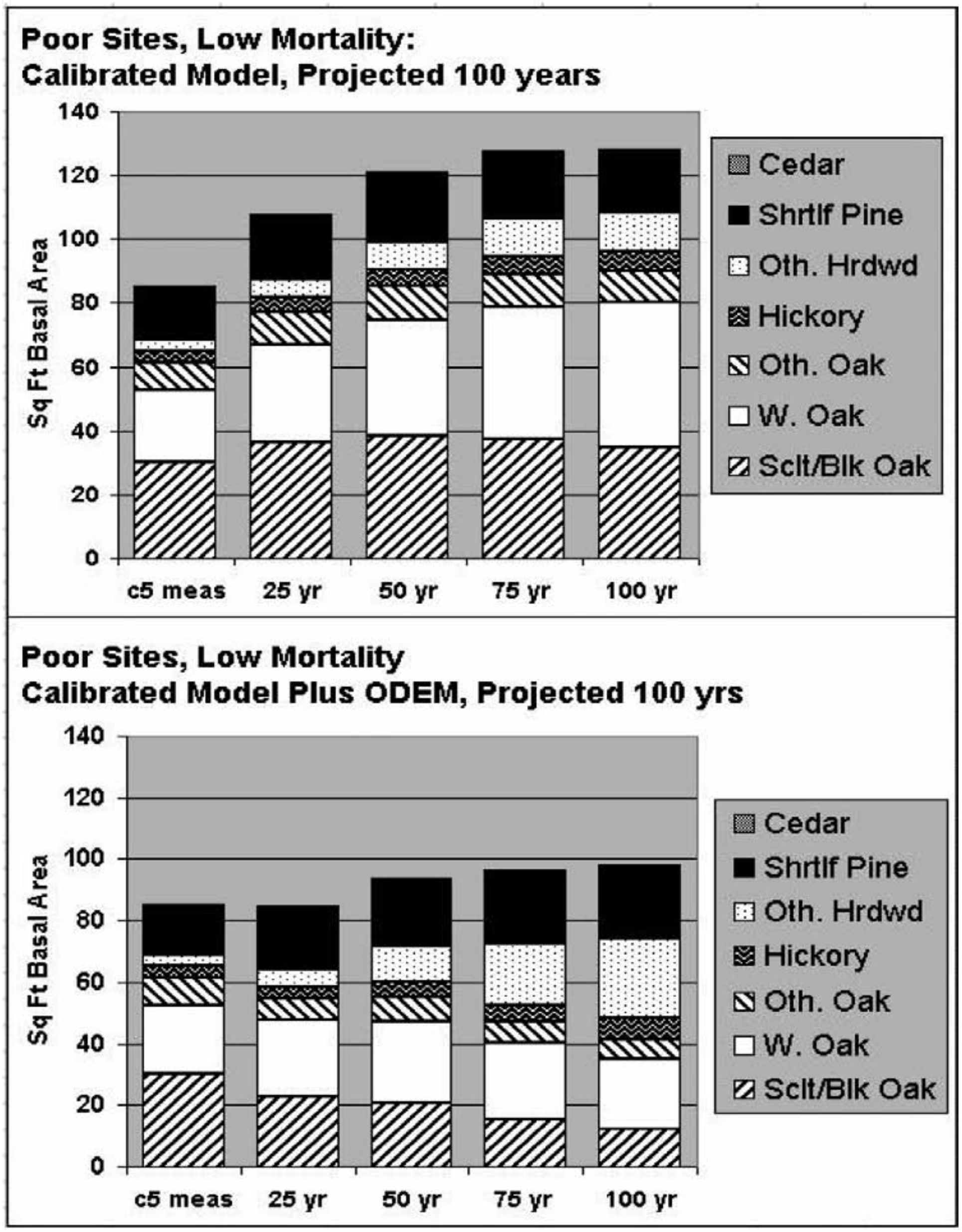


Figure 5—Projected basal area and species composition of poor sites with low mortality from cycle 5 for 100 years into the future using the FVS model with adjustments and the FVS model with adjustments with the ODEM addfile.

point sampling, tree expansion values change over time as a result of diameter growth. Consequently, per acre values differ when comparing repeat measurements. This adds complexity in interpreting trend information. Reliable monitoring estimates can only be made at the stratum level.

The ecological strata recognized by this study were correlated with differences in oak-hickory understory recruitment. We found that north aspects having high site productivity contained approximately half the oak-hickory small saplings as south aspects having low site quality. The ecotones between these (north aspect/low site and south aspect/high sites) had similar species compositions in the understory. They had more oak-hickory small saplings than the north aspect with high site potential but less than the south aspect with low site indices. Forest strata were defined by these ecological classes. These findings were valuable in development of regeneration estimation addfiles.

Since oak decline as a symptom was not recorded for the different FIA cycles, we needed to develop a method to infer the break-point between endemic and epidemic levels of mortality. We found the procedure suggested by Manion and Griffin useful insofar that it links forest structure to a predictable level of relative mortality. We applied their method for estimating baseline mortality per dbh class. Approximately 2 percent of the trees per acre per year die on the MTNF. This equates to about one-half of the trees surviving from a given 2-inch dbh class to the next larger class based on measured diameter growth and resultant tree survivorship. We used the 2 percent threshold to distinguish high from low mortality FIA plots.

In exploration of the data for regeneration estimation, we observed that north aspects of high site productivity did not commonly have a large amount of oak-hickory regeneration. Although these are good sites, they do not intrinsically favor oak-hickory tree species development. There is a high level of species diversity that would inherently be less susceptible to oak decline impacts. South aspects of low site quality are strongholds for oak-hickory development. We focused on these areas for comparing measured trends as revealed by three FIA cycles versus modeled effects as portrayed by FVS projections for the same time period.

Poor sites (south aspect, low site) with high mortality (>2% tpa/yr) as forecast by FVS demonstrated similar results in terms of stand basal area per acre as indicated by measured FIA data. Forecasts of species composition changes were less successful. Losses in the black oak species group (scarlet and black oak) were not as prevalent in the modeled runs as in the measured data. This was concluded over the 25-year period spanning 1976 to 2001. However, projecting this stand type forward 100 years demonstrated a greater loss in the black oaks and also in white oak. This may be an overstatement of the effects of oak decline on white oak. Measurement data revealed that white oak was less susceptible to oak decline agents and actually filled in the gaps resulting from mortality in the black oak species group.

Conclusions and Recommendations

Several conclusions can be drawn from our study of oak decline on the MTNF. The objective of this project was to investigate the utility of Forest Inventory Analysis data and the Forest Vegetation Simulator to address mortality impacts and resulting stand structure from impeding oak decline events. As indicated from our trials comparing the FVS model runs with and without adjustment techniques applied, it is recommended to pursue adjustment techniques: (1) perform FVS self-calibration, (3) obtain tree defect values, (3) derive maximums for stand density and tree attainment, and (3) develop a regeneration response. Each of these modifications contributes to crafting a FVS modeled run to perform similar to measurement trends. Future projections built on this basis can then be substantiated.

The Oak Decline Event Monitor addfile was developed specifically to induce effects of oak decline during a FVS model run. We found it to be particularly helpful in "scaling back" oak stocking when the FVS model was not adjusted, but less useful when the model had been fully adjusted to measured conditions. To obtain the most realistic results, we recommend always adjusting FVS. If the ODEM addfile is going to be used in conjunction with the adjustments, the user should consider reducing the levels of mortality it applies to white oak and increasing the level for other hardwoods.

As with the model runs for poor sites, the modeled runs for the moderate and good sites correlated well to actual measurements from cycle 3 to cycle 5. We hypothesize that the moderate and good sites would follow similar trends if forecast 100 years into the future. This would be a logical extension of this study. Also, calculation and comparison of net volume trends may provide additional information important to land managers.

References

Buckman, R.G. 1985. Performance of a tree survival model on National Forest. Northern Journal of Applied Forestry. 2: 114-116.

Courter, Anthony. 2005. The Oak Decline Event Monitor Users Guide. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team (FHTET). Fort Collins, CO, Interoffice publication. 6 p. Available: http://www.fs.fed.us/foresthealth/technology/od_rating.shtml

Gingrich, Samuel F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. Forest Science. 13(1): 38-53 p.

Law, J.R.; Gott, J.D. 1987. Oak mortality in the Missouri Ozarks. In: Hay, R.L; Woods, F.W; DeSelm, H.; Proceedings of the central hardwood forest conference VI; 1987 February 24–26; Knoxville, TN: 427–436.

Law, Jay R.; Melick, Ross; Stydyvin, Charly; Steinman, James R. 2004. Oak decline in Missouri: History revisited. In: Spaetich, Martin A. Upland oak ecology symposium: history, current conditions, and sustainability. Gen. Tech. Rep. SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 257-258.

Lawrence, R.; Motzan, B.; Moser, K. 2002. Oak decline and the future of Missouri's forests. Missouri Conservationist. 63: 11–18.

Manion, Paul D.; Griffin, David H. 2001. Large landscape scale analysis of tree death in the Adirondack Park, New York. Forest Science. 47(4): 542–549.

Miles, Patrick D. 1992. Forest Inventory Mapmaker Users Guide. Gen. Tech. Rep. NC-GTR-221. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 52 p.

North Central Research Station (NCRS). 1969. North Central forest survey field instructions, supplement to Forest Survey Handbook FSH 4813.1. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 84 p. Available: http://ncrs.fs.fed.us/4801/regional-programs/Inventory/fieldcrews/manuals/

North Central Research Station (NCRS). 1986. North Central forest inventory analysis field manual, Missouri and Minnesota. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 119 p. Available: http://ncrs.fs.fed.us/4801/regional-programs/Inventory/fieldcrews/manuals/

North Central Research Station (NCRS). 1999. National Forest inventory and monitoring core field guide. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 168 p. Available: http://ncrs.fs.fed.us/4801/regional-programs/Inventory/fieldcrews/manuals/

Oak, S.; Tainter, F.; Williams, J.; Starkey, D. 1996. Oak decline risk rating for the southeastern United States. Ann. Sci. For. 53: 721–730.

Puuri, Carl R.; Loftus, Nelson S., Jr.; Fitzgerald, Richard O. 1986. Stocking charts – Tools for forest management. In: Schmidt, Wyman C., comp. Proceedings – Forests of the Mountain West symposium; 1986 September 29–October 3; Missoula, MT: 87–92.

Shifley, Stephen R.; Fan, Zhaofei; Kabrick, John M.; Jensen, Randy G. 2006. Oak mortality risk factors and mortality estimation. Forest Ecology and Management. 229: 16–26.

Starkey, D.A.; Oliveria, F.; Mangini, A.; Mielke, M. 2004. Oak decline and red oak borer in the interior highlands of Arkansas and Missouri: Natural phenomena, severe occurrences. Gen Tech Rep SRS-73. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 217–222.

Vandendriesche, Donald A. 2006. Comparison of measured growth and mortality trends to modeled FVS projections relative to oak decline impacts as observed over three FIA inventory cycles. Interoffice publication. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 38 p. Available: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_mort-trends.php

---

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Preliminary Results of the FVS Gypsy Moth Event Monitor Using Remeasurement Plot Data from Northern West Virginia

Matthew P. Perkowski[1]
John R. Brooks[1]
Kurt W. Gottschalk[2]

Abstract—Predictions based on the Gypsy Moth Event Monitor were compared to remeasurement plot data from stands receiving gypsy moth defoliation. These stands were part of a silvicultural treatment study located in northern West Virginia that included a sanitation thinning, a presalvage thinning and paired no-treatment controls. In all cases the event monitor under predicted the initial mortality for all stands in terms of trees per acre. Prediction errors, with regards to trees per acre, were largest in stands receiving the heaviest defoliation. In terms of basal area prediction, those stands receiving the heaviest defoliation had predictions which were too high in the 4- to 5-year period following initial defoliation, after which prediction error diminished. For stands receiving light defoliation, predicted basal area was lower than in observed stands and this error increased with the length of the projection period.

Introduction

The Gypsy Moth Event Monitor (GMEM) is a keyword set that modifies growth and mortality within the Forest Vegetation Simulator (FVS) to simulate the effects of gypsy moth infestations. The event monitor classifies the relative susceptibility of a stand based on the percentage of susceptible species present within the stand. Outbreaks occur stochastically and range in intensity based on stand susceptibility. After an outbreak occurs, mortality is increased with the use of the FIXMORT keyword. Additionally, basal area growth increment is reduced using the BAIMULT keyword. These modifiers predominantly impact susceptible species on moderate outbreak levels, but may also impact resistant species when outbreaks are more severe. A previous silvicultural treatment study in northern West Virginia was designed to moderate the impact of gypsy moth infestation (Liebhold and others 1998). The purpose of this study is to compare stand density predictions, in terms of basal area and trees per acre, from GMEM modified FVS (GMEM-FVS) simulations using remeasurement data from the previous treatment study following a gypsy moth outbreak.

Data

The data are from a long-term experimental site located within the West Virginia University Research Forest (WVURF) in Preston County, West Virginia. The WVURF is a 7,664 acre forest primarily comprised of oak dominated and cove hardwood stands. In 1989, sixteen stands were selected to investigate the effects of silvicultural treatments on the impact of gypsy moth as discussed in detail by Liebhold and others (1998). Each stand was comprised of twenty 0.1-acre plots. Eight stands within the study received either a sanitation thinning treatment or presalvage thinning treatment. The sanitation thinning treatment was a modified thinning from below, performed on stands with less than 50 percent of the basal area comprised of susceptible species, to reduce stand susceptibility by removing highly vulnerable trees regardless of value (Gottschalk 1993). The presalvage thinning treatment was also a modified thinning from below; however it was performed on stands having greater than 50 percent of the basal area comprised of susceptible species, to reduce stand vulnerability while attempting to increase stand vigor and value. Each of the eight treatment stands were paired with a control comprised of similar species. The stands were remeasured annually until 1994, after which they were measured periodically until 2004. At each measurement period, tree species, vigor,

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Graduate student and Associate Professor, respectively, Forest Biometrics, West Virginia University, Morgantown, WV; e-mail jrbrooks@mail.wvu.edu.

[2] Research Forester and Project Leader, USDA Forest Service, Northern Research Station, Morgantown, WV.

Table 1—Observed gypsy moth defoliation and tree mortality, by treatment type and stand number, for stands located in Preston County, West Virginia.

Treatment type	Stand number	Defoliation level	Actual mortality
			%
Control	2, 4, 5, 8, 10, 12	Light	25–35
	14, 16	Heavy	50–60
Sanitation thinning	1, 3, 6	Light	20–30
	7	Heavy	20–30
Presalvage thinning	9, 11	Light	12–20
	13, 15	Heavy	30–37

defoliation, and dbh were recorded for every tree. Defoliation varied between stands, with stands 7 and 8 of the sanitation thinning treatment and stands 13 through 16 of the presalvage thinning treatment, receiving heavier defoliation than other stands within the same treatment groups (table 1). In the control stands that received only minimal defoliation, cumulative mortality ranged between 25 and 35 percent (in terms of trees per acre). The heavily defoliated control stands experienced higher cumulative mortality that ranged from 50 to 60 percent. In stands receiving the sanitation thinning treatment, mortality ranged from 20 to 30 percent with very little difference between the heavily defoliated and lightly defoliated stands. Two distinct populations existed within the presalvage treatment stands. The heavily defoliated presalvage treatment stands had mortality that ranged from 30 to 37 percent, while the presalvage stands that received light defoliation experienced mortality ranging from 12 to 20 percent.

Methods

The 1989 data were input into the northeast variant of FVS and projected until 2004. The projections were modified by the northeastern key component file of the Gypsy Moth Event Monitor. A gypsy moth introduction period of 1985 was used for the event monitor, based on literature (Hicks and Mudrick 1994). Outbreaks were stochastically determined for each run, using a random seed that was allowed to vary. Output was generated on a one-year cycle length. For this analysis, mean response was based on twenty simulations for each stand using FVS. Measured in-growth was removed from the data set during comparison to reduce confounding results. Simulated stand density, in terms of trees per acre (TPA) and basal area per acre (BAAC), was compared to actual recorded conditions.

Results

Simulation of Trees Per Acre

GMEM-FVS simulations under predicted mortality, for both the stands receiving sanitation thinning treatment and their paired control stands (fig. 1). For those sanitation treatment stands receiving the heaviest defoliation (Stands 7 and 8), over prediction of stand density increased quickly for three years, after which, both the treated stand and the paired control leveled off at an over estimation of approximately 38 TPA. Additionally, GMEM-FVS over predicted TPA for the sanitation treatment stands and their paired controls which received the lightest defoliation (Stands 1 through 6). Prediction errors for these stands followed a pattern similar to the heavily defoliated stands; however, the prediction error was greater for the untreated stands (Stands 2, 4, and 5). The GMEM modified FVS projection for Stand 1 had the smallest prediction error, approximately 20 TPA.

In most cases, GMEM-FVS simulations over predicted stand density for the stands receiving the presalvage treatment and their paired controls (fig. 2). This over prediction ranged from less than 20 TPA, under light defoliation conditions for most treated stands (Stands 9 and 11), to over 80 TPA for the heavily defoliated control stands (Stands 14 and 16). Prediction errors were slightly higher in the fourth remeasurement period for presalvage treatment stands receiving heavier defoliation (Stands 13 and 15), but this error decreased over the rest of the projection period. The largest over prediction of stand

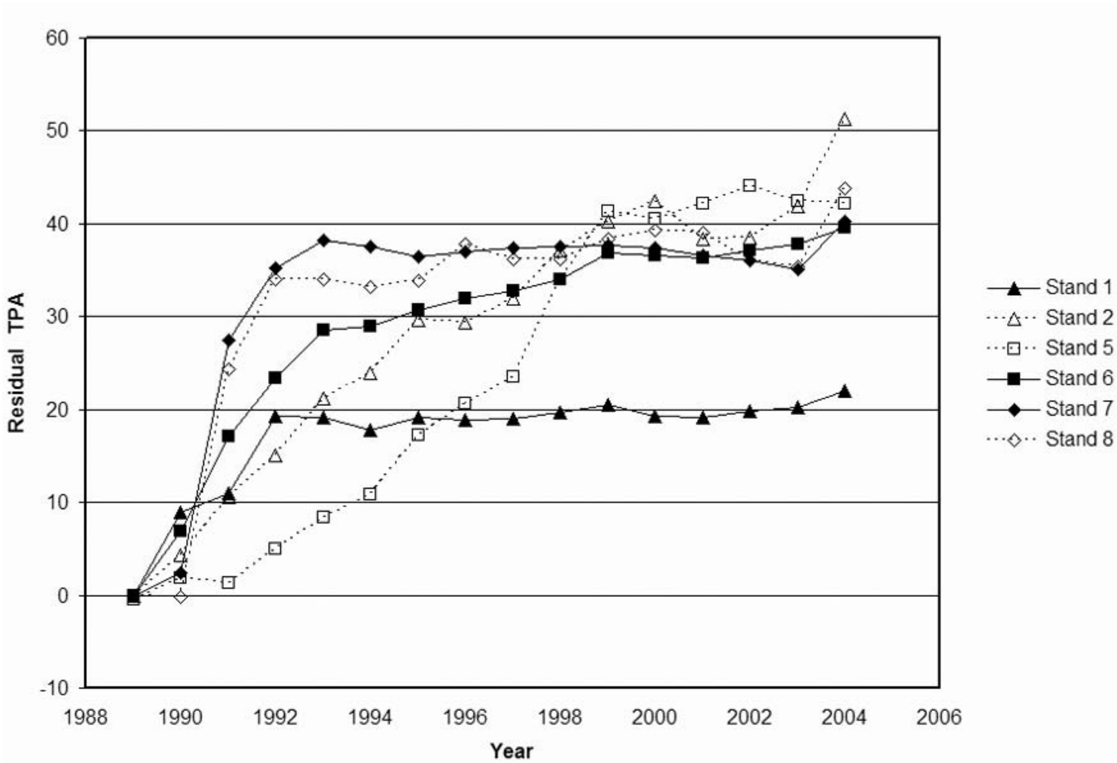


Figure 1—Residual (simulated–actual) TPA for stands receiving the sanitation thinning. Dark symbols reflect stands receiving the sanitation thinning treatment. Symbols of the same shape, but not filled in, are the paired non-treated controls

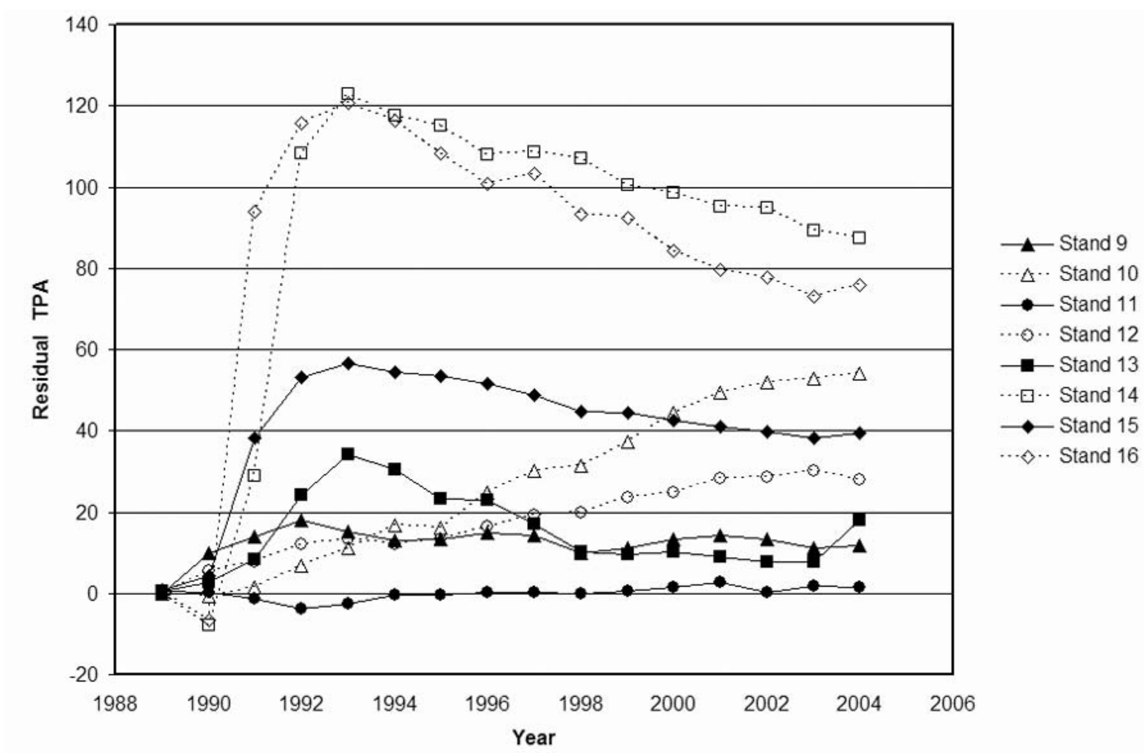


Figure 2—Residual (simulated–actual) TPA for stands receiving the presalvage thinning treatment. Dark symbols reflect stands receiving the presalvage thinning treatment. Symbols of the same shape, but not filled in, are the paired non-treated controls.

density was associated with the untreated control stands that experienced the heaviest defoliation (Stands 14 and 16). Prediction errors for these stands were the greatest at the fourth remeasurement period and declined over the course of the projection period.

Simulation of Basal Area per Acre

GMEM-FVS simulations generally over predicted BAAC for the sanitation thinning treatment stand and its paired control that received the heaviest defoliation (Stands 7 and 8, figure 3). The over prediction in these stands was greatest in the second through fifth remeasurement period, after which this error decreased with time. In all cases, the simulations under predicted BAAC for the sanitation thinning treatment stands and paired control stands which received the lightest defoliation (Stands 1 through 6). The magnitude of this prediction error increased with time.

GMEM-FVS simulations over predicted BAAC for presalvage thinning treatment and paired control stands by up to 70 ft^2/ac. at the fifth remeasurement period, for those stands receiving the heaviest defoliation (Stands 13 through 15) (fig. 4). The magnitude of this prediction error decreased with time, with the untreated control stands exhibiting higher prediction errors than the paired treated stands. In all cases, the simulations under predicted BAAC for presalvage thinning treatment stands and their paired controls that experienced light defoliation (Stands 9 through 12). This prediction error increased linearly to an under prediction of approximately 30 ft^2/ac.

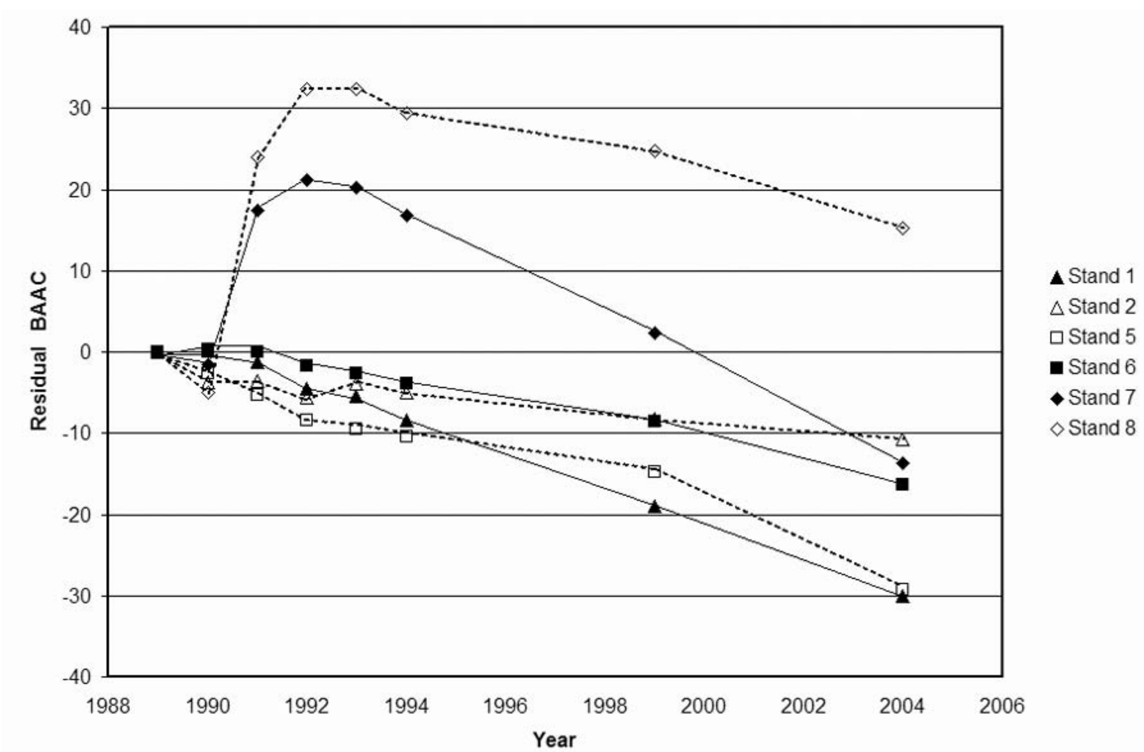


Figure 3—Residual (simulated–actual) basal area per acre for stands receiving the sanitation thinning. Dark symbols reflect stands receiving the sanitation thinning treatment. Symbols of the same shape, but not filled in, are the paired non-treated controls.

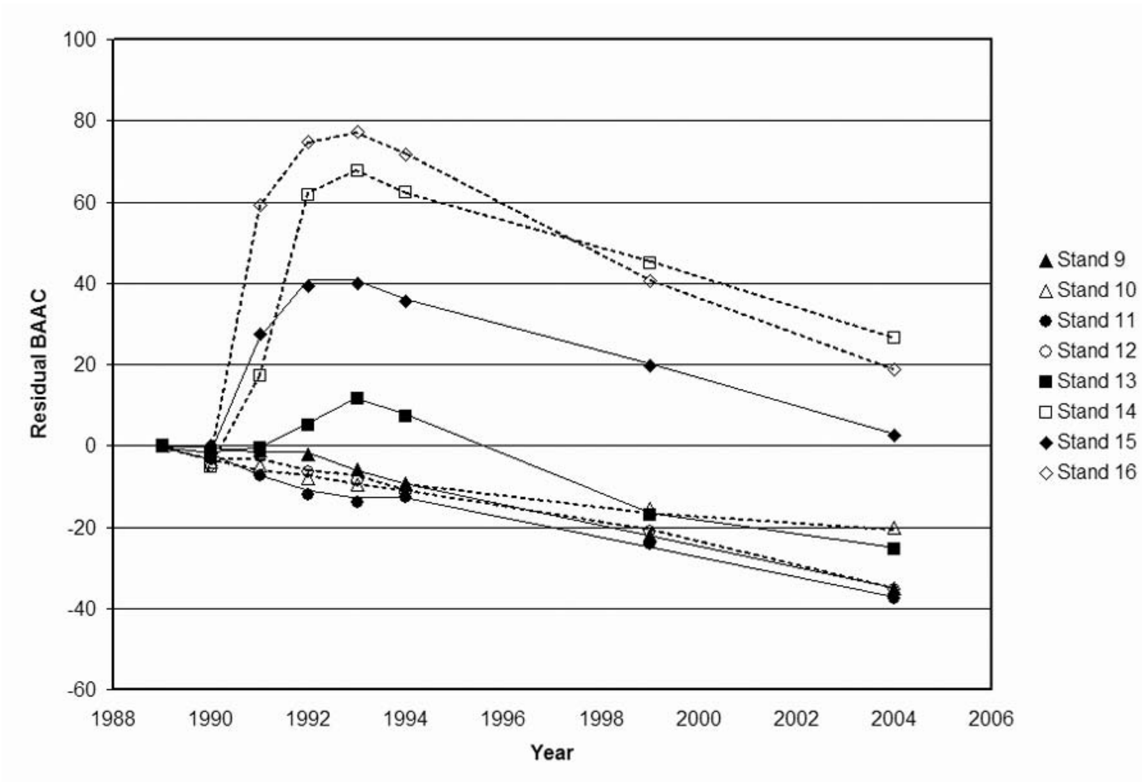


Figure 4—Residual (simulated–actual) basal area per acre for stands receiving the presalvage thinning treatment. Dark symbols reflect stands receiving the presalvage thinning treatment. Symbols of the same shape, but not filled in, are the paired non-treated controls.

Discussion

GMEM-FVS projections increasingly underestimated TPA mortality over the course of the projection period, for stands that experienced low defoliation levels. These stands exhibited an increase in actual mortality over time, which was continuously underestimated by the scheduled outbreaks simulated in FVS.

FVS simulations over predicted TPA at the point of initial mortality, regardless of stand treatment, for those stands that experienced high defoliation levels. For the heavily defoliated stand receiving the sanitation thinning treatment and its paired control (Stands 7 and 8), predicted TPA paralleled actual stand development after the initial defoliation event. This would indicate that equilibrium in overall stand density was achieved, but at a level higher than that in the observed stands. Actual stand mortality increased slowly following the initial defoliation event, which the event monitor accurately captured by scheduling several outbreaks over the course of the FVS projection period. Presalvage thinned stands and their paired controls that experienced high defoliation (Stands 13 through 16), exhibited little increase in actual mortality after the initial defoliation event. GMEM scheduled several outbreaks over the rest of the FVS projection period, which reduced the error in TPA associated with the presalvage thinning treatment.

The Gypsy Moth Event Monitor relies on the classification of stands into susceptibility levels, which scale the impact of outbreak. Stands 7 and 8 experienced high defoliation, but were classified as moderately susceptible stands by GMEM. This reduced the impacts of outbreaks scheduled by the event monitor and resulted in increased error associated with predicted stand density (TPA). This classification limitation reduces the accuracy of the event monitor. This suggests that users simulate these stands at multiple susceptibility classes when they are on the border of a classification level in order to obtain more accurate results.

Basal area per acre was initially over predicted for stands that experienced high defoliation levels. These prediction errors decreased over time due to multiple scheduled outbreaks present in the FVS simulations. Stands that experienced light defoliation exhibited little reduction in actual basal area growth over time. Basal area was under predicted by the event monitor, which often scheduled one or more outbreaks over the FVS simulation period. The outbreaks had a greater effect on the presalvage thinned stands and their paired controls, which had a higher susceptibility class within the event monitor. This higher susceptibility class resulted in greater prediction error due to higher severity outbreaks.

Overall, GMEM-FVS projections performed most accurately on stands where actual mortality increased slowly over the course of the simulation. The Gypsy Moth Event Monitor modified Forest Vegetation Simulator projections underestimated mortality for all stands, especially those that received high defoliation. Additionally, the simulations underestimated the basal area per acre reductions that accompanied heavy defoliation events. Further analysis is currently underway to determine whether the trends seen in this study are also observed for different stands, defoliated by the gypsy moth, throughout the Appalachian region.

References

Gottschalk, Kurt W. 1993. Silvicultural guidelines for forest stands threatened by the gypsy moth. Gen. Tech. Rep. NE-171. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 49 p.

Hicks, Ray R., Jr. Mudrick, Darlene A. 1994. 1993 forest health: A status report for West Virginia. Charleston, WV: West Virginia Department of Agriculture.

Liebhold, Andrew M.; Muzika, Rose-Marie; Gottschalk, Kurt W. 1998. Does thinning affect gypsy moth dynamics? Forest Science. 44(2):239–245.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Forest Planning

Development of State and Transition Model Assumptions Used in National Forest Plan Revision

Eric B. Henderson[1]

Abstract—State and transition models are being utilized in forest management analysis processes to evaluate assumptions about disturbances and succession. These models assume valid information about seral class successional pathways and timing. The Forest Vegetation Simulator (FVS) was used to evaluate seral class succession assumptions for the Hiawatha National Forest in Michigan's Upper Peninsula. Forest Inventory and Analysis (FIA) plots located on the Hiawatha were stratified by Ecological Land Type and major forest type. A set of algorithms was developed for FVS to grow and evaluate the size class of the plot at each time step of the simulation. Results were evaluated to determine the amount of time vegetation spends in each state before it succeeds. This information was used as basic input for both the Vegetation Dynamics Development Tool and the Spectrum forest planning model used by the Hiawatha for its 2006 forest plan revision.

Introduction

State and Transition Models

State and transition models are used to describe natural processes on a landscape. They can be thought of as a series of boxes and arrows that define the flow of resources through a process. Consider the model displayed in figure 1.The boxes in the figure 1 model are the different states a stand passes through over time and include a description of the state and the ages, or length of time, that the stand remains in that state before transitioning. The arrows are the transitions, and define how resources (in this case land area) pass between the states. The solid arrows in this diagram are used to represent succession, and the dashed arrows are used to represent disturbance. The probabilities associated with the succession transitions describe the likelihood of passage from one state to the next when the stand is at the end of the time it spends in the state. The probabilities of the disturbances represent the average proportion of the land area that passes from one state to the next at each time step. Transitions can be used to describe movement between states or within the same state such as the 1 percent disturbance associated with state 3.

Forest Planning (Linear Programming) Models

There are two typical linear programming formulations of the forest management problem, namely, Model I and Model II (Johnson and Scheurman 1977). National Forests have largely used a Model I formulation of their management problem (Chequamegon-Nicolet National Forest 2004; White Mountain National Forest 2005). Model I is a straightforward formulation whereby all possible future management activities are explicitly enumerated for each stand being analyzed. The strength of the Model I formulation is that exact management plans for each stand can be determined from the solution, and results can be mapped if desired. One drawback of the Model I formulation is that it is difficult to consider the impacts that result from stochastic events such as fires and disease outbreaks. It is also difficult to consider instances of succession.

A Model II linear programming (LP) formulation groups together stands regenerated in the same period into new management units called "transfer classes." Modifications of the Model II formulation have been used to capture the effects of stochastic disturbance and succession events. These modified models are sometimes called Model III (Boychuk and Martell 1996). The drawback of a Model II or Model III formulation is that the stochastic nature of disturbance outbreaks and the loss of stand autonomy that occurs with grouping acres into transfer classes makes exact mapping of the solution impossible. The Hiawatha National Forest used a Model III formulation in its planning process.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forest Analyst, USDA Forest Service, Hiawatha National Forest, Escanaba, MI; e-mail: ehenderson@fs.fed.us.

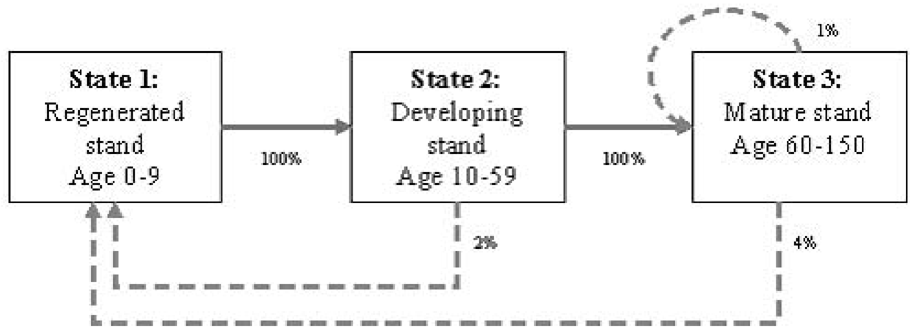


Figure 1—State and transition model example.

Model Synthesis

While a Model III LP formulation may capture the effects of disturbance and succession, it requires users define these parameters. Complete knowledge of disturbance and succession is unavailable, but modeling tools have been developed to help determine intelligent estimates. Merzenich and Hemstrom (2000) describe a method to test the assumptions of a Model III formulation with a state and transition model, the Vegetation Dynamics Development Tool (VDDT) (ESSA Technologies Ltd. 2005). The VDDT model allows for simple succession and disturbance assumption analysis as results are obtained quickly in user-friendly format. Refined succession and disturbance probabilities can then be input into the Model III formulation and an optimal timber management schedule can be determined. The Spectrum linear programming model (USDA Forest Service 2000) was used to solve the Model III formulation used in this study.

Stand development rates and the length of time spent in each state influence how soon a stand can be managed and how likely it is to be disturbed. The Hiawatha National Forest formulated desired vegetation conditions based on the amount of area in each state and had an objective to achieve and maintain the desired state conditions. To optimize a management strategy that allows for the quickest achievement and most robust retention of the desired state, accurate estimates of the parameters of those states must be identified. The Forest Vegetation Simulator (FVS) (Dixon 2003) was the model chosen to strengthen the succession assumptions used in the 2006 Hiawatha National Forest Plan revision. FVS is an individual tree semi-distance-independent tree growth model that can be used to predict stand growth in many parts of the United States (Dixon 2003). This study shows how the FVS model can be used to support or supplement specialist-derived succession assumptions used by the VDDT and Spectrum models.

Objectives

The overall objective of forest planning is to develop a management plan that best achieves the forest's desired conditions. Specifically, there are three key questions to answer:

1. What are the desired conditions (what should the forest look like in the long-term)?
2. What are the natural processes to consider when designing a plan to achieve desired conditions?
3. How are desired conditions efficiently achieved?

The first two questions were addressed by a panel of resource specialists seeking to strike a balance between ecological, wildlife, and timber supply issues. Experiential, empirical, and scientific data were evaluated to estimate desired conditions and recommend an initial set of natural processes to consider. Assumptions were then tested and refined using VDDT. The third question was addressed by using the Spectrum forest management model that combined the assumptions derived from the first two questions to arrive at an optimal management strategy for achieving desired conditions.

The objective of the study was to refine the state classes and succession rates used to model the Hiawatha National Forest. To be clear, disturbance probabilities were not evaluated in this study. State definitions were initially determined by a panel of resource specialists using local knowledge and literature review. FVS was then used to test those assumptions. Specifically, each state was evaluated to determine the average length of time a stand spends in that state before transitioning to a different state. The ages associated with each state were modified as appropriate.

Methods

The Study Area

The Hiawatha National Forest is located in Michigan's Upper Peninsula. It is comprised of approximately 900,000 acres in two distinct geographic units of comparable size. The Eastern Unit is located between St. Ignace, Michigan on Lake Michigan and the southern shore of Lake Superior's Whitefish Bay. The Western Unit is located between Lake Michigan's Big Bay de Noc and the town of Munising, Michigan on Lake Superior. Figure 2 shows the Upper Peninsula of Michigan and the proclamation boundaries of the Hiawatha National Forest.

Ecological Context

The Hiawatha National Forest identified eight succession/disturbance systems within its boundaries, termed Ecological Land Types (ELT):

1. Dry pine (10/20)
2. Rich pine (30)
3. Rich northern hardwood (40/50/90)
4. Transitional (60)
5. Shallow acidic wet (70A)
6. Shallow basic wet (70B)
7. Deep acidic wet (80A)
8. Deep basic wet (80B)

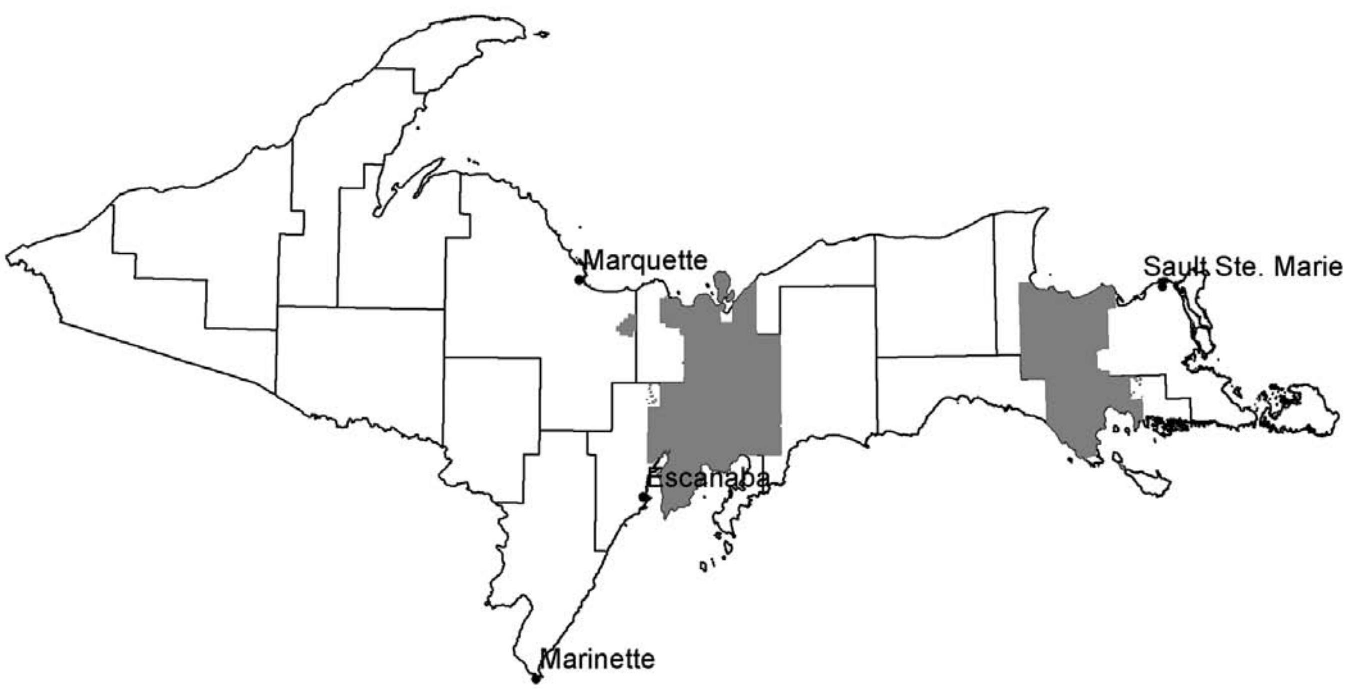


Figure 2—Hiawatha National Forest proclamation boundary in Michigan's Upper Peninsula.

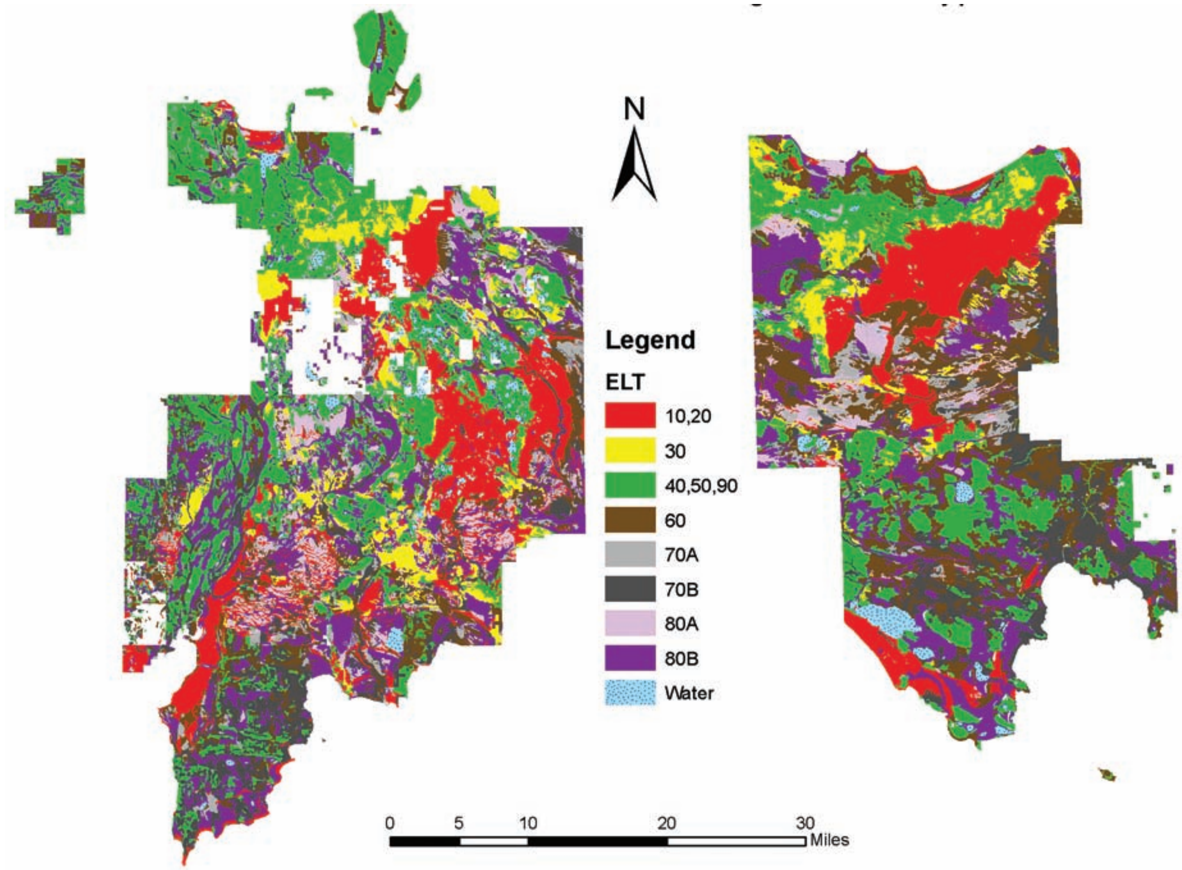


Figure 3—Hiawatha National Forest Ecological land types.

Each ELT has a distinct ecological function. Within each ELT soils are similar, vegetation growth is similar, and disturbance regimes are similar. However, there is a distinct difference between ELTs. A unique set of assumptions, and thus a different VDDT and Spectrum model, was developed for each of the ELTs. A map of the ELTs within the Hiawatha National Forest proclamation boundary is shown in figure 3.

Seral Classes

The panel of resource specialists identified the successional states that occur within each Ecological Land Type. Successional states were combinations of seral stage and size classes called "seral classes." For instance, a "mid" seral stage with a size class of "1" was called a "mid-1" seral class. Seral stage was dependent on major forest type and consisted of aspen, jack pine, mid and late seral stages. Mid and late seral stages were defined differently for each ELT; for example dry pine (10/20) mid seral was an oak/jack pine mix, whereas the rich northern hardwood (40/50/90) mid seral was red pine. There were five size classes used to determine seral class:

1: Stand is composed of trees 0–4.5 feet in height
2: Trees 4.5 feet tall to 5 inches in diameter
3: Trees 5–9 inches in diameter
4: Trees 9–18 inches in diameter
5: Trees 18 inches and greater in diameter

Within each ELT, up to twenty seral classes were identified. Not all seral stages were identified in each ELT.

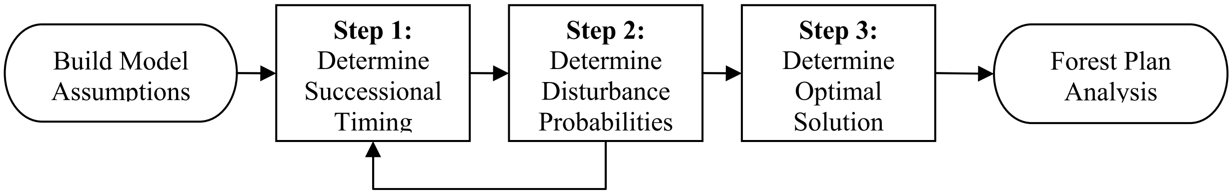


Figure 4—Flowchart of Hiawatha National Forest model development.

Model Development

The process used by the Hiawatha National Forest to develop models for the 2006 management plan revision is shown in figure 4. Within each ELT, seral class successional pathways and disturbance probabilities were determined (Step 1) using resource specialist knowledge and literature review. In Step 2, VDDT was used to fine-tune the successional pathway portion of the assumptions developed at Step 1. The Spectrum linear program model was then used to determine a management scenario to move the forest to its desired ecological condition in an economically-efficient way (Step 3). This resulted in a set of outputs used by the forest to evaluate the management strategy for implications to flora, fauna, economics, and other stakeholders in the forest.

FVS as a Tool to Evaluate Succession Assumptions

The processes described in this paper were used between Step 1 and Step 2 of figure 4. The succession assumptions used in the VDDT and Spectrum model were tested and strengthened with the FVS model.

Data Sources—Forest Inventory and Analysis (FIA) plots located on the Hiawatha National Forest were stratified by Ecological Land Type (ELT) and major forest type and used as input to the FVS model. Data from three FIA cycles was used (1980, 1993, and 2001). There were 26 major ELT/forest type groups identified and evaluated that had at least six FIA plots on Hiawatha National Forest lands.

Calibration—Several FVS calibration exercises were conducted to ensure that the FVS Lakes States variant accurately represented growth specific to the Hiawatha National Forest. This process is described in detail in a document contained in the Hiawatha National Forest planning record (Henderson 2005). Calibration methods used in this study were based on methods developed for other forest plan revision efforts, such as those used on the Chattahoochee-Oconee National Forest (Keyser and Stephens 2002) and the Black Hills National Forest (Vandendriesche 2004). Briefly, the calibration dynamics considered in this model consisted of:

- Local diameter growth calibration based on single-tree re-measurement in different FIA cycles.
- Evaluation of actual maximum stand density index values entered as a constraint (based on Michigan FIA data).
- Evaluation of actual maximum basal area values entered as a constraint (based on Michigan FIA data).
- Evaluation of the largest diameter a species of tree will attain (based on state-wide inventory data) and fitting a senescence curve to approximate that maximum size (using the TreeSzCp keyword).
- Allowing for appropriate in-growth of natural regeneration using the REPUTE software (Vandendriesche 2005) to evaluate in-growth conditions at different stand ages.

Algorithm Development—State transitions were captured in FVS through the use of keywords to track the approximate state of each plot at each time step. Three algorithms were developed to address three possible successional trajectories; one for single-species even-aged stands (such as aspen or jack pine), one for multiple-species single-aged stands (such as balsam fir and white spruce mixed stands), and one for multiple-species, multi-aged stands (such as a northern hardwoods system). The algorithms are unique to the state definitions developed by the Hiawatha National Forest, so only one (single-species even-aged) is included here as an example. Each forest using the methods in this paper will need to develop their own algorithms for their own vegetation definitions.

For even-aged, single forest type plots:

- Determine whether the stand is still the same forest type:
  - If the basal area of the trees in the forest type of interest is less than 30% of the total basal area of the plot and the number of trees per acre of the forest type of interest is less than 20% of the total trees per acre, the plot is removed from calculation (it is assumed to have succeeded to a different forest type or seral stage).
- Determine whether it is regeneration (size class 1):
  - If the plot has not succeeded, then
  - If the average height of the trees between the 30th and 70th tree of the forest type of interest (based on trees per acre) is less than 4.5 feet and the number of trees per acre shorter than 4.5 feet is greater than the number of trees per acre taller than 4.5 feet, then the stand is size class 1
- Determine size classes 2–5:
  - If the size class is not 1 then
  - The size class (2–5) with the greatest basal area of the forest type of interest is used to designate the size class of the stand

Size and Scope of the Analysis—Each of the 26 major forest type groups was run through FVS for a 100-year time frame, using five-year time steps. These runs were done in the absence of any management practices, and were known as “natural growth runs.” Appropriate calibration keywords (discussed above) were used to model more realistic growth. The outputs were assumed to represent the conditions of a stand on a simple successional trajectory. The keywords developed for the appropriate algorithm were added to capture the successional state at each time step.

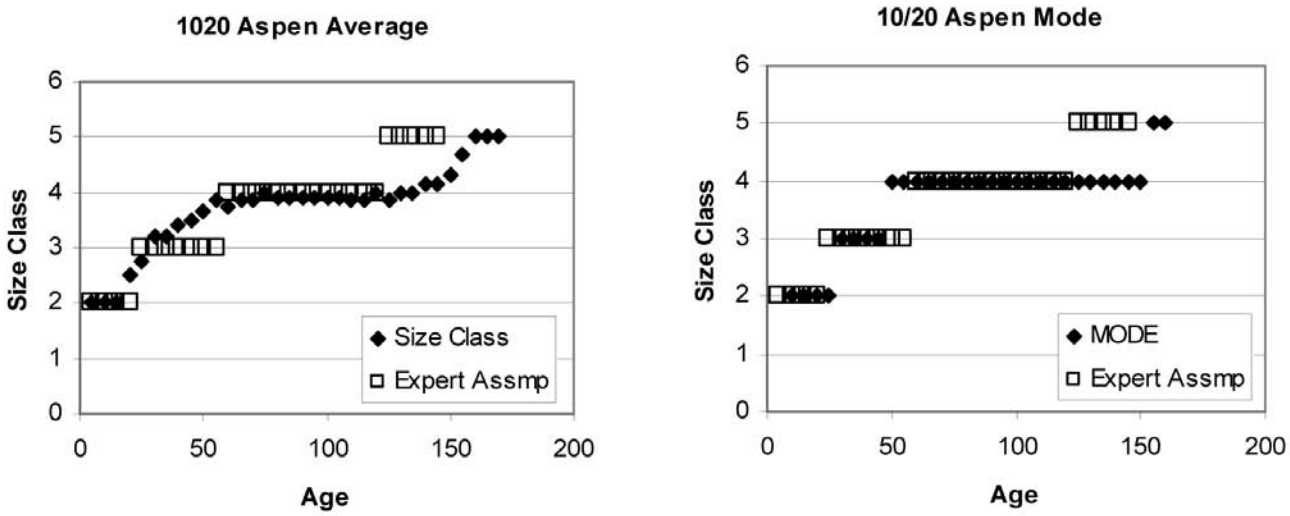
Results and Discussion

Quantifying the Outputs

Each FIA plot’s state at each point in time was output from FVS. Outputs from all plots were then combined and evaluated to determine the average time at which transitions between states occurred. First, outliers and forest type changes were removed from the output files. Three metrics were then calculated, graphed and provided for review by the specialists on the forest. These consisted of the average state, modal state and the number of plots used to calculate the state at all ages represented by the simulation. The existing assumptions were then superimposed (graphically) onto the FVS outputs to give the specialist panel a visual idea of the differences in the assumptions. Figure 5 is an example of the aspen successional pathway in the dry pine ELT (10/20). The solid diamonds represent the FVS output at each age. The hollow squares are the original assumptions that were tested. Each of the 26 successional pathways was run through FVS and quantified in this manner.

Updated Assumptions

Parts of eight successional pathways were modified based on the FVS outputs. Table 1 displays the original ages of the successional pathways as well as the revised ages resulting from this analysis. Generally, modifications involved a 15–20 year shift in age classes. Notable exceptions were the jack pine in the dry pine ELT (10/20) that shifted only 5 years and the late seral in the rich northern hardwood ELT (40/50/90) that involved a 60-year shift. These shifts were based on a sample of over 40 plots in the dry pine ELT and over 120 plots in the rich northern hardwood ELT. In other instances, the FVS model runs either supported the initial estimates, or there was insufficient data to cause the panel to change the assumptions.



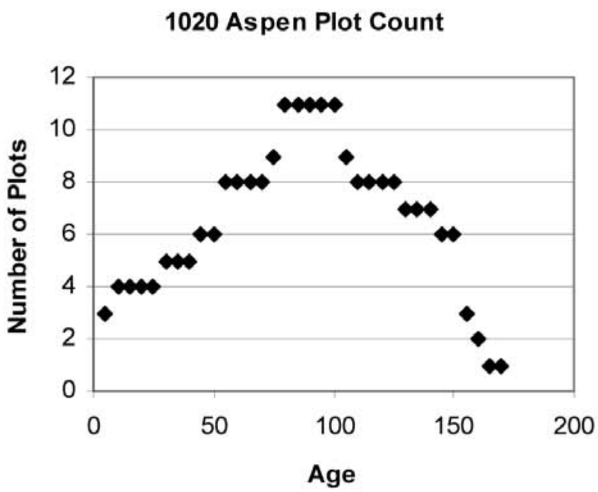


Figure 5—Average state, Mode state, and plots used to calculate the state at different ages.

Discussion

This analysis adequately validated the initial assumptions used in the Hiawatha National Forest plan revision and is included in the plan project record to serve as supporting documentation. Though most initial assumptions were confirmed, this analysis helped modify areas where specialist opinion was not clear. In the end, better assumptions about forest processes and growth will lead to a better forest plan and more informed management decisions.

This study evaluated the amount of time vegetation remains in a specific size class, but ignored transitions to different seral stage trajectories. If after growing out of a size class the plot was a part of the same seral stage, it was used for further analysis. If the plot was a part of a different seral stage, it was ignored. However, timing and proportions of seral stage changes can be used as inputs to VDDT and Spectrum to create more realistic models. The FVS analysis presented here, with slight modification, can be used to identify proportions and timing of transitions to different seral stages.

For future planning projects, FVS may be run prior to the initial resource specialist meeting, i.e., before Step 1 of figure 4. This may allow for final decisions to be made earlier in the planning process without as many iterations between specialist review and model testing. Earlier information can lead to more efficient use of time and an expedited planning process.

Table 1—Original and revised ages of successional pathways.

ELT	Size class	Aspen		Jack pine		Mid seral		Late seral	
		Original ages	Revised ages[a]	Original ages	Revised ages[a]	Original ages	Revised ages[a]	Original ages	Revised ages[a]
	1	1–5		1–5	1–10	1–10		1–10	
	2	6–25		6–25	11–25	11–30		11–30	
10 20	3	26–60		26–60		31–60		35–50	
	4	61–125		61–125		61–125		51–125	
	5	126–150		126–150		126–250		125+	
	1	1–5		1–5		1–10		1–10	
	2	6–25		6–25		11–30		11–40	
30	3	26–50		26–50		31–55	31–45	41–65	
	4	51–100		51–100		56–90	46–115	66–100	
	5	101–150		101–150		91–400	116–400	101+	
	1	1–5				0–5		0–5	
	2	6–20				6–25		6–30	
40 50 90	3	21–45		[b]		26–55		31–90	
	4	46–90				56–125		91–250	91–190
	5	91–150				126–300		250+	190+
	1	0–5		0–5		1–10		1–10	
	2	6–25		6–25		11–30		11–40	
60	3	26–55		26–55		31–60		41–80	
	4	56–100		56–100		61–100		81–180	81–150
	5	101–150		101–150		101–400		181+	150+
	1	1–5		1–5		1–5		1–10	
	2	6–30		6–30		6–40		11–40	
70 A	3	31–60		31–60	31–75	41–75		41–90	41–120
	4	61–110		61–110	76–110	76–150		91–225	121–225
	5	111–150		111–150		151–200		226+	
	1	1–5				1–10		1–10	
	2	6–30				11–40		11–40	
70 B	3	31–60		[b]		41–75		41–90	41–70
	4	61–110				76–150		91–200	71–200
	5	111–150				151–250		201+	
	1					1–10		1–20	
	2					11–40		21–60	
80 A	3	[b]		[b]		41–80		61–100	
	4					81–150		101–200	
	5					151–250		201+	
	1					1–10		1–15	
	2					11–35		16–50	
80 B	3	[b]		[b]		36–75		51–100	51–85
	4					75–150		101–200	86–200
	5					151–250		201+	

[a] Only modified successional pathways show revised ages.
[b] Successional pathways not defined in this ELT.

References

Boychuck, D.; Martell, D. 1996. A multi-stage stochastic programming model for sustainable forest-level timber supply under risk of fire. Forest Science. 42:10–26.

Chequamegon-Nicolet National Forest. 2004. Final environmental impact statement Appendix B. R9-CN-FEIS. Park Falls, WI: U.S. Department of Agriculture, Forest Service, Chequamegon-Nicolet National Forest. 74 p. Online: http://www.fs.fed.us/r9/cnnf/natres/final_forest_plan/feis_appendices/CNNF_2004_FEIS_APP_B_DescriptionAnalysisProcess.pdf

Dixon, Gary E., comp. 2003. *Essential FVS: A user's guide to the Forest Vegetation Simulator*. Internal Report. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.

ESSA Technologies Ltd. 2005. Vegetation Dynamics Development Tool user guide, Version 5.1. Vancouver, BC: ESSA Technologies Ltd. 188 p. Online: http://www.essa.com/downloads/vddt/VDDT-51-User-Guide.pdf

Henderson, Eric B. 2005. Yield table development for the Hiawatha National Forest. Hiawatha National Forest 2006 planning record. Escanaba, MI. 35 p.

Johnson, K. N.; Scheurman, H. L. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives—Discussion and synthesis. Forest Science Monograph. 18.

Keyser, C.; Stephens, R. 2002. Calibrating FVS for the Chattahoochee-Oconee National Forest planning effort. In: Crookston, N. L., Havis, R. N., comps. Second Forest Vegetation Simulator conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 45–51.

Merzenich, J.; Hemstrom, M. 2000. Ecosystem modeling using Spectrum and RELMDSS: Analyzing vegetative succession for forest plan revisions. In: Seventh symposium on systems analysis in forest resources; Traverse City, MI; 1997 May 28–31. Gen. Tech. Rep. NC-205. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 22–26.

U.S. Department of Agriculture, Forest Service 2000. Spectrum user's manual. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Inventory and Monitoring Institute. 230 p. Online: http://www.fs.fed.us/institute/planning_center/download_center.html#spectrum

Vandendriesche, D. 2004. Description of the analysis process regarding the construction of vegetative yield profiles. In: Black Hills National Forest Phase II Amendment. Custer, SD: U.S. Department of Agriculture, Forest Service, Rocky Mountain Region, Black Hills National Forest. 130 p. Online: http://www.fs.fed.us/r2/blackhills/projects/planning/assessments/phase_II/constrct_veg_yield_profiles.pdf

Vandendriesche, D. 2005. Advance FVS topics for forest planning. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. Online: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_advance-topics.php

White Mountain National Forest. 2005. Final environmental impact statement Appendix B. Laconia, NH: U.S. Department of Agriculture, Forest Service, White Mountain National Forest. 54 p. Online: http://www.fs.fed.us/r9/forests/white_mountain/projects/forest_plan_revision/pdf_documents/FEIS_PDF/B_FEIS_analysis.pdf

The content of this paper reflects the views of the author, who is responsible for the facts and accuracy of the information presented herein.

Use of FVS for a Forest-Wide Inventory on the Spokane Indian Reservation

Ted Hensold[1]

Abstract—The Forest Vegetation Simulator (FVS) was used with Continuous Forest Inventory (CFI) data on the Spokane Indian Reservation to provide predicted yields over a 100-year period for 994 1/5 acre plots. The plots were grouped into five strata based on habitat type groupings, projected separately, and the stratum results were combined after processing. Results from the projections provided information which was useful in management planning. Problems with the unbalanced age-class distribution of the forest were shown to be largely compensated for by differing rates of the development among the different strata. Although stocking levels and harvest yields within most strata fluctuated over time, the variations of forest-wide averages were considerably smoother. The results also predicted which components of the forest would likely suffer the highest rates of mortality in the near-term, and should receive more management attention. At the outset, this study also sought to test several differing options for management, such as precommercial thinning, regeneration density, and type of regeneration. However, FVS only demonstrated a difference in yields in the last case.

Introduction

The Spokane Indian Reservation has a system of Continuous Forest Inventory (CFI) plots which are used to monitor forest growth, mortality, and health problems. The system has been in place since 1957, and periodic measurements are used to calculate an annual allowable cut for the reservation.

In the most recent inventory (1998), data were projected in the Forest Vegetation Simulator (FVS) model (Wykoff and others 1982) to provide a comparison with more conventional analysis tools used in the past. To accomplish this, 1/5-acre plot data were expanded to a per-acre basis, converted to FVS-ready files, and projected in FVS. Plots were projected individually; however, five groupings were used for applying base parameters such as habitat type, calibration factors, and management options. The results were compiled for each of the five groups in FVSSTAND and then the groups were combined in a spreadsheet to present forest-wide results.

Three methods were used in the inventory analysis; FVS a semi-distance-independent growth and yield model, the Australian formula (Recknagel 1913), a method based on growing stock and increment, and the area-volume check, a stand analysis method based on area and increment by age class (Davis 1987). These methods were evaluated to determine the most accurate and efficient method or combination of methods to set an allowable cut.

Objectives for the Analysis

In analyzing the 1998 CFI data, two objectives were set forth for the task of computing an annual allowable cut (AAC). The first was to duplicate as nearly as possible the chief methods used with the previous (1985) inventory, for comparison purposes. The second was to also employ a newer method that might have some advantages over those used formerly.

The Austrian formula and the area-volume check methods were used in the 1985 Inventory Analysis, and were replicated in the 1998 analysis. For a third method of analysis, growth was projected on inventory data using the Inland Empire variant of the Forest Vegetation Simulator (FVS) model. Projections also included natural mortality factors, timber harvests, precommercial thinning and regeneration. However, unlike the more conventional analysis methods, FVS projections did not produce an AAC in the usual sense, but provided projected yields from timber harvests over time for a given management regime. A long term average of the yields projected by FVS was compared with the Austrian formula and the area-volume check methods.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forester, Bureau of Indian Affairs, Spokane Agency, Wellpinit, WA; e-mail: thensold@icehouse.net.

Extending CFI Utility Using FVS

Using conventional CFI data analysis tools, we are only able to analyze in detail stand development over the most recent measurement period. Looking backwards beyond that point, conclusions can only be very broadly drawn, and 41 years into the past is as far as the Spokane Reservation CFI system goes. The most recent 13-year growth period is just a snapshot compared to the long-term perspective needed to evaluate progress in forest regulation. The FVS model provides the capability of projecting development of inventory plots into the future for a longer period of time to obtain a long-range picture of stand dynamics.

Growth

Under traditional AAC calculation methods, measured growth rates for the last growth period are used in order to determine the cut for the future. The problem, however, is that growth rates may increase or decrease in the future based on changes in stand conditions, weather conditions and other factors. Growth rates in FVS do vary according to stand density and development, and this hopefully will indicate imminent changes in the forest.

Mortality

Mortality is an important component of the AAC calculation. If insects and diseases take a larger share of the potential volume in the future, we must harvest less. However, none of the other methods offer any way of predicting if mortality in the next period will follow suit with the previous period, increase or decrease. A review of mortality measured in previous inventories indicates that it is the least stable parameter tracked. FVS does simulate mortality in projections, as “background” mortality, mortality based on stand density, and from a variety of specific agents.

Harvest Yields

One crucial issue in this analysis was the effect that the unbalanced age-class distribution of the forest might have in determining a level of yield from the forest which could be sustained indefinitely without fluctuation or decline. The FVS model provides the opportunity to grow plots forward in time, independently, starting at their current point of development. Growth and mortality rates can be adjusted, based on that which has been measured. Current silvicultural regimes (as well as alternatives) were applied to each plot independently. The yields from all plots were then combined, cycle by cycle, to project the effects of the existing age-class distribution on long-term harvest yields.

Calibration

The FVS model has built-in functions for the various growth components as well as mortality; these are based on site factors (such as habitat type, slope, aspect, elevation) and stand conditions (density, overstory effects). It also uses measured growth, if available, to calibrate growth. In addition, there are user-controlled keywords that can be invoked to bring model growth and mortality projections more in line with the rates observed in our inventory.

How FVS Was Used in This Analysis

The overall approach in this analysis was to provide the tribal decision-makers with the range of solutions that resulted from each of these methods, and allow them to select an AAC that the data could support and that meets tribal objectives as a whole.

Mindful of the strengths and weaknesses of the FVS model, we proposed to use projections to provide some perspective on future trends, especially in areas where the other methods fall short. In particular, the following questions were addressed.

- What yields will current management practices produce over the next 40 to 50 years?
- Does FVS forecast an increase in mortality that might impact yields?
- Will the current age-class distribution of the forest result in a future down-cycle in harvest yields?
- Can FVS be used to identify the more vulnerable components of the forest as a means to focus harvest in the coming decade?
- Can yields be improved using alternatives to current management on a long-term basis?

Data Conversion

The Bureau of Indian Affairs Northwest Regional Office provided the CFI-to-Suppose program that converted CFI plot data into formatted FVS-ready files. The plot header data for each plot was read by the program to create one line of data for the FVS stand list files (*.slf). The program also read CFI tree data to create an FVS tree file (*.fvs) for each plot. FVS allows for up to two different plot sizes for each plot, whereas the Spokane CFI uses four plot sizes. Sawtimber is measured on a 1/5-acre plot; poletimber on a 1/20-acre minor plot; saplings on 1/80-acre minor plot; and seedlings on 1/240-acre. As an additional step, the program expands pole data by four to a 1/5-acre plot basis, and the seedling data by three to a 1/80-acre basis.

Stratification

The FVS model is designed to use stand exam data. This type of inventory differs from a CFI in many ways. It would typically be run in aggregation, with many plots making up a single data set run as a unit. CFI data is extensive; the plots are widely scattered, have widely varying attributes and are not designed to give stand level information. Projecting CFI plots in aggregate would give misleading results. So for the purposes of these projections, each plot was projected separately as a unit and the results were aggregated at the end.

Although CFI plots are not spatially related to each other, many share similar site features. These can be a basis for grouping plots for the purposes of calibration, regeneration input, growth simulation and management activities. In this analysis, the plots were grouped into four strata based on habitat type (Cooper and others 1991; Zamora 1983). The model did not support all habitat types recognized in the CFI, so type codes that were supported by FVS had to be substituted in some cases. These are listed in table 1 with data relevant to the groups.

Dry Pine Stratum

This grouping represents the driest sites on the reservation, all ponderosa pine (*Pinus ponderosa*) climax. It presents a challenge for the Inland Empire variant of the model, since only one of the four habitat types in the group (Pipo/Agsp) is supported by the model. To match measured increment, it was necessary to dampen growth in FVS considerably using model calibration.

Pine-Fir Stratum

This stratum represents the largest acreage and the most plots of the four, including wet ponderosa pine and dry Douglas-fir sites. One or both of these two species dominate the stands in this stratum. Western larch (*Larix occidentalis)* and lodgepole pine (*Pinus contorta)* are also present as small fractions on some of the plots. All three habitat types of this stratum are supported by FVS.

Ninebark Stratum

This represents both Douglas-fir/ninebark (*Pseudotsuga menziesii* / *Physocarpus malvaceus)* and grand fir/ninebark (*Abies grandis* / *Physocarpus malvaceus)* types found in the inventory. It was a problem that FVS does not recognize the grand fir/ninebark

Table 1— Habitat type codes used for FVS runs, 1998 Spokane CFI.[a]

Stratum name	Habitat types	FVS habitat types Code	FVS habitat types Name	Number of plots	Estimated acres
Dry pine	Pipo/Stco	130	Pipo/Agsp	227	24,045
	Pipo/Agsp	130	Pipo/Agsp		
	Pipo/Feid	130	Pipo/Agsp		
	Pipo/Putr	130	Pipo/Agsp		
Pine-fir	Pipo/Syal	170	Pipo/Syal	388	41,311
	Psme/Syal	310	Psme/Syal		
	Psme/Caru	320	Psme/Caru		
Ninebark	Psme/Phma	260	Psme/Phma	217	22,986
	Abgr/Phma	260	Psme/Phma		
Wet grand fir	Psme/Vaca	250	Psme/Vaca	159	16,948
	Abgr/Libo	520	Abgr/Clun		
	Abgr/Clun	520	Abgr/Clun		
	Thpl/Clun	530	Thpl/Clun		

[a] Zamora 1983; Cooper and others 1991.

habitat type. This became a significant issue in the input of regeneration—the plots that were on Douglas-fir habitat types could not be expected to produce grand fir seedlings; the grand fir types would. This was resolved by calculating a count of the grand fir trees on the plot in each cycle. If the count was greater than zero and regeneration input was prescribed, then natural regeneration called into the routine would include grand fir, as well as greater numbers of the other species. Two different management simulations were tried, one which allowed for the prospect of planting western larch and ponderosa pine, and one which confined regeneration inputs to natural seeding, dominated by the more shade tolerant species.

Wet Grand Fir Stratum

These are the wettest sites on the reservation, and the most complex in terms of species mixes. Although this group has the smallest number of plots, it was further subdivided into two substrata to enable different treatments for plots with lodgepole pine as opposed to those without. This would allow more realistic inputs of regeneration as well as varying the other treatments to better reflect actual management practices. Unlike the method used for the ninebark stratum, these groups were run as separate strata; the set without lodgepole pine included 92 plots, the set with lodgepole pine, 68 plots. These two strata also were tried with different regeneration options, one with planted ponderosa pine and western larch and the other with only natural seeding.

Model Calibration, Adjustments, and Inputs

The Inland Empire variant was built with little data that included sites as dry as the Spokane Reservation, and ponderosa pine growth functions are particularly weak (William Wykoff, personal communication, September 1999). So that projections would better reflect current local conditions, growth and mortality functions were calibrated using data from the CFI in the latest measurement period. It should be noted that calibration was not determined and applied on a plot-by-plot basis, but rather stratum by stratum.

Large Tree Diameter Growth

Each stratum was run through the model for a single cycle using the CALBSTAT keyword, to obtain an overall average for the stratum of the scaling factors computed for individual plots. These averages were used as permanent scaling factors for each stratum with the READCORD keyword and no further scaling or attenuation was allowed (NOCALB).

Large Tree Height Growth

There is no scaling factor calculated for this component and no simple way to compare height development with inventory data. However, preliminary runs appeared to attain unrealistic standing volumes of timber, even with diameter growth calibrated, so height growth seemed suspect. To look at how heights developed in the model, some bare-ground runs were generated, and top-40 heights were tracked and graphed. For a real-world comparison, some CFI plots were selected to graph as an age-height scatterplot. Plots were selected which had a simple even-aged structure, included a range of stand ages, were measured in both 1985 and 1998, showed a reasonable and predictable diameter increase from 1985 to 1998, did not have a significant harvest in that period, and had at least 40 trees per acre in 1998.

These plots were graphed and compared to the age-height curve of the bare-ground FVS runs. This was done for two strata, pine-fir and ninebark. In both cases, FVS heights developed more rapidly and attained greater heights than the comparison plots. Early growth rates, up to about 50 years of age, were most strikingly different. To scale back FVS growth rates, the FIXHTG keyword was used, applying it only to trees 0.1” to 7.5” DBH. After several trials, it was found that a multiplier of 0.60 lowered the projected height curve into the range of the CFI plot observations for the two strata considered. This adjustment was used for all species in all strata.

Regeneration Inputs

The FVS model is capable of automatic natural regeneration inputs, controlled by factors such as stand density and habitat typing (Ferguson and others 1991). Initial runs were made allowing this input. However, this option seemed to multiply the complexity of the runs beyond what was either beneficial or desirable given the objectives at hand. Instead, the automatic inputs were suppressed (NOAUTOES) and whenever density was reduced to a given level, either by natural conditions or harvest, regeneration was invoked using the PLANT or NATURAL keywords. The questions of how much and what species of regeneration would be invoked were resolved by running each stratum through the Spokane CFI program to generate a regeneration summary. This provided an average count of seedlings per acre by species from the seedling subplot. These runs were limited to plots that had a seedling/sapling understory. The results yielded some rough guidelines as to how much regeneration and what species should be invoked.

This approach has some shortcomings. By limiting the Spokane CFI program sample runs to those plots with a seedling/sapling understory, it may have effectively eliminated open areas where natural regeneration had failed. Also, using an average for all plots might tend to obscure the negative aspects of having some areas with excessive stocking and others that are marginally stocked. An ideal solution might be to use a randomized input, where regeneration falls within a normal range of distribution around a specified mean. However, this was not attempted.

On most sites on the reservation, natural regeneration does not seem to be a problem when an opening is created. This generalization is most true on the kinds of sites represented in the pine-fir stratum and the wet grand fir stratum. In these strata, the approach of invoking an average stocking for reproduction when stocking fell below a given level seems reasonable. For the other two strata, this approach probably led to some underestimation of the growth losses resulting from incomplete or patchy regeneration patterns.

Mortality Functions—Maximum Basal Area

In reviewing the preliminary runs, it was apparent that inventory trees fared better inside the model than out in the woods. Mortality in projections seemed consistently lower than what was seen in the last growth period of the CFI. The 1998 inventory registered rates of mortality which, although higher than those from the 1985 inventory, were in line with earlier measurements. So it appeared reasonable to calibrate the model to approximate current mortality, at least into the first growth cycle or two.

The first function that was looked at was maximum basal area. This varies with habitat type and controls background mortality in the model. The closer the stand is to the maximum, the more trees die. Given the fact that there are still plenty of stands in the forest that have not yet been thinned, one might compare the highest basal area

CFI plots for each habitat type with those used in the model. This was done, and in all cases was found to be lower for the inventory data. To adjust this, the BAMAX keyword was used, with the appropriate level specified for each stratum.

Mortality Functions—Mortmult

The BAMAX keyword increased mortality slightly, but still fell short of approximating mortality for some species in some strata. Next, mortality rates, expressed as a ratio of cubic-foot mortality to cubic-foot stocking (by species) were compared between the 1985–1998 measurement and the first cycle projection in FVS (1999–2008). In the two strata where root disease is prevalent, only non-diseased plots were used for the comparison, since root disease mortality could be adjusted separately in the Western Root Disease Model extension. From these comparisons, multipliers were calculated for each species in each stratum. These were fed into the model using the MORTMULT keyword.

Mortality Functions—Western Root Disease Model

The Western Root Disease Model extension was invoked on plots where root disease had been diagnosed in 1998 inventory. For these plots, even with both BAMAX and MORTMULT adjustments in the run-stream, it was noted that (compared to 1998 CFI results) mortality for Douglas-fir was underestimated in the wet grand fir stratum, while mortality for grand fir was underestimated in the ninebark stratum. Using the root disease model, mortality was further adjusted using both the TTDMULT and INFMULT keywords. It took several trial iterations varying the multipliers to arrive at mortality rates for all species that approximated in the first projection period what had been measured in the latest CFI growth period.

The FVS Run-Streams

The first step in building the FVS run-streams was to create the basic set of keywords for each stratum to control program outputs, volume equations, growth and mortality functions, etc. These keywords were read into a base *.kcp file for each stratum to streamline the process of building other runs.

The Management Regime

A set of keywords was assembled for each stratum that was designed to simulate the full management regime that a stand (or in this case, a plot) might undergo over a 100-year period. Using condition statements, the model would recognize the particular state of development and condition at which a plot entered the simulation; simulate a management activity based on that condition; grow the plot forward for 10 years; again assess the plot conditions; simulate a new management activity based on the new set of conditions (if called for); and repeat this process for ten 10-year projection cycles. During the full 100 years of projections, most plots would go through a similar cycle of stand development and stand treatments, including precommercial thinning, one or more commercial thinnings, a regeneration harvest (with regeneration added), and an overstory removal to reduce stocking of residual trees. What differed between plots was the stage of development at which they entered the sequence.

The Event Monitor Function

Since each plot entered the model separately and at its own particular stage of development, the management options were invoked through the Event Monitor function of the model (Crookston 1990). This function allows the application of a particular treatment to be made contingent on the stand meeting a given set of parameters at the beginning of each cycle.

The condition statements were designed to recognize the stand conditions that would typically initiate a particular treatment in actual management under current regimes. They were also designed (for the most part) to be mutually exclusive: for example, if a plot met the conditions for a commercial thinning, it could not, in the same cycle, meet the conditions for a regeneration cut or any other management option. Condition statements variously used the following parameters for timing treatments.

- Stand age
- Total basal area per acre
- Sawtimber basal area per acre
- Total number of trees per acre
- Number of trees per acre of saplings and/or pole sizes
- Ratio of cubic-foot mortality to cubic-foot stocking
- Stand mistletoe rating
- Quadratic mean diameter

Stand age was one of the plot attributes read into FVS in the data conversion, and it had an important role in conditioning and ordering management activities. When a regeneration harvest was invoked, the stand age of the plot was reset to reflect the age of new regeneration.

Management Activities

Simulated treatments were developed through repeated trial runs and examination of outputs to determine if treatments were invoked when desired and whether the application of the treatments matched what might be expected in actual management. The range of treatments that made up the management regime for each stratum were essentially the same, except that the conditions required to invoke them, the residual densities, regeneration specifications, and so on, were varied as appropriate for the stratum. Following is a description of each type of treatment included in the management regime for each stratum.

Initial Input of Regeneration—This was invoked to provide an input of regeneration into the model on plots that began simulations with a light or scattered overstory and an unstocked or understocked understory, This was only applied in cycle 1 and was designed to provide regeneration for plots that had been subjected to a recent overstory reduction and where regeneration had not yet come into the plot.

Overstory Removal—This was applied to plots with a stand age less than 31, a light to scattered overstory and a well-stocked understory. Overstory was reduced to a few reserve trees.

Precommercial Thinning, Alternative 1—The condition statement recognizes plots with greater than 500 trees per acre from seedling to 5" dbh and invokes a precommercial thinning. This may occur in the same cycle as a commercial harvest.

Precommercial Thinning, Alternative 2—This was formulated because the first precommercial thinning alternative failed to thin older stands that had dense conditions in pole-size trees but fewer than 500 trees per acre in smaller sizes. This is often the case in stands on the reservation that have never been thinned and have stagnated before reaching commercial size.

First Commercial Thinning, Alternative 1—This treatment was applied to stands reaching merchantable size for the first time (usually 50 to 80 years old) to reduce stocking in overly dense stands and to harvest volume.

First Commercial Thinning, Alternative 2—The previously described first commercial thinning occasionally missed stands with an age less than 50 that nonetheless had considerable basal area in sawtimber. These are most likely plots with multiple age/size classes, in which the selected stand age call applied to the younger group rather than the older group. Plots were thinned to the same target as alternative 1.

Second Commercial Thinning—This thinning was applied to slightly older stands, usually occurring about 20 years after a first commercial thinning, and leaving a slightly higher basal area.

Regeneration Cut, Light Stocking—This regeneration harvest was applied to plots with stand age greater than 100 (or 80 in the lodgepole stratum) with a low basal area. The stand is harvested, leaving some residuals, regeneration is invoked and stand age is reset.

Regeneration Cut, High Mortality—A regeneration cut was applied to older stands when the mortality in cubic-foot volume for a cycle exceeded 30 percent of total stocking. The stand is harvested, leaving some residuals, regeneration is invoked and stand age is reset.

Regeneration Cut, Mistletoe—A regeneration cut was applied to older stands with a stand mistletoe rating that exceeded 1.8. The stand is harvested, leaving some residuals, regeneration is invoked and stand age is reset.

Mature Stand Maintenance Thin—This is a light commercial thin for older stands that have continued to build basal area after the second commercial thin, but thus far not met any conditions for a regeneration cut.

Other Program Control Functions

Some additional constraints were placed on the stand treatments as they were invoked. First of all, treatments that removed harvestable volume could not be invoked until at least 20 years after the last harvest. This was designed to imitate the 20-year management cycle in use on the reservation. Second, each treatment had a particular repeat delay set for it. For example, regeneration cuts were permitted at a minimum interval of 80 years; precommercial thinnings were on a 40-year interval. Many of the condition statements that controlled the management options were based partly on stand age. This also had the effect of limiting the possibility that a particular management activity be repeated.

Management Options

As noted above, one of the objectives for using FVS was to test different management options. This was only attempted in a fairly limited way, since an encyclopedic testing of management regimes for each of the five plot strata was well beyond the scope of an inventory analysis. But it seemed worthwhile to test the sensitivity of the results to some simple variations in management, particularly those that addressed changes currently under consideration. Some of the options that were considered are outlined below. In some cases, it was concluded that FVS was not suited to analyze the option in a comparative way.

Regeneration Unit Size (Uneven-Aged vs. Even-Aged)

This was suggested as an appropriate option to test using FVS simulations, since the use of even-aged management and specifically even-aged regeneration cuts is currently under review for the upcoming management plan. So the comparison would basically be between regeneration by group selection vs. regeneration by clearcut with residuals.

However, given the fact that the FVS simulations were based on projecting individual fifth-acre plots, it seemed impossible to make any distinction between the group selection cut and a larger even-aged regeneration cut. As applied on the reservation, both are done leaving some residual stocking, and both are carried out over areas larger than 1/5-acre. So this comparison was mooted.

Regeneration Type, Natural vs. Planted

For types represented by the two drier inventory strata, natural regeneration has been effective on the reservation, and no alternative to that has been seriously considered. On wetter types, however, both natural and planted regeneration methods have been used, and are the subject of some debate and controversy. In fact, this is an aspect of even-aged vs. uneven-aged management that could be tested. Up to the present, planting has been considered a viable option only in even-aged management on the reservation.

In this comparison, the key distinction at the plot level is the species and amount of regeneration that is introduced in a planted treatment, versus that which is obtained by natural seeding. Natural regeneration inputs (tried as “option 1”) were determined for each stratum by analyzing the CFI data as previously described. These runs were compared to “option 2,” which simulated planting of ponderosa pine and western larch in the numbers usually prescribed for planting treatments on the Spokane Reservation.

Option 2 also included natural regeneration in reduced numbers from option 1, as based on stocking surveys from areas which have been planted on the Spokane Reservation.

Regeneration Density

As noted earlier, some concerns were raised over the use of average figures across the board for natural regeneration input. To test the effects of higher versus lower densities, some initial runs were tried at varying densities and results were compared. Surprisingly, varying the density of natural regeneration inputs into the model had very little effect on long-term volume yields.

Precommercial Thinning

Another aspect of management that was considered for testing was the relative efficacy of precommercial thinning. The use of these treatments is not controversial or considered for revision. However, precommercial thinning is not uniformly implemented on all stands that need treatment. So it seemed worthwhile to try a set of runs without precommercial thinning and to compare that to runs with the treatment. If this showed a large difference in yields, it might indicate the need to discount yields in accordance with the percentage of stands that might not receive the treatment as needed.

Precommercial thinning was found to have practically no effect on overall yields. Although stand mean diameters were affected, overall yields on a board-foot per acre were nearly identical. The results from these last two tests provoked some skepticism concerning performance of the model.

FVS Projection Results and Discussion

The output from the runs was post-processed using the FVSSTAND module. This module combined all the plot outputs (which were each projected separately) into summary tables for an entire stratum. These stratum summaries in turn were combined into an “all strata” summary table, which weighted each stratum by the proportion of the mapped acres it represented. Charts were produced from these summary tables.

The charts show how FVS-projected stocking, harvest yields and mortality change over time. Data are displayed for each stratum and for all five strata combined. For the wetter sites, which include the ninebark, grand fir, and lodgepole strata, charts show trends for two different management options. Option 1 represents current management treatments, with input of only natural regeneration when regeneration cuts are made. Option 2 (applied only to the wetter sites and not the dry pine and pine-fir strata) uses all the same treatments, except that regeneration cuts are accompanied by an input of planted ponderosa pine and western larch, as well as natural regeneration in reduced numbers.

Stocking Projections

Figures 1 through 6 show board-foot stocking for each stratum and for the combined data weighted by plot proportion. Note the scale of the y-axis differs from chart to chart when comparing overall stocking levels.

One thing evident in each stratum is that while stocking varies up to the year 2048, after 2048 stocking climbs steadily. This may indicate a tendency in the model to build unrealistic volumes, which becomes most pronounced in later projections as real measured tree data is gradually replaced by trees that have entered projections as regeneration inputs. For this reason, projected volume levels after 2048 may be suspect, although the relative difference between option 1 and option 2 are of interest.

Stocking changes over time vary greatly depending on the stratum. The pine-fir stratum (fig. 3) shows the most even stocking levels up to 2048, staying between 9,000 and 10,000 board-feet per acre for that entire period. This might indicate that the pine-fir stratum currently has the most diverse age-class distribution. The dry pine stratum (fig. 2) alone climbs continuously in volume, which may indicate a greater proportion of plots in younger age classes. In fact, this stratum has 26 percent of its plots with a stand age less than, 60, more than any other stratum.

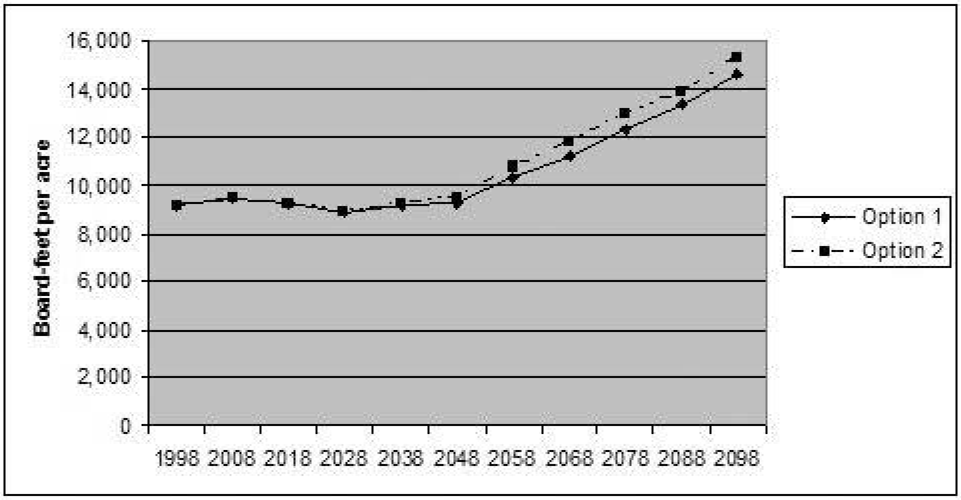


Figure 1—Board-foot stocking projections from FVS, all strata combined.

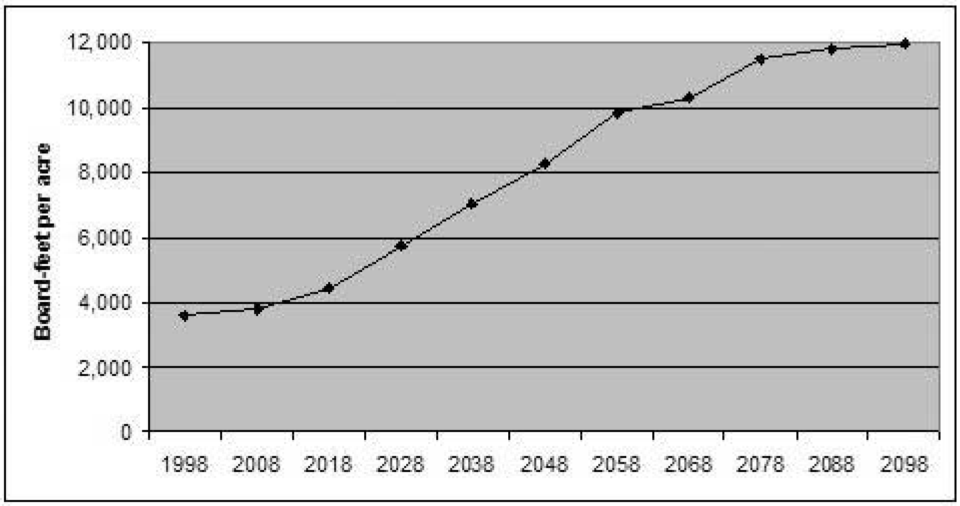


Figure 2—Board-foot stocking projections from FVS, dry pine stratum.

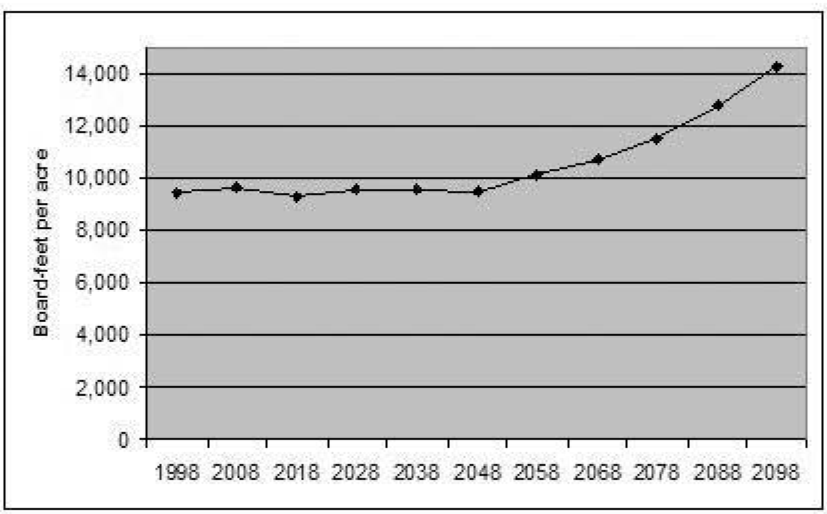


Figure 3—Board-foot stocking projections from FVS, pine-fir stratum.

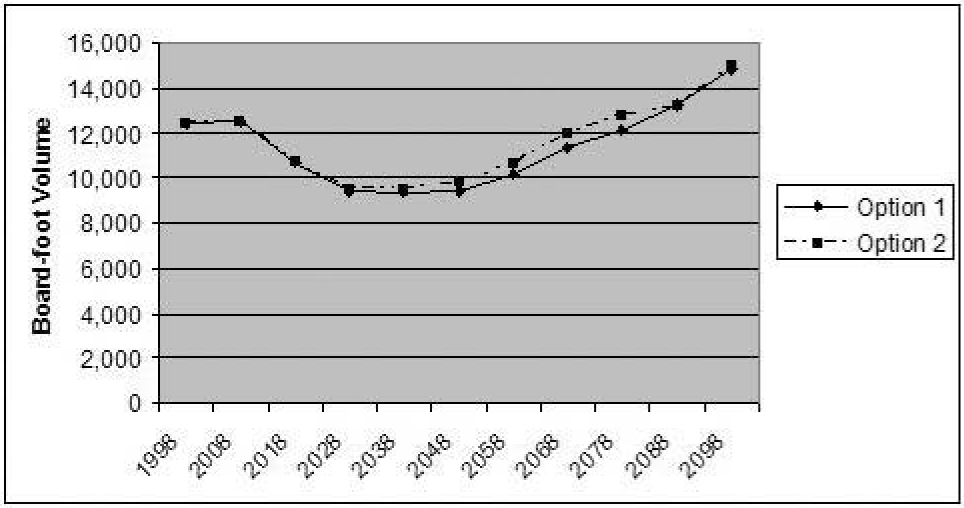


Figure 4—Board-foot stocking projections from FVS, ninebark stratum.

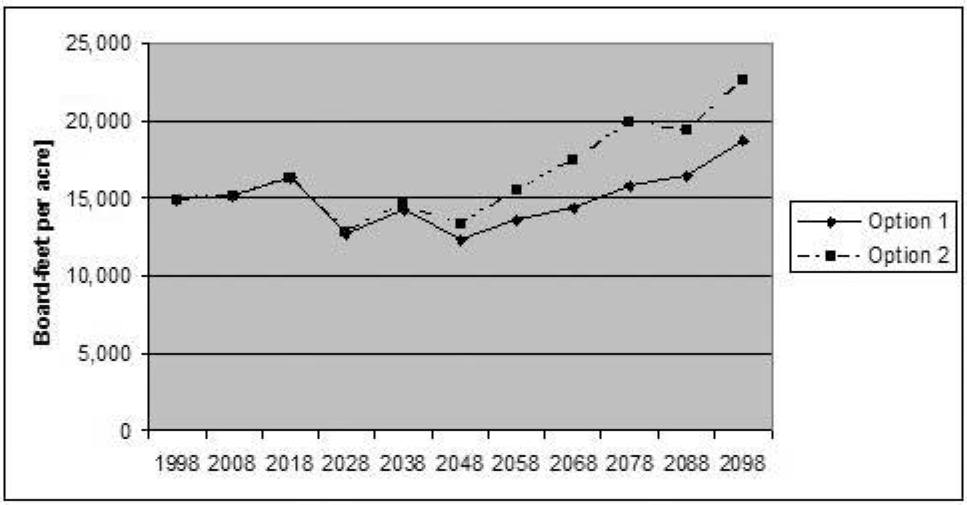


Figure 5—Board-foot stocking projections from FVS, grand fir stratum.

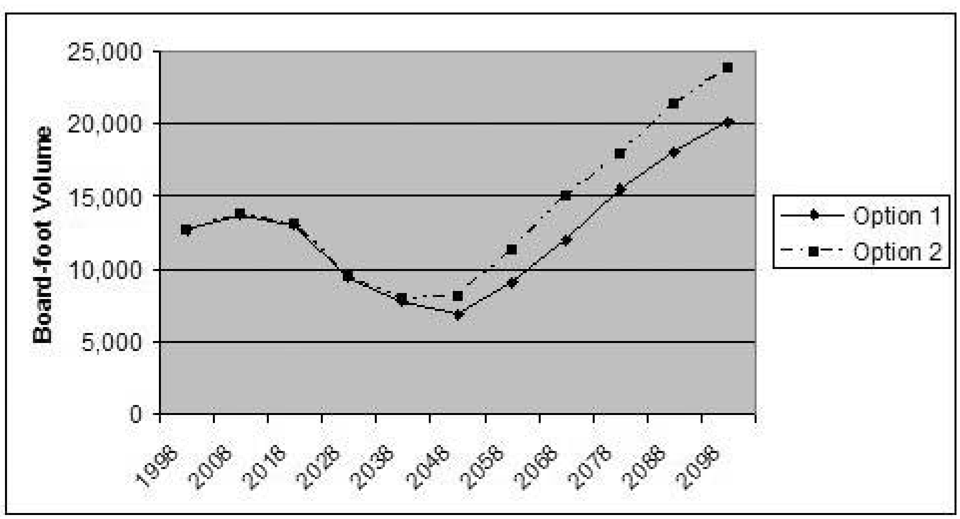


Figure 6—Board-foot stocking projections from FVS, lodgepole stratum.

The ninebark, grand fir and lodgepole strata (figs. 4, 5 and 6) all decline in volume during the first 50 years of projection: ninebark bottoms out at around 2028; the other two, 10 to 20 years later. These indicate the period in which mature stands are being gradually replaced by younger stands, which produce no measurable board-foot volume for 30 to 50 years. The all strata chart (fig. 1) shows that when viewed on a forest-wide basis, the various cyclical trends of the individual strata are mutually compensating and so the dip in stocking about 30 years in the future is relatively slight.

Option 2 in the three strata in which it was tried shows slightly higher volumes overall in the last 50 years of projections, and these differences are noticeably higher in the wet grand fir and lodgepole strata. It is logical that these differences are not seen until 50 years into the future, because it would take that long for the differing regeneration inputs to finally be expressed in board-foot volume. The improved volumes from option 2 are probably attributable to two causes. First, natural regeneration inputs on wetter types are more dominated by root disease susceptible species, and the Western Root Disease Model component of FVS should be reducing volumes of these species accordingly. Also, in the lodgepole stratum, ponderosa pine and larch stocking replaces lodgepole pine in option 2, and over time these species do attain greater standing volumes per acre than lodgepole pine because of greater height and diameter growth potential.

Harvest Yield Projections

The harvest yield projections shown in figures 7 through 12 are expanded from a per acre basis to total annual volumes in thousand-board-feet units (MBF). Expansion factors are based on the current commercial forest acreage estimated for each of the strata. Deduction for defect is included. The harvest yield projections made in the FVS model are based on simulated management treatments in the model that, as much as possible, imitate current practices. These are not designed to show the greatest yields possible in either the short- or long-term, but merely reflect what might be expected given continuing management. No attempt was made to optimize yields or create a non-declining and even yield pattern.

The harvest charts show an erratically fluctuating yield. This is probably an artifact of condition statements for harvest that specify that (a) when given conditions are met for any plot, a regeneration cut shall be done immediately, and (b) a plot may not be harvested in two consecutive cycles. Most likely, a large percentage of plots are simultaneously meeting conditions for regeneration and a large harvest (many plots aggregated) occurs in one cycle. Ten years later relatively few plots are eligible for harvest because of the number of plots harvested in the previous cycle. One more cycle later, plots regenerated 20 years earlier are eligible for overstory removal, as well as numerous plots available for a second commercial thinning. In reality, all plots theoretically eligible for harvest would not be cut in one decade as it takes about 20 years to move through the whole reservation. A more realistic harvest level would plot a midpoint through the see-sawing levels seen in these charts.

In viewing the harvest volumes associated with each stratum, note that since these are expanded by stratum acreages, the magnitude of the total volumes reflect the geographic size of the stratum (shown in table 1), as well as volumes per acre. The all strata chart (fig. 7) provides an indicator of what the reservation-wide annual harvest might be.

The yield patterns shown for the individual strata fluctuate more widely than the stocking charts in the previous section. The ninebark stratum (fig. 10) peaks earliest at around 2018; lodgepole (fig.12) peaks in 2028; and grand fir (fig. 11) between 2028 and 2048 (taking the midpoint between peaks). The drier strata fluctuate far less, with pine-fir (fig. 9) peaking in 2048 and dry pine (fig. 8) in 2058 or later. When the yields are averaged together for all strata (fig. 6), the overall picture appears more stable.

This provides a hopeful sign that, although the age-class distribution is not at all balanced in this forest, the current management scheme for prioritizing harvests and the rate at which stands on different sites develop might nonetheless provide a yield flow from the forests which is does not vary greatly. This is especially true if we chart a midpoint between the more widely fluctuating consecutive cycles. Still, overall annual yields for the first 50 years of projections average about 2 million board-feet more than the average for the second 50 years. This is most likely due to the current distribution of age classes on the reservation forests.

The 100-year average of harvest yields simulated under option 1 is about 16.8 million board-feet per year. Is that realistic? First of all, consider that yields after 2048 are quite

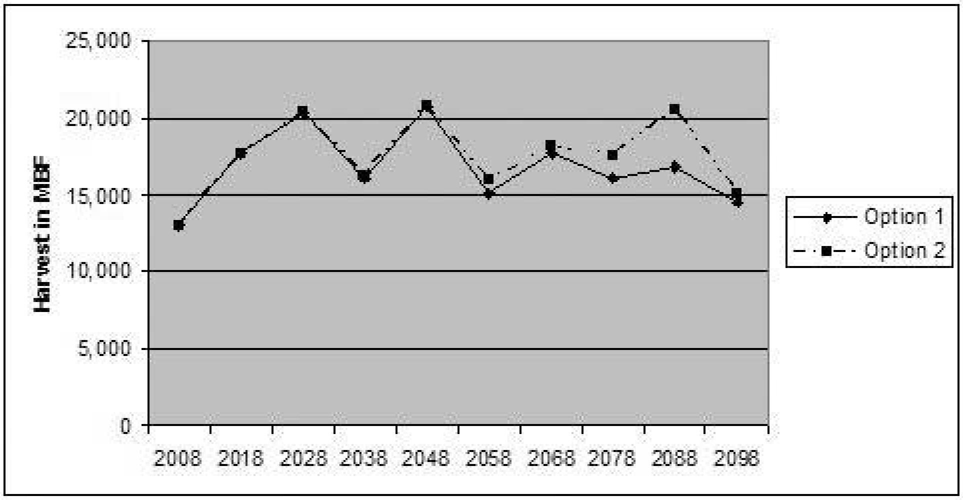


Figure 7—Harvest yield projections from FVS, all strata combined.

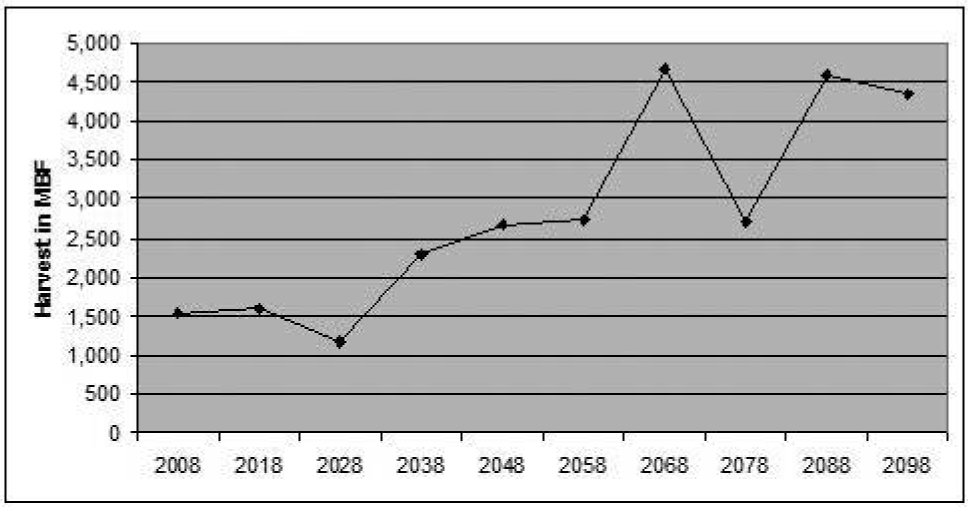


Figure 8—Harvest yield projections from FVS, dry pine stratum.

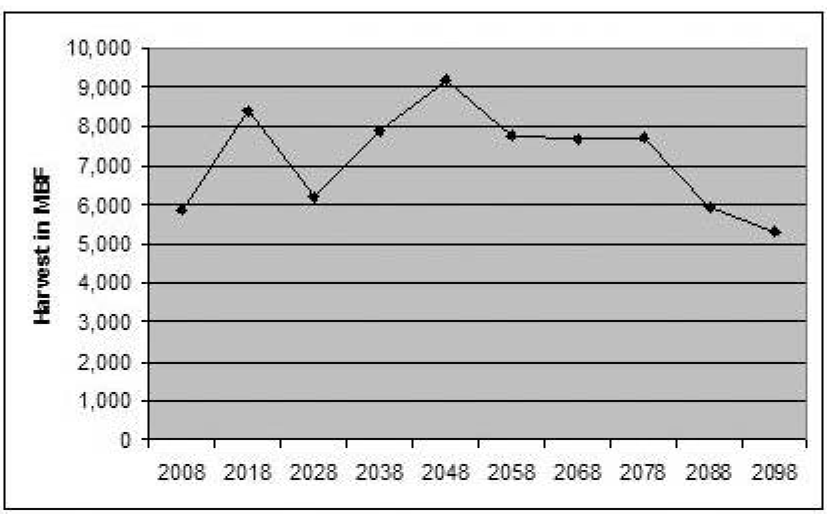


Figure 9—Harvest yield projections from FVS, pine-fir stratum.

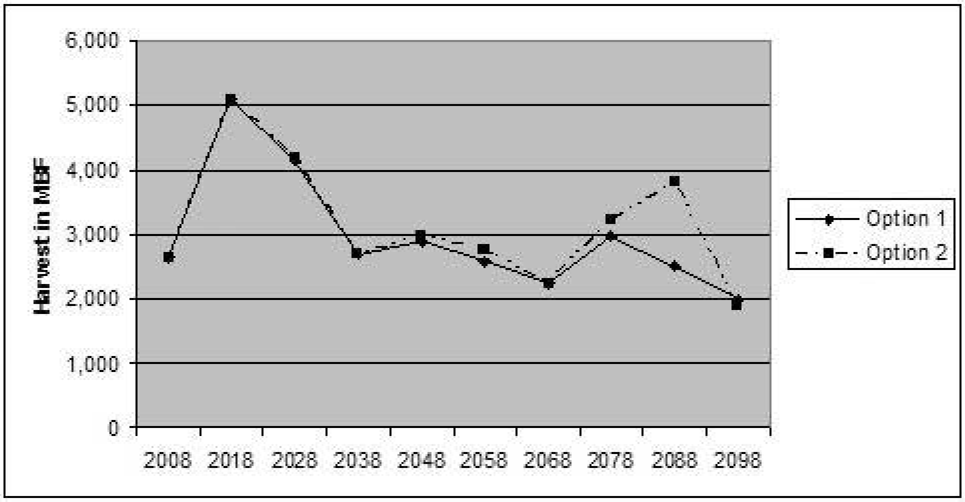


Figure 10—Harvest yield projections from FVS, ninebark stratum.

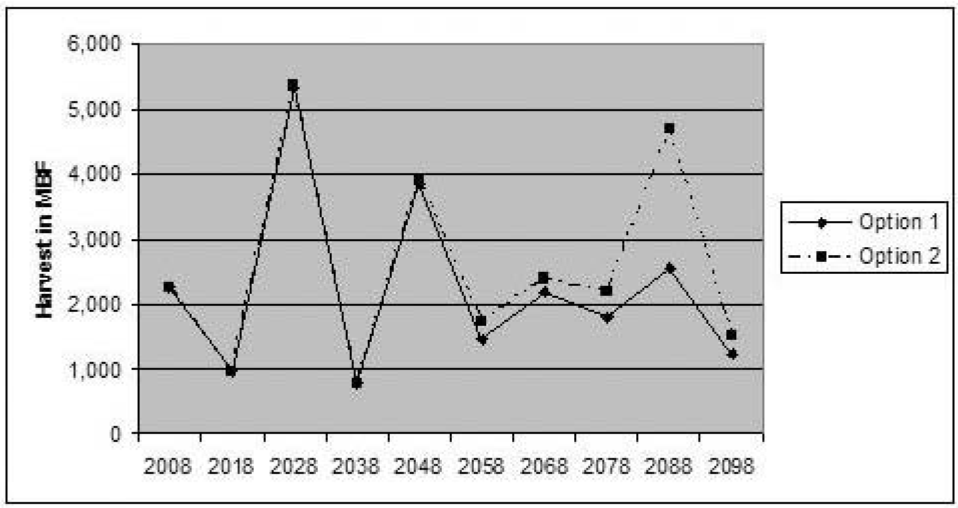


Figure 11—Harvest yield projections from FVS, grand fir stratum.

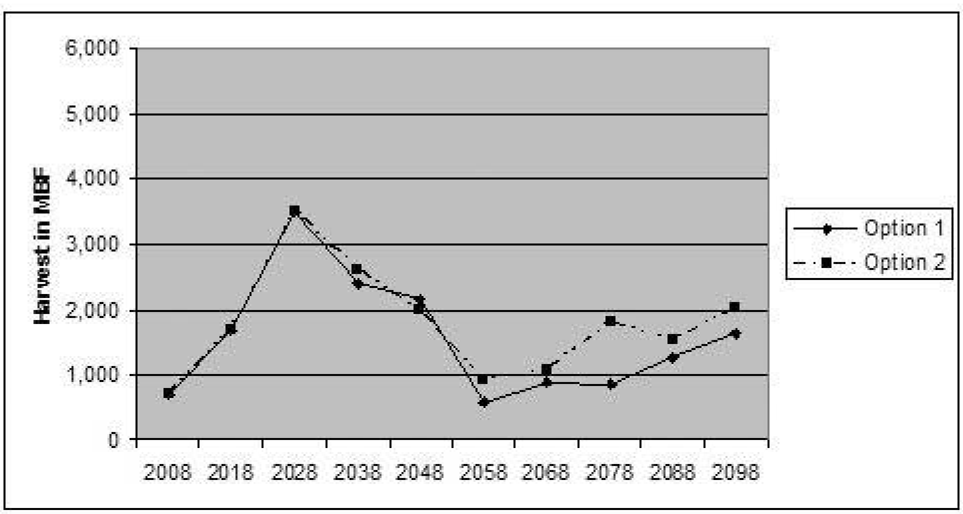


Figure 12—Harvest yield projections from FVS, lodgepole stratum.

dependent on model-generated trees. If growth rates for these are overblown, then yield could fall off even more than indicated in the second 50 years of the projection period. Secondly, the ability to maintain fairly high, even yields for the first 50 years is very dependent on mortality trends. Dramatic increases in mortality in the next 20 years beyond levels foreseen by FVS could present a choice between accelerating harvest for the first 25 years at the expense of the second 25 years, or allowing a diminished level of harvest overall for the first 50-year period.

On the wetter sites, option 2 shows higher harvest yields than option 1, with the lodgepole stratum showing the greatest differential over time. These distinctions do not appear until fairly late in the projections, which is what would one expect given the time it would take for the model-generated regeneration to reach mature sizes. If the differences shown are realistic, they would most likely persist beyond the 100-year projection period as long as these regeneration practices are continued.

If we look at the second 50 years of projections alone (since the first 50 years will not reflect different harvest yields between options 1 and 2), yields from option 2 are noticeably higher than option 1. For the ninebark stratum, option 2 yields over the last 50 years of projection are 13 percent higher; wet grand fir option 2 yields are 37 percent higher; lodgepole option 2 yields are 41 percent higher.

Mortality Projections

Volume loss due to natural mortality is highly dependent on stocking volume for a particular stratum or time period. So in order to provide a uniform basis for comparing the mortality between strata and between cycles, cubic-foot mortality was converted to percent of cubic-foot stocking.

To evaluate how FVS mortality projections compare to the rates recently measured in the 1998 CFI, annual cubic-foot mortality for that growth measurement period (generated from CFI program output) was expanded for a 10-year period and converted to a percent of cubic-foot stocking. These are listed as follows for the four main strata and for all strata combined. (The wet grand fir mortality percentage includes the plot sets for both the grand fir stratum and lodgepole stratum from the FVS projections.)

- Dry pine: 4.1 percent
- Pine-fir: 6.0 percent
- Ninebark: 5.5 percent
- Wet grand fir: 6.1 percent
- All strata combined: 5.8 percent

In reviewing these comparisons, we find that despite measures to calibrate the model to reflect mortality levels measured in 1998 CFI, FVS rates (figs. 13 through 18) are still mostly lower than measured rates for the period. The grand fir and lodgepole strata (figs. 17 and 18, respectively) are the only exception to this. This might indicate a need to discount yield projections posted by FVS in the event that mortality continues at or increases from 1985–1998 rates.

FVS projects that average mortality for all strata (fig. 13) would peak at around 2018, subside slightly, and finally return to that level again about 50 years later. The wetter types drive this peaking in the near term; the dry pine (fig. 14) and pine-fir strata (fig. 15) do not show this trend. The lodgepole stratum (fig. 18) shows the highest mortality rate in terms of percent of volume lost, peaking at over 9% in 2018; the grand fir stratum (fig. 17) has the second highest level, over 7%. Lodgepole also shows the most widely varying trend over the period projected.

The comparison between options 1 and 2 on the wetter strata yields some interesting results. It appears that mortality for option 2 rises above that of option 1 at about 2058 and then drops to about the same level 30 years later. Actual cubic-foot mortality volumes are pretty steady for option 2 after 2058. However, as seen in figures 4 through 6, stocking is steadily rising throughout that period, and so mortality expressed as a percent of stocking falls in comparison.

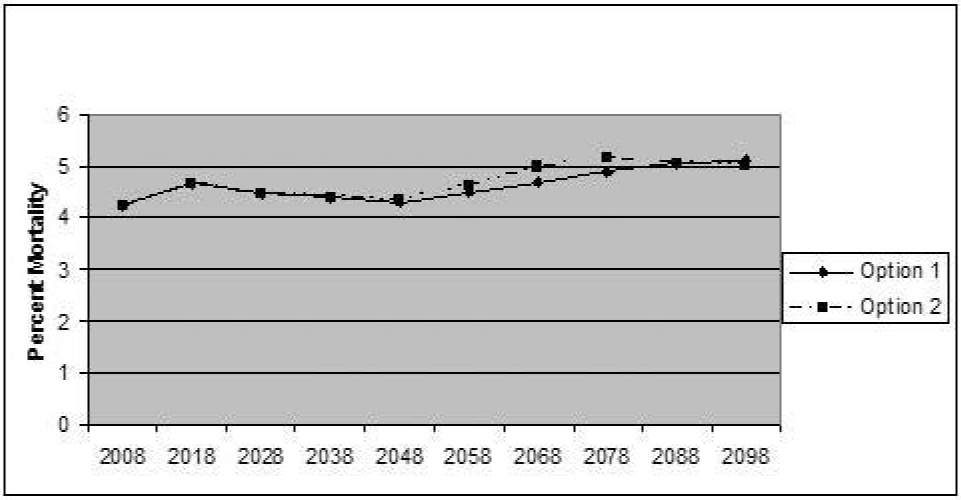


Figure 13—Mortality as percent of stocking from FVS, all strata combined.

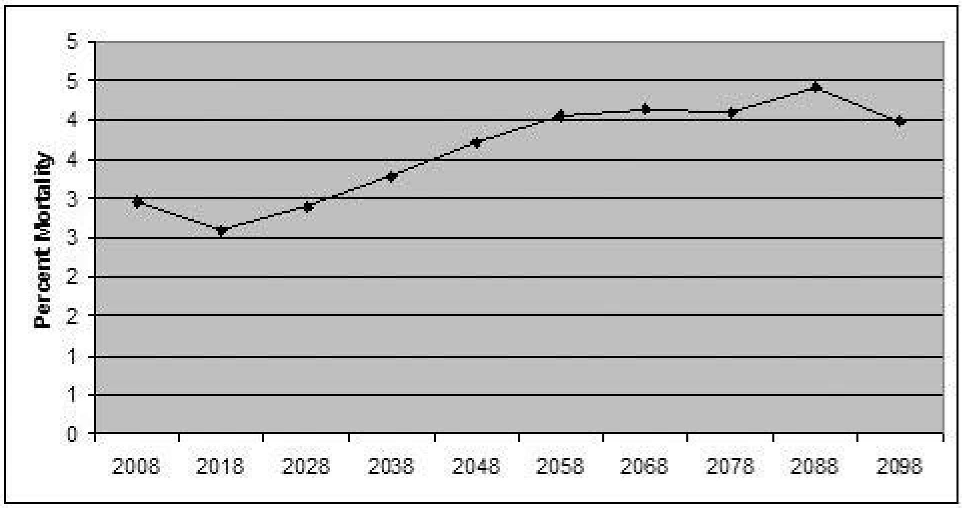


Figure 14—Mortality as percent of stocking from FVS, dry pine stratum.

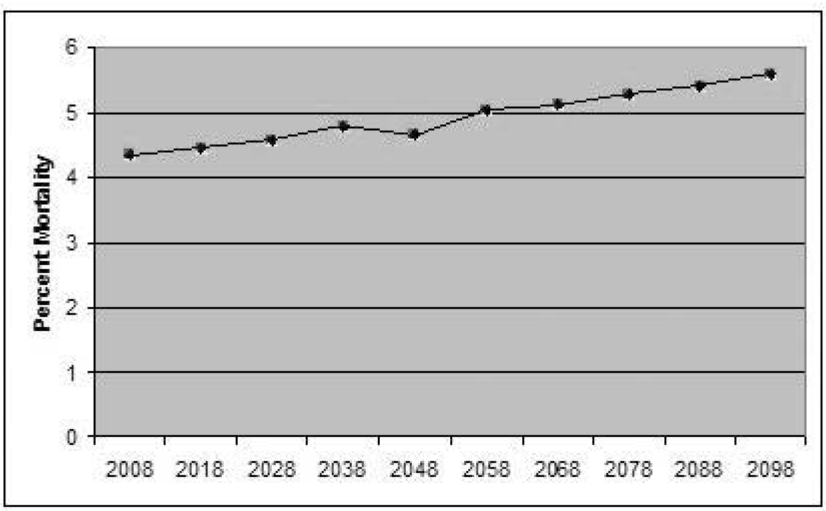


Figure 15—Mortality as percent of stocking from FVS, pine-fir stratum.

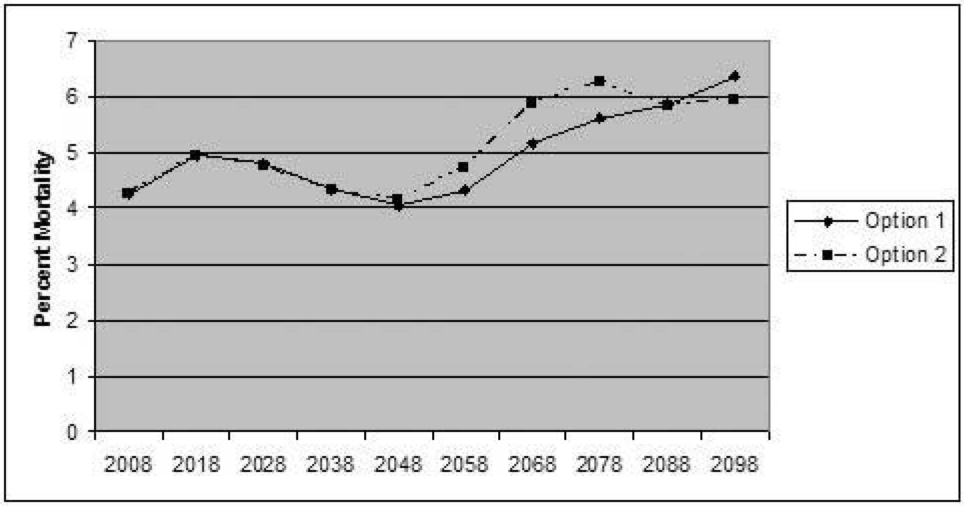


Figure 16—Mortality as percent of stocking from FVS, ninebark stratum.

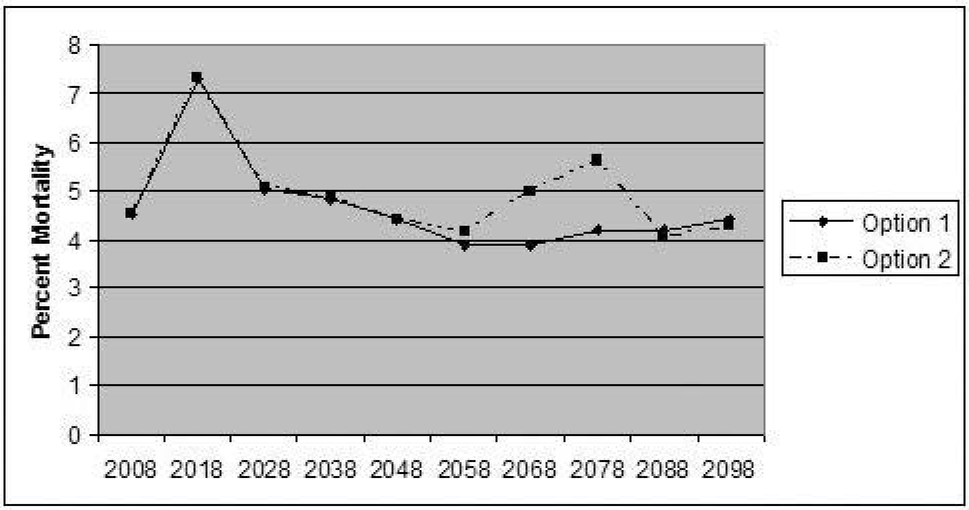


Figure 17—Mortality as percent of stocking from FVS, grand fir stratum.

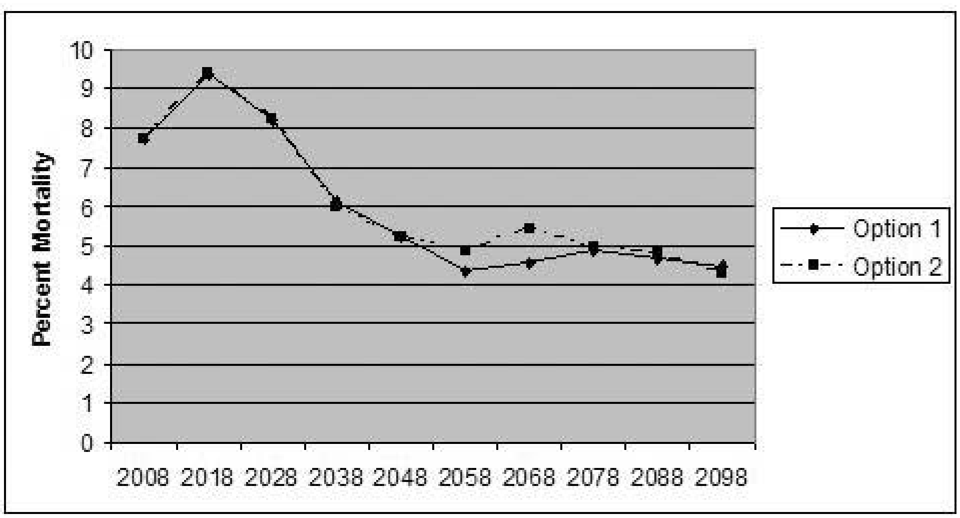


Figure 18—Mortality as percent of stocking from FVS, lodgepole stratum.

Conclusions

In general, FVS was a useful supplement to the traditional annual allowable cut computation methods for this CFI analysis. The harvest yields projected by FVS for the first 20 years were in line with other AAC computation methods. Long-term FVS harvests were considerably higher, however, and may reflect overestimation of growth by the model that was not completely corrected by calibration.

The question of how the current age-class distribution of the forest might affect harvest yields in the future seemed to be one for which the model was particularly well-suited. FVS results projected a great deal of fluctuation in harvest yields for the individual strata. However, the combined yields indicated that the dynamic trends of the individual strata may balance one another during the transition period to a regulated forest.

Some of the FVS results could be useful for guiding silvicultural treatments in the future. In viewing mortality projections, it appears that wetter sites (particularly with lodgepole stands) are prone to increased mortality in the next two decades. This would support a strategy that makes these areas a high priority for regeneration harvests in the near future. Also, the results indicate that planting ponderosa pine and western larch vs. natural regeneration on disease prone sites will lead to higher yields.

Acknowledgments

The author wishes to acknowledge the invaluable assistance rendered by a number of people. Preparation of the raw data for analysis was done by Terry Shand of the BIA Northwest Regional Office in Portland, OR. Don Vandendriesche and others at the USFS Forest Management Service Center provided advice and troubleshooting in all aspects of calibrating and running the FVS model. Connie Mehmel of the Wenatchee USFS Forest Health Office and Helen Maffei, of the USFS Deschutes National Forest helped in getting the Western Root Disease Model calibrated for this project. The reviewers of this paper are also thanked for the edits and improvements suggested.

References

Cooper, Stephen V.; Neiman, Kenneth E.; Roberts, David W. 1991. Rev. Forest habitat types of northern Idaho: a second approximation. Gen. Tech. Rep. INT-236. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 143 p.

Crookston, Nicholas L. 1990. User's guide to the event monitor: part of Prognosis model version 6. Gen. Tech. Rep. INT-275. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 21 p.

Davis, Kenneth. 1987. Rev. Forest management. New York, NY: McGraw-Hill. 790 p.

Ferguson, Dennis E.; Crookston, Nicholas L. 1991. User's guide to version 2 of the Regeneration Establishment Model: part of the Prognosis Model. Gen. Tech. Rep. INT-279. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 34 p.

Recknagel, A.B. 1913. The theory and practice of working plans (forest organization). New York, NY: John Wiley and Sons. 235 p.

Wykoff, William R.; Crookston, Nicholas L.; Stage, Albert R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station 112 p.

Zamora, Benjamin A. 1983. Forest habitat types of the Spokane Indian Reservation. Res. Bull. XB-0936-1983. Pullman, WA: Washington State University, Agriculture Research Center. 64p.

The content of this paper reflects the views of the author, who is responsible for the facts and accuracy of the information presented herein.

Landscape Analysis Software Tools

Don Vandendriesche[1]

Abstract—Recently, several new computer programs have been developed to assist in landscape analysis. The "Sequential Processing Routine for Arraying Yields" (SPRAY) program was designed to run a group of stands with particular treatment activities to produce vegetation yield profiles for forest planning. SPRAY uses existing Forest Vegetation Simulator (FVS) software coupled with a user interface that allows easy input of stand types, their associated silvicultural prescriptions, and possible timing options. Additionally, two support programs that facilitate data processing and interpretation are available. The "Combine" program was developed to summarize data at the strata level. This entails compiling output from individual samples (i.e. inventory plots or stands) and reporting composite values that can be used by SPRAY during batch processing. The "Yield Examination Program" (YEP) provides a graphical display of the vegetation yield profiles. YEP imports data from SPRAY output files to populate the data sources used for rendering scatter plots. A brief synopsis of each program is presented.

SPRAY Program

Planning at the landscape scale requires grouping many stands of like attributes, analyzing numerous vegetation treatment options, and assessing their related outputs. The "Sequential Processing Routine for Arraying Yields" (SPRAY) program was designed to address this purpose. SPRAY assembles multiple groups of stands with their associated keyword sets and creates many yield streams within a given processing run. Several Forest Vegetation Simulator (FVS) (Dixon 2002) post processors are linked into the data processing stream. The FVSStand Alone (Vandendriesche 1997) program generates either time or age based yield output. The Compute (Van Dyck 2003) program extracts Event Monitor (Crookston 1990) user defined variables from the FVS main output report. The Combine program (presented later in the text) determines mode, median, and mean values from nominal, ordinal, and interval/ratio data reported by the FVSStand Alone and Compute (Van Dyck 2003) post processors. The resultant vegetation yield profile can be arrayed based on projection year or stand age. The strength of the SPRAY program is its ability to be rapidly modified to run numerous vegetation yield profiles sequentially. SPRAY is independent of geographic location.

Suppose Connection

The founding principle in the development of the SPRAY program was to utilize existing FVS software as much as possible. Then, design a user interface that would allow easy input of stand types, their associated silvicultural prescriptions, and possible timing options. SPRAY uses Suppose (Crookston 1997) to construct FVS keywords that describe basic inventory parameters. Suppose builds the StdIdent, InvYear, ModType, StdInfo, Locate, Design, Growth, BAMax, SDIMax, SiteCode, NumCycle, TimeInt, Open, TreeData, SPLabel, and Process keywords per plot. SPRAY uses Suppose to create and manage these keywords. A base keyword set for the entire inventory data set is generated through Suppose (fig. 1).

For SPRAY, there should be only one stand type label per inventory plot. This is done simply by creating a Stand List File {*.slf} containing one primary vegetation group code on Record Type C lines. Stand type labels usually characterize the dominant forest cover, its relative size class, and associated crown density. The SPRAY program needs this label to organize its processing tree. Adding a pointer within the Suppose.loc file to the newly created stand list file completes the task.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forester, USDA Forest Service, Forest Management Service Center, Fort Collins, CO; e-mail: dvandendriesche@fs.fed.us.

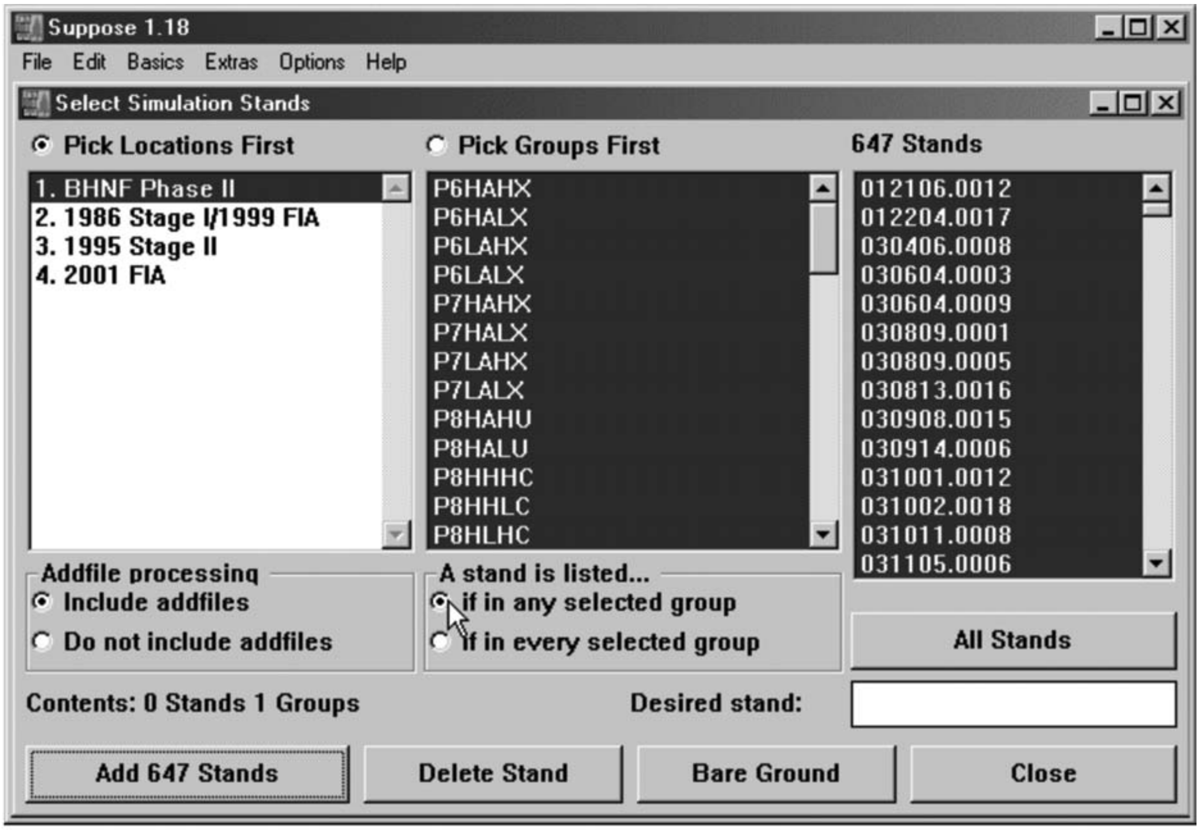


Figure 1—Suppose builds the base project keyword file.

SPRAY Setup

There are a few initial setup steps prior to running the sequential processing tree. The "Setup" menu option on the main SPRAY form provides access to the Common Year, Index Strata, and Select Variant configuration forms.

- Common Year—Establishes the inventory year, the number of cycles, and the time interval for each plot in the base keyword file. The inventory year can be derived from the most recent year recorded for all plots or it can be supplied by the user.
- Index Strata—Creates a "Spray.key" file containing FVS keywords. Suppose interface lines are removed from the base keyword set. The "Spray.key" file is formatted for 'direct access' to allow rapid retrieval of specific records. This step also creates a complementary "Spray.idx" index file that links stand type labels with line numbers in the "Spray.key" file. Thus, a connection is established between the "Spray.key" and "Spray.idx" files.
- Select Variant—Designates the FVS geographic variant to use in the simulation runs. Model extension can be chosen as well.

SPRAY Nodes

The Sequential Processing Routine uses a treeview similar to the Windows Explorer program. SPRAY is designed to process a four-level hierarchical tree. The "tree" is comprised of cascading branch "nodes" and each node consists of a label and a set of assigned FVS "addfiles" (i.e. auxiliary keyword files) (refer to fig. 2).

The base hierarchy for SPRAY begins with an assignment of a root node. Subordinate nodes are then declared for vegetative types, silvicultural treatments, and timing options. Using the "Add Node" menu option will display a new subordinate node. Using the "Remove Node" will delete an existing node. Using the "Label Node" will allow renaming the current node assignment. Using the "Associate Add-files" will prompt a window to appear that allows designating specific keyword component files (a.k.a. FVS addfiles) to a path node.

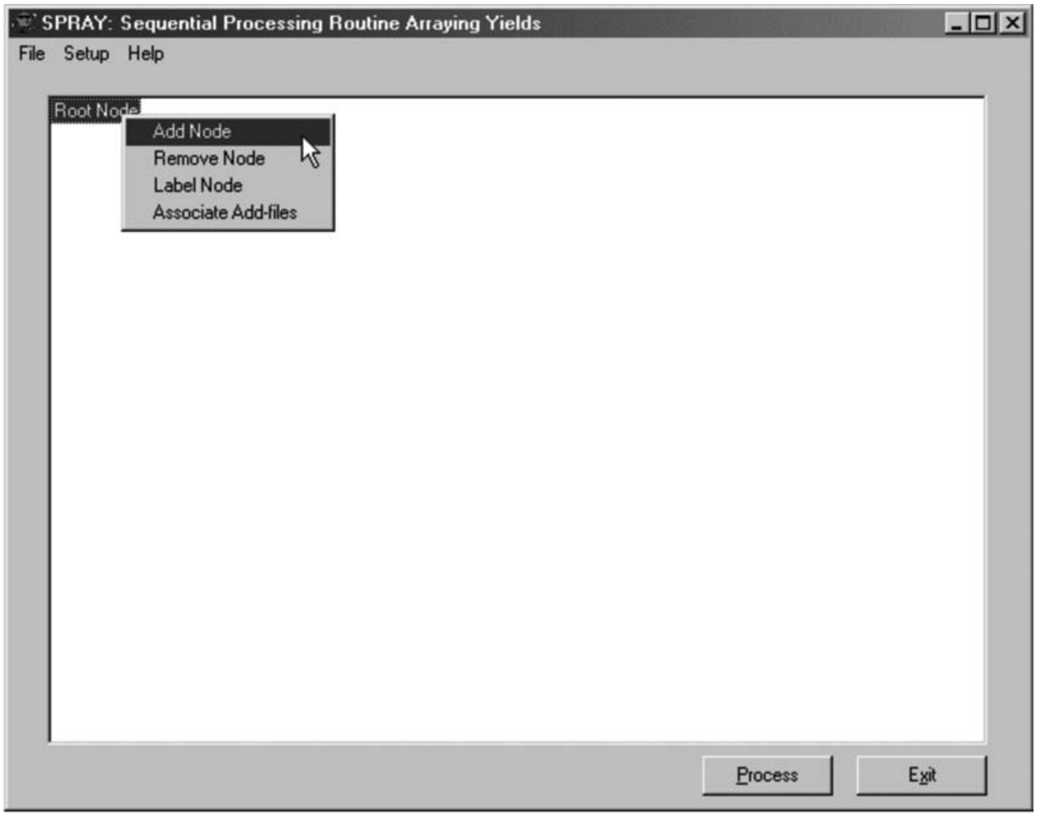


Figure 2—SPRAY treeview window.

SPRAY Associates

Various pre-built keyword component files (*.kcp) can be assigned to a tree node. Files are appended sequentially to the FVS keyword run. As displayed in figure 3, once the frame on the right is properly populated with associated addfiles, the list can be saved for retrieval at a later time. This aids in quickly assigning FVS *.kcp files to processing nodes.

After the pathway nodes have been defined (fig. 4) and FVS addfiles assigned, the runstream can be processed. The SPRAY program captures user input in two files. The "Spray.prj" file contains the FVS variant designated for the projection run and the layout of the pathway nodes. This allows easy retrieval of existing project files (*.prj). The "Spray.add" file contains a listing of the associated addfiles per node assignment.

The SPRAY program builds a composite keyword file set ("Spray.sim" file) per stand type per silvicultural prescription per timing option. Once created, the runstream is processed through the specified FVS variant. The FVSStand, Compute, and FireTbl post processors can then be called upon to generate report variables. Finally, the Combine program synthesizes the output files from the post processing programs into one composite yield profile. The processing continues with the next combination of vegetation stand type, silvicultural prescription, and timing option until all combinations have been completed. The resultant yield files supply input values to forest planning models.

SPRAY Applications

SPRAY provides a shell that brings together the specified FVS variant and several post processing programs. SPRAY is independent of geographic location and can be setup to run for any area. To date, SPRAY has been used for forest planning efforts on 18 National Forests located in most regions of the country.

SPRAY relies on two support programs that add functionality for processing and interpretation of vegetation yield profiles. The "Combine" program was written to take output from various FVS post processing programs and merge the resultant values. The

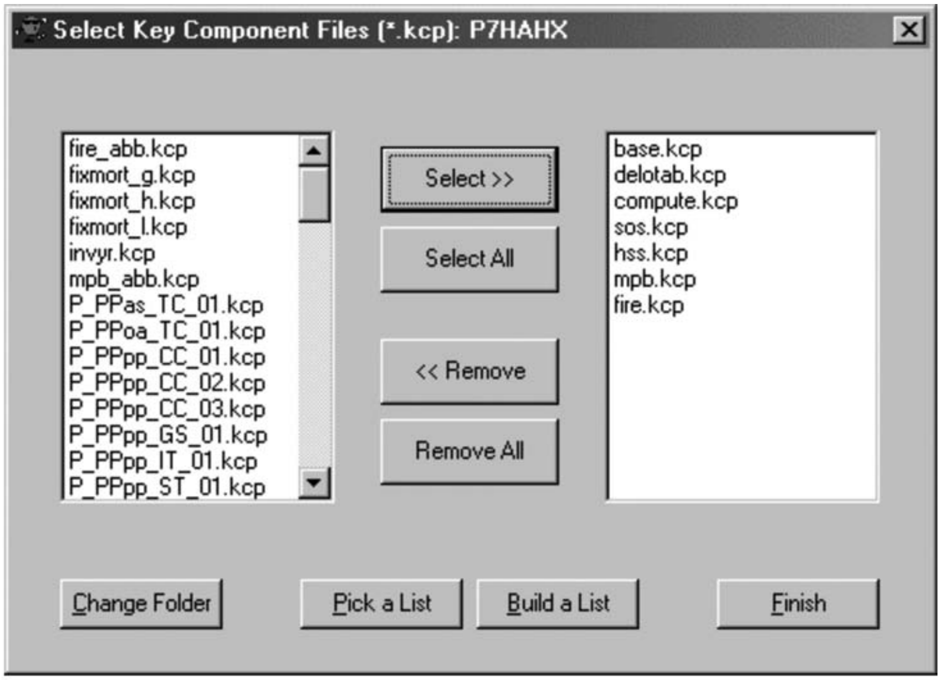


Figure 3—Assigning FVS addfiles to SPRAY treeview nodes.

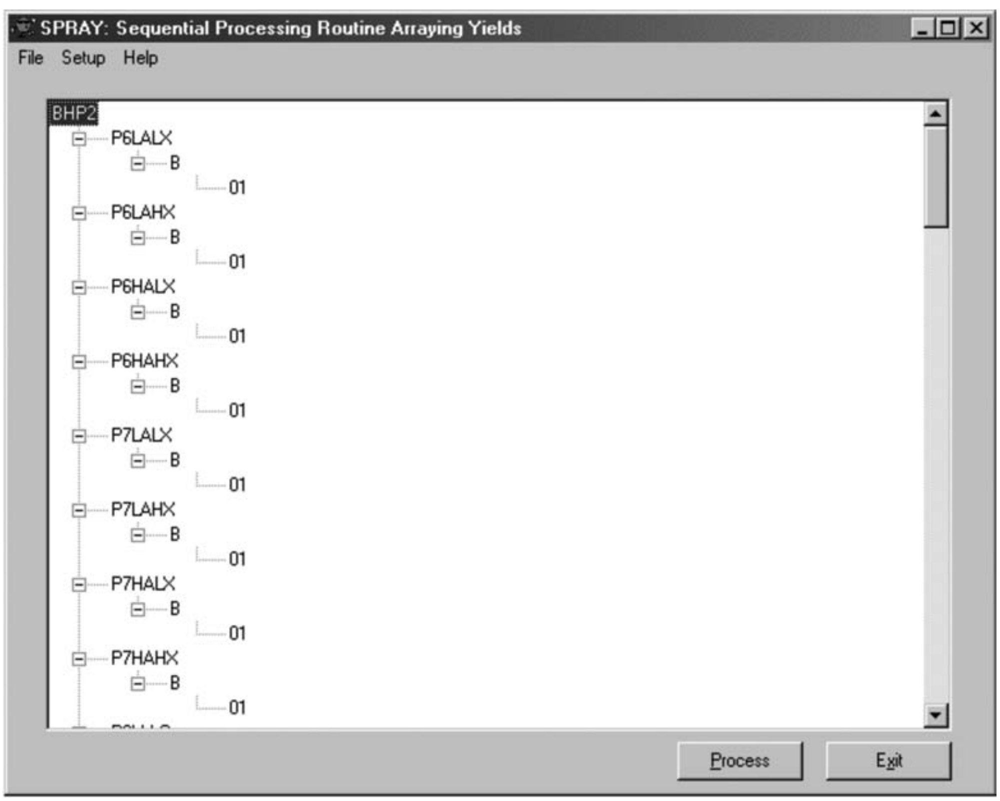


Figure 4—SPRAY hierarchical processing tree. *Root Node*: Project Area = Black Hill Forest Plan Amendment, Phase II (BHP2); *Vegetation Node*: Stand Type = Ponderosa Pine Cover Type (P)/Seedling Size Class (6L)/ All Density Class (A)/Low Site (L)/No Understory (X); *Activity Node*: Silvicultural Prescription = Shelterwood (B); *Timing Node*: Entry Interval = 30, 60, 90, 120 years (01). Processing note: FVS addfiles are appended sequentially per subordinate node to the base keyword set for the associated inventory plots that represent the stand type. Post processing programs such as FVSStand, Compute, and Combine aggregate simulation results for each SPRAY branch.

"Yield Examination Processor" (YEP) provides a visual assessment tool to assist forest planning staffs in evaluating vegetation yield profiles.

Combine Program

The "Combine" program was written to facilitate the derivation of pre-eminent values. Combine aggregates means, modes, medians, and much more. Forest planning projects often require summarizing data at the strata level. This usually involves compiling output from individual inventory plots or stands and reporting composite values. Vegetation yields can be expressed in quantitative and qualitative terms. Quantitative data, such as average trees per acre, basal area, or volume units, are described by continuous variables that render 'mean' or average value estimates. Qualitative data, such as structural stage, insect hazard, and fire severity, are described by classification variables that render 'mode' or count value estimates. The class with the maximum count represents the strata condition.

Combine is straightforward to use: (1) click the checkbox for the FVS post processing output tables you would like to merge, (2) declare the variables to include, (3) define the aggregation method per variable, and (4) proceed to combine the results.

The window displayed in figure 5 is used to indicate the processing type and the current status of a specific variable. Prior to designating variable assignments, it is important to signify the type of processing to occur with the FVS projection. Two forms of data aggregation are available: either a 'Time Basis' or 'Age Basis' can be chosen. Time basis indicates to array the data by projection cycle. Age basis signifies that the resultant data should be arranged using stand age.

A variable's assignment can be changed by selecting the variable in the left list box and choosing the appropriate method and type in the middle and left list boxes, respectively. Reselecting the variable in the left list box will reveal its updated assignment. Once satisfied with the inclusion/exclusion of variables, choosing the "Save" button stores the assignments to a parameter list file. Upon return to this form, the "Load" option can be use to retrieve the preset configurations.

An input window allows specifying the minimum sample size to include in the output file. When combining plots using an age basis, it is quite possible to have limited number

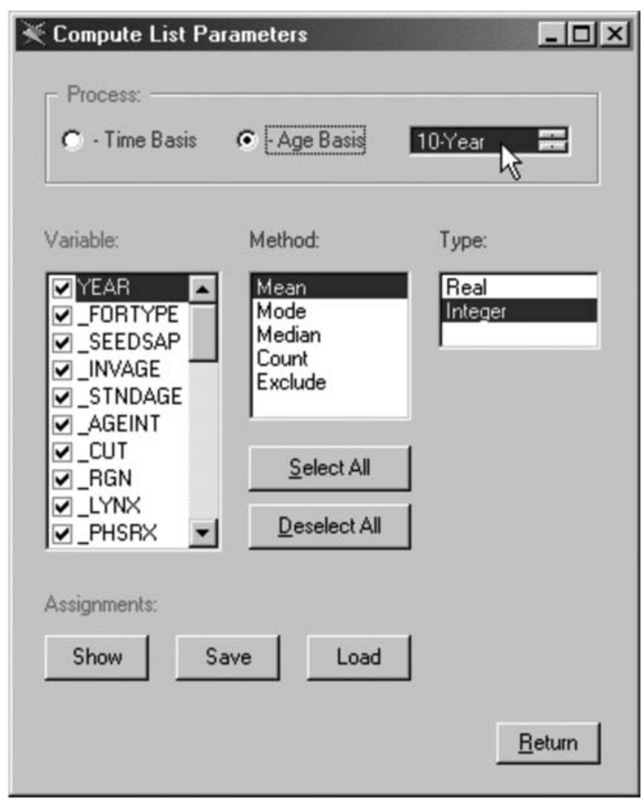


Figure 5—Combine variable designation window.

of samples at younger and older ages. The computed means and modes may be obscured by the minimal plot set. It is best to indicate the lowest acceptable sample size to ensure adequate interpretation of results.

The Combine program supports batch processing. Input parameters can be entered from the command line. This capability allows integration of the Combine program with the SPRAY program.

YEP Program

The Yield Examination Program (YEP) provides a graphical user interface to allow perusing the vegetation yield files built from the SPRAY program. YEP imports tabular data from text files and displays the results in scatter plots. The 'Select X/Y' form allows selecting any available data columns within the yield files (fig. 6).

YEP automatically displays a scatter plot of basal area per acre versus stand age. A natural log trendline is fit to the data (fig. 7). There are 15 different trendlines available for viewing. Related coefficients are presented per trendline at the bottom-left of the display screen. A hard copy of the scatter plot can be obtained by clicking the 'Print' button on the main form. The scatter plot is captured and sent directly to the default printer specified for the computer. The 'Combine' button can be used to merge several yield files into one composite for graphing. This can be useful where yield tables are delineated by size or density class.

Available Documentation

User guides to SPRAY, Combine, and YEP programs (Vandendriesche 2005) can be obtained from the USFS Forest Management Service Center Web Page at the following address:

http://www.fs.fed.us/fmsc/fvs/documents/gtrs_advance-topics.php

The software is also available at this site.

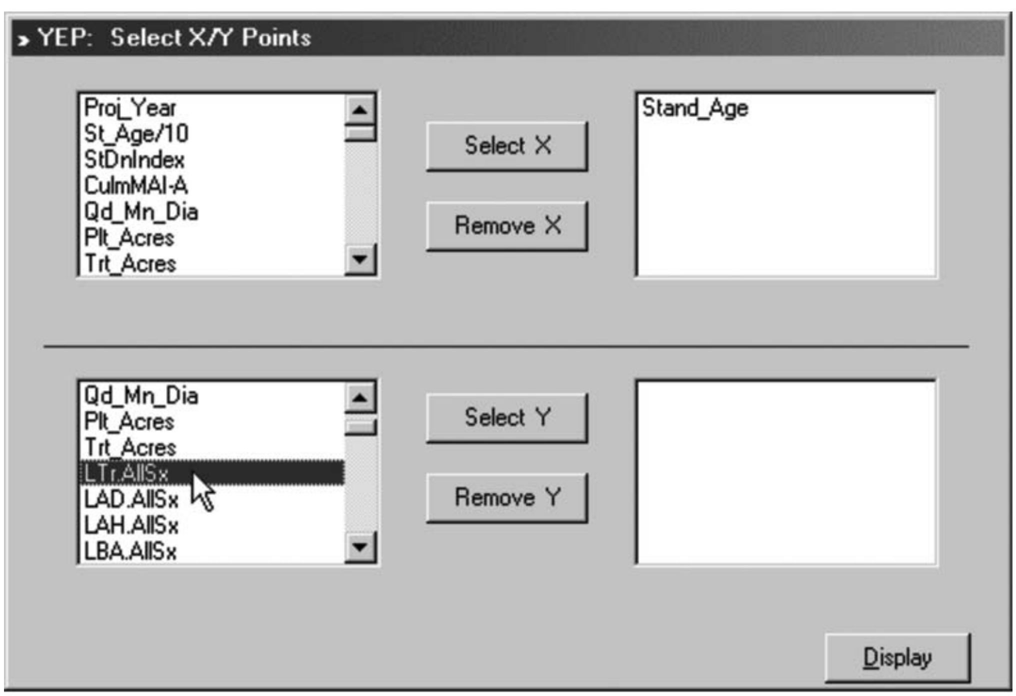


Figure 6—YEP variable selection window.

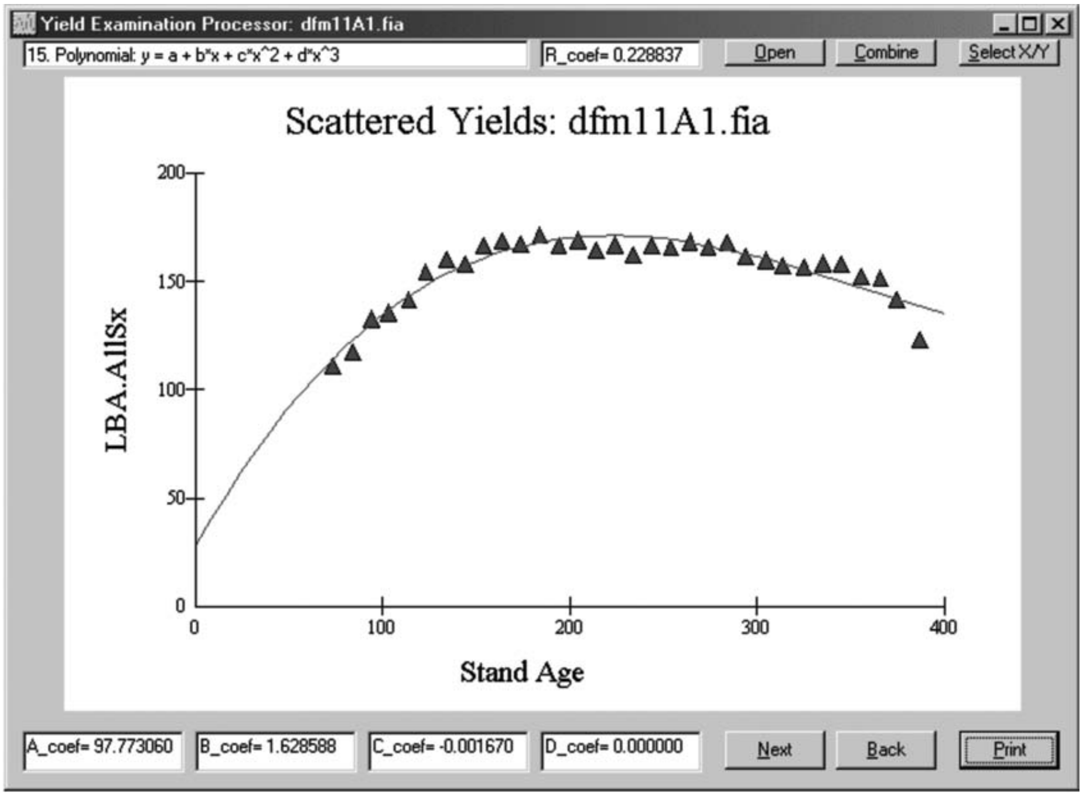


Figure 7—YEP scatter plot for Douglas-fir Moist large size class natural growth run (dfm11A1), (LBA.AllSx = Live Stand Basal Area, All Species, All Size Classes).

References

Crookston, Nicholas L. 1990. User's guide to the Event Monitor: Part of Prognosis Model version 6. Gen. Tech. Rep. INT-275. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 21 p.

Crookston, Nicholas L. 1997. Suppose: An interface to the Forest Vegetation Simulator. In: Proceeding: [1st] Forest Vegetation Simulator Conference. Fort Collins, CO. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 7-14.

Dixon, Gary E. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Interoffice publication. Fort Collins, CO. U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 204 p.

Vandendriesche, Donald A. 1997. FVSSTAND Alone: Generate dynamic yield reports from the Forest Vegetation Simulator. In: Proceeding: [1st] Forest Vegetation Simulator Conference. Fort Collins, CO. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 168-177.

Vandendriesche, Donald A. 2005. Advanced FVS Topics for forest planning. Interoffice publication. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 119 p.

Van Dyck, Michael G. 2003. User's guide to the Post Processors for the Forest Vegetation Simulator. Interoffice publication. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 59 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

FVS Data

Forest Inventory and Analysis Data for FVS Modelers

Patrick D. Miles[1]

Abstract—The USDA Forest Service, Forest Inventory and Analysis (FIA) program has been in continuous operation for over 70 years. FIA's primary objective is to determine the extent, condition, volume, growth, and depletion of timber on the Nation's forest land. To accomplish this objective, FIA collects sample plot information on all ownerships across the United States.

The Forest Inventory and Analysis Database (FIADB) (Miles and others 2001), was developed to provide users with a nationally consistent format for FIA data. FIADB files can be obtained for any State inventory conducted after 1988 for the Eastern United States or 1994 for the Western United States. All data in FIADB format can be exported into FVS-ready files for use in the Forest Vegetation Simulator (FVS) program. The FIA program is working with a variety of cooperators to develop alternative pathways for delivering FIA data to FVS users.

Introduction

The U.S. Forest Service Forest Inventory and Analysis (FIA) program has been reporting forest statistics for over 70 years. These reports are based on a statistical sample of field plots collected on all ownerships across the United States.

For clarity, FIA data are classified as being either "periodic" or "annual." Prior to 1999, states were periodically inventoried approximately every 10 years. Regional field crews would measure all of the plots in a state, then move on to the next state, only returning to the initial state when all other states in the region had been inventoried. Beginning in 1999, an annual inventory system was established where field crews are in every state every year. Under the annual system, from 10 to 20 percent of the plots in all states are measured each year. Currently, annual inventory data have been collected, and are available, for all states with the exception of Hawaii, Mississippi, New Mexico, Oklahoma, Wyoming, interior Alaska, and west Texas.

When the annual inventory system is fully implemented, there will be at least one sample plot taken for each 6,000 acres of forestland for the contiguous United States. This constitutes a pool of more than 125,000 plots. Each year approximately 15,000 to 20,000 of these plots will be re-measured. This field data, collected to national standards, with strict quality assurance/control standards, is in the public domain and can be freely obtained over the Internet.

Traditionally FIA data have been used to produce publications of forest statistics that could be used in policy analysis and strategic planning. Over the last 25 years an increase in computing power and data storage and distribution capabilities has led to an increase in the use and application of FIA data. Tools such as the Forest Inventory Mapmaker program (Miles 2001) have been developed that allow users to query the FIA database over the Internet to produce customized reports. Currently over 24,000 queries are completed annually using the Forest Inventory Mapmaker program.

Power users, who use FIA data in sophisticated analyses, have requested that FIADB formatted data be made available over the web. Last year nearly 8,000 FIADB State inventories were downloaded via the FIA Data Mart website. GIS users have requested that FIA data be provided in formats that meet their needs. To that end, GIS users can now download summarized FIA data in ESRI© shapefile format and are doing so at a rate of over 900 downloads per year. FVS users have similarly requested that FIA data be summarized in an FVS-ready format. This paper briefly describes the FIA dataset and efforts to provide FIA data in a format that will meet the needs of the FVS community.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Research Forester, USDA Forest Service, Northern Research Station, Forest Inventory and Analysis Unit, St. Paul, MN; e-mail: pmiles@fs.fed.us.

FIA Data Availability

Annual Inventory Data

The annual inventory sampling design is fully documented elsewhere (Bechtold and Patterson 2005). A brief description is provided here. A grid was superimposed over the entire United States. Each cell in the grid is approximately 6,000 acres in size. Under a single intensity survey, a single plot is randomly located in each grid cell (in some cases double or triple intensity surveys have been implemented when additional funding was provided by a State or other land management agency). Field plots are established and monumented on all forested plots. An area is considered forested if it is at least one acre in size, at least 120 feet wide and at least 10 percent stocked with trees or recently stocked with trees; recently burned over areas and harvested lands are considered forestland unless there is evidence that the plot will be put to a different land use.

Field crews establish four 1/24th-acre subplots at each plot location on which trees 5 inches in diameter will be measured. Seedlings and saplings, defined as trees less than 5 inches in diameter, are measured on four 1/300th-acre microplots. Optionally, four 1/4th-acre macroplots can be used to measure large diameter trees (currently only used in parts of the West for trees 24 inches in diameter and larger).

Periodic Inventory Data

Data collected prior to the implementation of the annual inventory system is referred to as periodic data. These data were collected using a variety of sampling designs. In most cases variable radius plots were used. Users should contact the appropriate regional FIA unit for additional information regarding the sampling design used in their periodic inventories.

Availability of Annual and Periodic Data

All core field data are processed and then stored in the FIADB with the exception of the exact plot locations and specific ownership information. The latitude and longitude stored in the FIADB is correct within at least one mile for at least 95 percent of the plots. Up to, but generally far less than, five percent of the plots in a county may have their plot locations switched with other similar plots in the county. These procedures are commonly referred to as "fuzzing and swapping" and are required to meet FIA's legal requirements to retain landowner confidentiality while providing as much data as possible to the public.

The FIADB currently contains only data that are collected consistently nation-wide. Regional add-ons to the national program are not currently in the FIADB. Many regional add-ons will be available in the next version of the FIADB slated for release in the summer of 2007.

FIADB formatted data and information about changes to the format can be found at www.fia.fs.fed.us. Data currently available for downloading are identified in table 1.

Distribution of FIA Data in FVS-Ready Format

Currently there are two primary methods of delivering data to FVS users. Forest Service personnel have access to FIA data through the Natural Resource Information System (NRIS) while non-Forest Service users have access to FIA data through the Forest Inventory Mapmaker program.

The Forest Inventory Mapmaker program has a module that allows users to download FIA data in FVS-ready format. The Mapmaker program can be accessed on the Internet at the following link http://www.ncrs2.fs.fed.us/4801/fiadb/fim21/wcfim21.asp. To generate data in FVS-ready format the user will need to:

1. Select the report type: Forest Vegetation Simulator (FVS) ready dump files.
2. Select the geographic area of interest: (for example, Alabama and Georgia).
3. Specify any filter options (for example, Forest type, ownership, stand age).
4. Select the appropriate FVS variant (for example, SE = Southeast states).
5 Enter a project name.

Table 1—FIA data availability by inventory year as of March 2007.

State	Periodic inventories	Initial annual inventory	Re-measured annual inventories
ALABAMA	1990, 2000	2001–2005	
ALASKA (coastal)	1998	2004–2005	
ARIZONA	1985, 1999	2001–2005	
ARKANSAS	1995	2002–2005	
CALIFORNIA	1994	2001–2005	
COLORADO	1984	2002–2005	
CONNECTICUT	1985, 1998	2003–2005	
DELAWARE	1986, 1999	2004	
FLORIDA	1987, 1995	2003–2005	
GEORGIA	1989, 1997	1998–2004	
IDAHO	1991	2004–2005	
ILLINOIS	1985, 1998	2001–2005	
INDIANA	1986, 1998	1999–2003	2004–2005
IOWA	1990	1999–2003	2004–2005
KANSAS	1981, 1994	2001–2005	
KENTUCKY	1988	2000–2004	
LOUISIANA	1991	2001–2005	
MAINE	1995	1999–2003	
MARYLAND	1986, 1999	2004	
MASSACHUSETTS	1985, 1998	2003–2005	
MICHIGAN	1980, 1993	2000–2004	2005
MINNESOTA	1977, 1990	1999–2003	2004–2005
MISSISSIPPI	1994		
MISSOURI	1989	1999–2003	2004–2005
MONTANA	1989	2003–2005	
NEBRASKA	1983, 1994	2001–2005	
NEVADA	1989	2004–2005	
NEW HAMPSHIRE	1983, 1997	2002–2005	
NEW JERSEY	1987, 1999	2004	
NEW MEXICO	1987, 1999		
NEW YORK	1993	2003–2004	
NORTH CAROLINA	1984, 1990	2002	
NORTH DAKOTA	1980, 1995	2001–2005	
OHIO	1991	2001–2004	
OKLAHOMA	1993		
OREGON	1992, 1999	2001–2005	
PENNSYLVANIA	1989	2000–2004	
RHODE ISLAND	1985, 1998	2003–2005	
SOUTH CAROLINA	1986, 1993	1999–2001	2002–2005
SOUTH DAKOTA	1980, 1995	2001–2005	
TENNESSEE	1989, 1999	2000–2004	
TEXAS	1992	2001–2005	
UTAH	1993	2000–2005	
VERMONT	1983, 1997	2003–2005	
VERMONT	1997	2003–2005	
VIRGINIA	1984, 1992	1998–2001	2002–2005
WASHINGTON	1991	2002–2005	
WEST VIRGINIA	1989, 2000	2004	
WISCONSIN	1983, 1996	2000–2004	2005
WYOMING	1984, 2000		

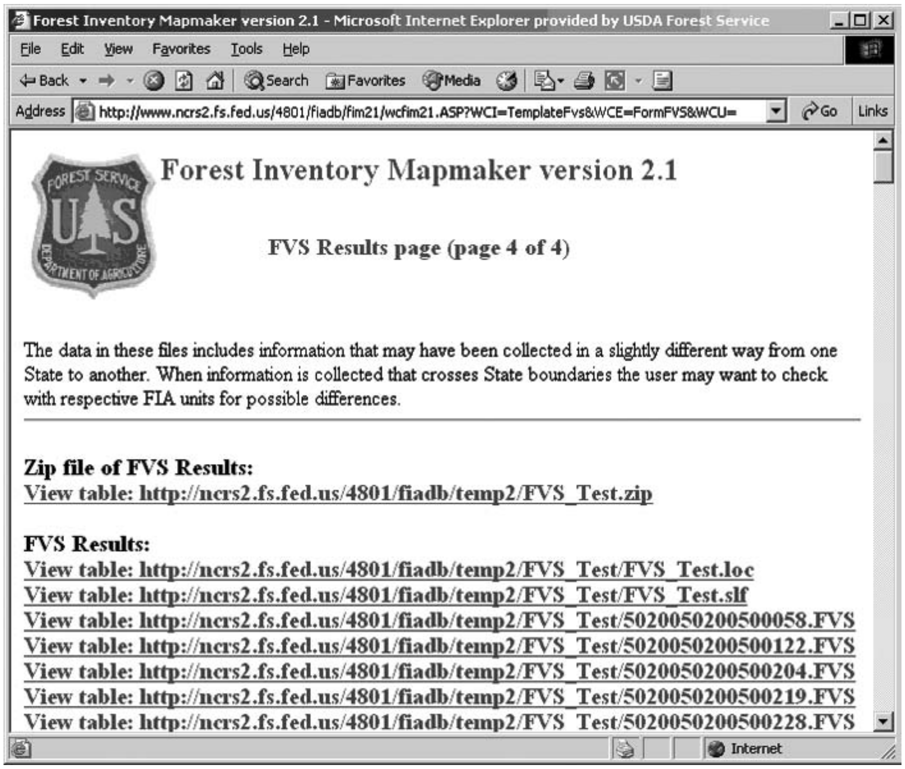


Figure 1—Example output from Forest Inventory Mapmaker program.

The module will then return a web page (fig. 1) containing links to the resulting FVS-ready files. These files include the standard FVS .loc (location), .slf (stand list), and .fvs (tree input) files.

Results

Over the past four years 2,386 retrievals of FIA data in FVS format (table 2) have been completed. Nearly all of these retrievals have been for geographic areas defined by state or county boundaries. Only 50 retrievals have made use of the feature allowing the user to define their geographic area of interest as a circle or polygon. This suggests that users may be retrieving entire FIA State datasets and performing additional filtering of the data using GIS software and or programs such as Pre-Suppose (Vandendriesche and Miles 2005).

More than half (1,246) of the Forest Inventory Mapmaker FVS-ready data retrievals employed some degree of filtering. The most common filter was to restrict the data retrieved to plots of specific ownerships (465 retrievals) and national forests (363). Filtering by forest types (410 retrievals) and stand age (148) was also common.

Retrievals have been made for all 48 contiguous states (fig. 2). More than 100 retrievals have been completed using data from the inventories of Maine, Wisconsin, Oregon, Montana, California, Michigan, Minnesota and Colorado.

Table 2—FVS-ready retrievals by retrieval type.

Retrieval type	Number
Circle	33
Polygon	17
State/county	2336
Total	2386

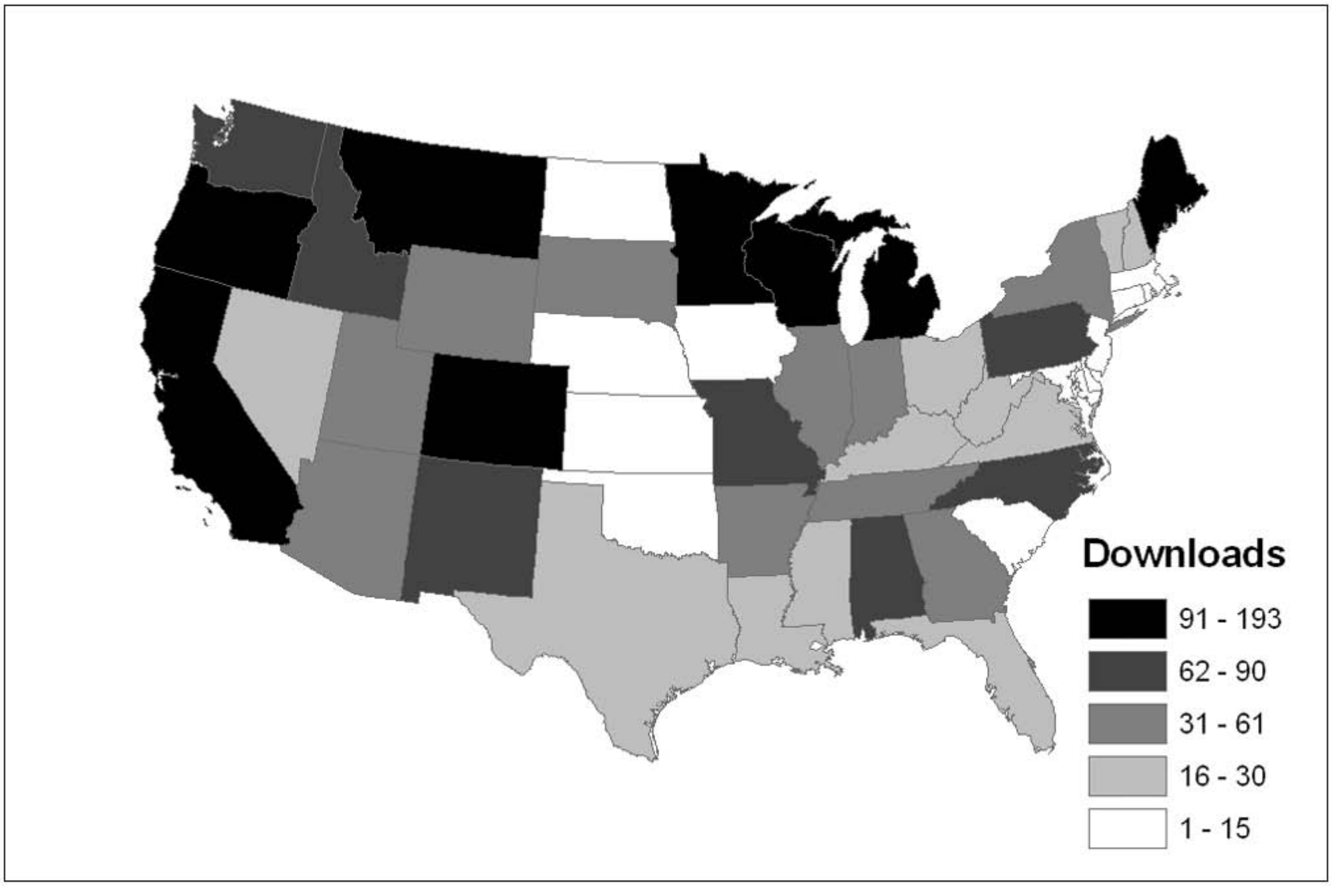


Figure 2—FVS retrievals by state

Conclusion

FVS users of FIA data make up a small but extremely important part of the overall FIA user community. It is important to maintain the delivery of FIA data to this user group.

An opportunity exists to redesign and improve the delivery of FIA data to the FVS community. The Forest Inventory Mapmaker program will soon be replaced by the Forest Inventory Data On-line (FIDO) suite of programs. FIDO is based on web services technology making it possible to deliver FIA data directly to other web-enabled programs. The transfer of FIA data to FVS could be streamlined by bypassing the need to create text files.

References

Bechtold, William A.; Patterson, Paul L., eds. 2005. The enhanced forest inventory and analysis program—national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Miles, Patrick D.; Brand, Gary J.; Alerich, Carol L.; Bednar, Larry F.; Woudenberg, Sharon W.; Glover, Joseph F.; Ezzell, Edward N. 2001. The forest inventory and analysis database: database description and users manual version 1.0. Gen. Tech. Rep. NC-218. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 130 p.

Miles, Patrick D. 2001. Forest Inventory Mapmaker users guide. Gen. Tech. Rep. NC-221. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 52 p.

Vandendriesche, Donald A.; Miles, Patrick D. 2005. Forest planning using forest inventory and analysis data and the Forest Vegetation Simulator. Proceedings; 2005 Society of American Foresters Annual Convention; Fort Worth, TX. 10 p.

The content of this paper reflects the views of the author, who is responsible for the facts and accuracy of the information presented herein.

Forest Vegetation Simulator Translocation Techniques with the Bureau of Land Management's Forest Vegetation Information System Database

Timothy A. Bottomley[1]

Abstract—The BLM uses a database, called the Forest Vegetation Information System (FORVIS), to store, retrieve, and analyze forest resource information on a majority of their forested lands. FORVIS also has the capability of easily transferring appropriate data electronically into Forest Vegetation Simulator (FVS) for simulation runs. Only minor additional data inputs or corrections are required to transfer FORVIS data to the FVS.

Introduction

The Bureau of Land Management (BLM) is responsible for the management of approximately 258 million acres of public land. About 69 million of these acres are forested (BLM 2006). The BLM manages these forested lands according to the principles of multiple-use and sustained-yield as required by the Federal Land Policy and Management Act (FLPMA) of 1976 and the Oregon and California Railroad Act, which covers forest lands in western Oregon. National priorities for these forests include maintaining and restoring forest health, salvaging dead and dying timber, providing high-quality wildlife and fish habitat, and providing economic opportunities in rural communities by making timber and other forest products, including biomass, available from vegetation management treatments.

Forest Vegetation Information System

With the exception of its public lands in western Oregon, the BLM uses an agency-developed database called the Forest Vegetation Information System (FORVIS) to store, retrieve, and analyze forest resource data. FORVIS was initially released in 2001, with an update (Version 2) released in 2006. FORVIS has distributed databases, stored at BLM State Offices, and uses an Informix relational database manager. Users can access the FORVIS database through a Microsoft (MS) Access application and an open database connectivity (ODBC) driver.

FORVIS allows data storage from inventories of various intensities—from photo interpretation to individual plot data. The database contains 32 related tables; however, only two ("stand_data" and "tree_data") are needed for retrieving data related to the Forest Vegetation Simulator (FVS). A view of the BLM FORVIS plot measurement record (fig.1) shows a very similar format to the order of data input for the stand list and tree data files of an FVS run. This similarity is due to the fact that those applicable tables in FORVIS were based on the requirements for the FVS runs.

In addition to simulating forest stand growth under a variety of different scenarios, the BLM also uses the FVS to make some basic stand-level calculations, such as trees per acre, quadratic mean diameter, basal area, stand density index, and volume per acre. This use of the FVS negates the need for the BLM to develop and maintain their own programs to make these calculations.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forester, USDI Bureau of Land Management National Science and Technology Center (recently renamed the National Operations Center) Denver, CO; e-mail: tim_bottomley@blm.gov.

BLM FORVIS PLOT MEASUREMENT RECORD

Location Common Name or Legal Desc: Page______of______

Polygon Identifier Observer Name : Date :

Stand Data and Sample Design

Habitat type:	**Slope:**	**BAF:**	**No. plots:**	**Dia. Grow period:**	**Site species:**
Birth year:	**Elevation:**	**Plot size:**	**Acres:**	**Mortality period:**	**Site index:**
Aspect:		**DBH break:**	**Stockable %:**		**Remarks**

Tree Data																							Plot Data					
Plot number	Tree number	Tree count	Tree history	Species	Diameter	Number of stems	Diameter growth	Tree age	Tree height	Height to top kill	Height growth	Crown ratio	Damage code 1	Damage severity 1	Damage code 2	Damage severity 2	Damage code 3	Damage severity 3	Tree value class	Prescription code	Slope	Aspect	Habitat type	Topographic position	Site preparation	
XXXX	XXX	XX	X	XXX	XXX.X	XX	XXX	XXX	XXX	XXX	XXX.X	X	XX	XX	XX	XX	XX	X	X	X	XX	XXX	XXX	X	X	

Figure 1—BLM FORVIS plot measurement record.

Data Transfer from FORVIS to FVS

A FORVIS user can select stand and plot data for a specific stand with the option of either first viewing or not viewing the raw data. Within the MS Access FORVIS application, a command button using a Visual Basic for Application script creates the stand list and tree data files. The user must create the location (*.loc) file. The user must also select the appropriate FVS variant and nearest National Forest location for the stand list file using the FVS SUPPOSE interface.

FORVIS also has the capability of electronically transferring and storing some of the results of the FVS runs, specifically the stand summary data described previously (i.e., year of summary data, trees per acre, quadratic mean diameters, basal area, stand density index, and volume).

One additional capability of FORVIS is the ArcMap extension created by the BLM that allows a link to spatially show much of the data that is in FORVIS.

Data Transfer Issues

Issues that have come up in transferring data from old BLM forest inventories are primarily the result of using "legacy data." For example, data collected in the late 1970s and early 1980s using the Forest Service's Stage II protocols result in seedling diameters being recorded as 0.00 inches instead of the FVS requirement of 0.01 inches. Additionally, some damage codes have changed. For example, the presence of dwarf mistletoe disease was originally recorded as "61." The FVS utilizes a code of "30" for dwarf mistletoe disease. Users must make both of these corrections prior to making a FVS run. These edits can be done either while in the FORVIS database or through use of the stand list file and the FVS tree data edit functions in SUPPOSE.

Conclusion

The BLM has found the FVS program a very valuable tool in forest resource management and has incorporated many of the data requirements for an FVS run in their forest inventory database, the Forest Vegetation Information System (FORVIS). Only minor issues with data transfer are encountered and these are related to "legacy data."

References

Bureau of Land Management. 2006. BLM Forest Lands Report—2006: Status and condition. BLM/ST/ST-07/001+5000. Denver, CO: Bureau of Land Management. 111 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Aggregating Pixel-Level Basal Area Predictions Derived from LiDAR Data to Industrial Forest Stands in North-Central Idaho

Andrew T. Hudak[1]
Jeffrey S. Evans[1]
Nicholas L. Crookston[1]
Michael J. Falkowski[2]
Brant K. Steigers[3]
Rob Taylor[3]
Halli Hemingway[4]

Abstract—Stand exams are the principal means by which timber companies monitor and manage their forested lands. Airborne LiDAR surveys sample forest stands at much finer spatial resolution and broader spatial extent than is practical on the ground. In this paper, we developed models that leverage spatially intensive and extensive LiDAR data and a stratified random sample of field plots across two mixed conifer forest landscapes in north-central Idaho. Our objective was to compare alternative models for producing unbiased maps of basal area per acre (BAA; ft2/acre), towards the greater goal of developing more accurate and efficient inventory techniques. We generated 60 topographic or stand structure metrics from LiDAR that were used as candidate predictor variables for modeling and mapping BAA at the scale of 30m pixels. Tree diameters were tallied in 1/10 and 1/5 acre fixed-radius plots (N = 165). Four models are presented, all based on 12 predictor variables. The first imputes BAA as an auxiliary variable from an imputation model that uses the machine learning algorithm randomForest in classification mode, and was developed in a prior study to map species-level basal areas of 11 conifer species; the second uses randomForest in regression mode to predict BAA as a single response variable from these same 12 predictor variables. The third is a linear regression model that predicts ln-transformed BAA using a best subset of 12 different predictor variables; the fourth again uses randomForest in regression mode, based on the same best subset of 12 variables selected for the linear regression model. We aggregated the pixel-level predictions within industrial forest stand boundaries, and then used equivalence plots to evaluate how well the aggregated predictions matched independent stand exams (having projected the tree growth in FVS and updated the stand tables to July 2003, the time of the LiDAR acquisition). All four models overpredicted BAA, but the bias was significant only in the case of the regression model. Predictions from the two randomForest models run in regression mode were very similar, despite using different predictor variables. We conclude that randomForest can be used to impute or predict canopy structure information from LiDAR-derived topographic and structural metrics with sufficient accuracy for operational management of conifer forests. In the future, tree lists could be imputed from LiDAR-derived canopy structure metrics empirically related to plot-level tree measurements. This will allow projections of tree growth at the pixel level across forested landscapes, instead of at the stand level as is the current norm.

Keywords: forest inventory; forest management; Forest Vegetation Simulator (FVS); imputation; modeling and mapping; randomForest; regression; remote sensing

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Research Forester, Landscape Ecologist, Operations Research Analyst, respectively, USDA Forest Service, Rocky Mountain Research Station, Moscow, ID, e-mail: ahudak@fs.fed.us.

[2] PhD. Candidate, University of Idaho, Moscow, ID.

[3] GIS Supervisor, and Manager, respectively, Potlatch Forest Holdings, Inc., Lewiston, ID.

[4] GIS Administrator, Bennett Lumber Products, Inc., Princeton, ID.

Introduction

LiDAR Remote Sensing

An analysis comparing alternative remote sensing technologies demonstrated that LiDAR is more sensitive to forest canopy structure than passive optical imagery (Lefsky and others 2001). Canopy structure attributes characterized by LiDAR correlate well with stand structure attributes measured in field plots (Lefsky and others 2005a,b). This is true even in high biomass forests, where passive optical sensors become saturated. Correlations between LiDAR canopy structure metrics and stand structure metrics appear stronger in coniferous than in deciduous forests, due to the conical architecture of conifer trees allowing for greater penetration of LiDAR pulses into the canopy (Lefsky and others 2002).

Forest industries have taken note of the groundswell of promising research results regarding the utility of LiDAR data for forestry applications. LiDAR surveys are expensive but on a per acre basis can be competitive with the cost of traditional forest inventory, as labor costs have increased, especially in a market with stiff international competition. LiDAR costs are also counterweighted by the potential benefits of having highly detailed forest structure information mapped across the entire landscape surveyed. These factors have led to increased interest in operational use of LiDAR by forest industries.

Inventory Designs

The two industry partners in this project, Potlatch Forest Holdings, Inc. and Bennett Lumber Products, Inc., use similar stand-based inventory systems on their forest lands (Dennis Murphy, personal communication). The basic operating units are stands, which are delineated from aerial photographs. Trees within the delineated stand boundary are the population of interest and are sampled in randomly placed plots of variable radius (fig. 1a). The density of plots within a stand is based on a target sampling error for estimating volume. Plot design can vary between stands but generally is consistent within stands. Stand level parameters are generated from the plot level data using simple random sample estimators that vary depending on plot design. The stand-based inventory is updated using the Forest Vegetation Simulator (FVS) at six-month intervals (after the spring and fall growing seasons) by processing the original tree list at the plot level.

Scanning LiDAR systems provide spatially intensive and extensive canopy height measures that could facilitate forest inventory at the much finer scale of pixels rather than polygons (fig. 1). To estimate forest structure attributes of interest besides canopy height, the LiDAR height measures must be related to field measures of these attributes, measured in field plots randomly distributed across the full range of variation. This requires a preliminary stratification to distribute sample plot locations in an objective and representative manner within the forested landscape of interest. The sampling intensity of LiDAR could dramatically reduce the sampling intensity of inventory plots required, provided they are accurately geolocated. The reduced plot count in an inventory that uses LiDAR data (fig. 1b) argues for using fixed-radius plots for more accurate canopy structure characterization than with variable-radius plots. The field plots can then be used as training data, or reference observations, for predicting or imputing the forest structure attributes of interest to target pixels across the entire landscape. Neither the spatially explicit model inputs nor map outputs would rely on stand boundaries, which are subject to change, but could be aggregated to stand units if desired.

RandomForest

The randomForest (RF) method is so named because it uses random samples of data and variables through multiple model iterations, to generate a large group, or forest, of classification and regression trees (CART) (Breiman 2001). The classification output from RF represents the statistical mode of many decision tree classifications, hence achieving a more accurate and robust model than a CART. Randomly subsetting predictor variables allows RF to derive variable importance values and prevents problems associated with correlated variables and overfitting (Breiman 2001). The RF package in R (R Development Core Team 2004) includes two measures of variable importance (Liaw and Wiener 2002). The first measure quantifies each variable's effect on the mean squared error (MSE). Variables that markedly lower the MSE have higher importance

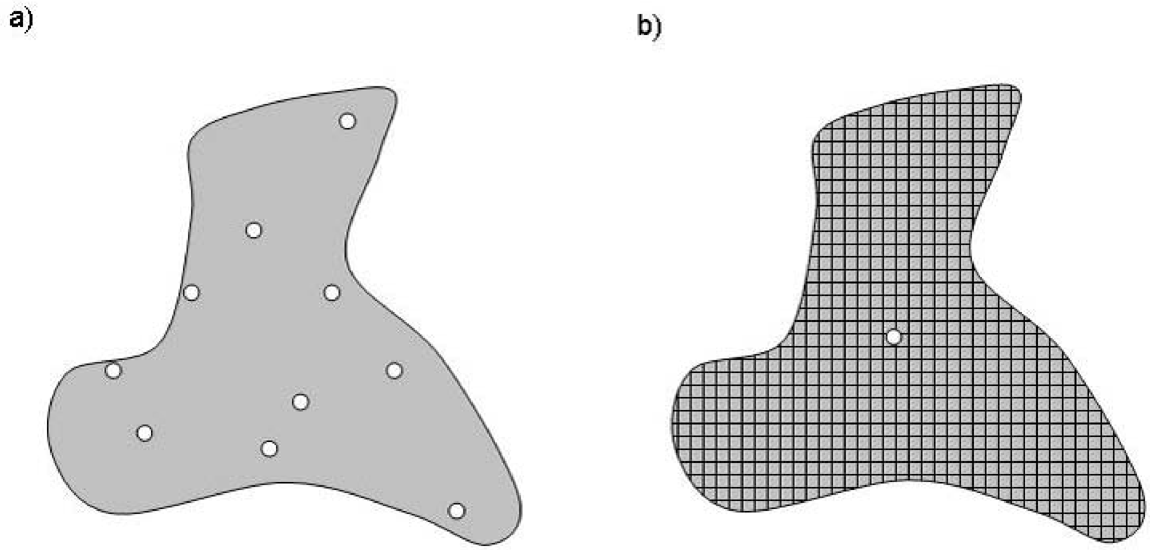


Figure 1—Conceptual diagrams illustrating a) current inventory design based on polygon units versus and b) proposed inventory design based on pixel units. The white dots represent field sample plots, which in a) have variable radius and are randomly located within the stand, but in b) have fixed radius and are randomly located within the landscape. The map unit in a) is the entire stand, while in b) each pixel is a map unit independent of the stand boundary.

values as compared to variables the have little effect on the MSE. The second measure, the Gini index, is a measure of node purity. Stronger predictor variables produce more consistent nodes across the forest of classification trees, thus having a higher Gini index. Because RF is nonparametric, the data may be rank-deficient, meaning the data may have more variables (columns) than observations (rows), have colinearities, or both. Skewed distributions in the response variables are also not a concern.

Crookston and Finley (2008) developed the "yaImpute" package in R, which includes a method based on RF classification along with several more traditional imputation algorithms methods. Imputation uses empirical relationships between attributes of interest (Y variables) measured on a sample of the observations (called reference observations) and predictor variables (X variables) available on all observations. These empirical relationships are calibrated using the reference observations. Observations that have no measured Y variables are termed target observations. A reference observation that is the nearest neighbor of a target in the multidimensional space is the source of values of Y variables that are imputed to the target. Nearness can be measured several different ways, including the most similar neighbor method introduced by Moeur and Stage (1995) and the gradiant nearest neighbor method introduced by Ohmann and Gregory (2002). The method introduced by Crookston and Finley (2008) that is based on the RF classification algorithm identifies a nearest neighbor by first concatenating the forest of classification trees across terminal nodes, and then finding the reference observation that most often shares terminal nodes with the target observation. In the case of either imputation or RF classification in yaImpute, the user defines the number of nearest neighbors to use, k, which can vary from 1 to n.

Independently of using RF in classification mode for imputation in yaImpute, the user can also run RF in regression mode to predict a single Y variable of interest (Liaw and Wiener 2002). In regression mode, the random vector takes on numerical values rather than class labels, as in classification mode (Breiman 2001). As in classification mode, out-of-bag estimation allows importance values to be assigned to the predictor variables, thus providing insight on the predictive ability of the model.

Objective

Our objective was to relate predictor variables derived from LiDAR to field data within field plots placed using a statistically rigorous sampling design to map BAA across mixed-conifer forest in north-central Idaho that is actively managed and predominantly owned by forest industry. This objective was motivated by our access to stand exam data provided courtesy of our industry partners, to independently validate our pixel-level predictions, after aggregating them to the stand level.

This objective is an important step towards the greater goal of using FVS (Dixon 2002; Stage 1973) for imputing tree lists to spatial map units, be they cells (pixels) or stands (polygons), using LiDAR-derived predictor variables. This would enable forest managers to project growth, mortality, and the other processes already incorporated into FVS across entire landscapes.

Methods

Study Areas

The Moscow Mountain (80,789 acres) and St. Joe Woodlands (137,539 acres) study areas are situated in north-central Idaho (fig. 2). Conditions at Moscow Mountain are drier than at the St. Joe Woodlands, so forest canopies tend to have a more open structure on Moscow Mountain. Individual conifer species occur along a temperature/moisture gradient as has been described by Daubenmire (1966), beginning at the warm/dry end with *Pinus ponderosa* mostly on Moscow Mountain, to *Pseudotsuga menziesii*, *Larix*

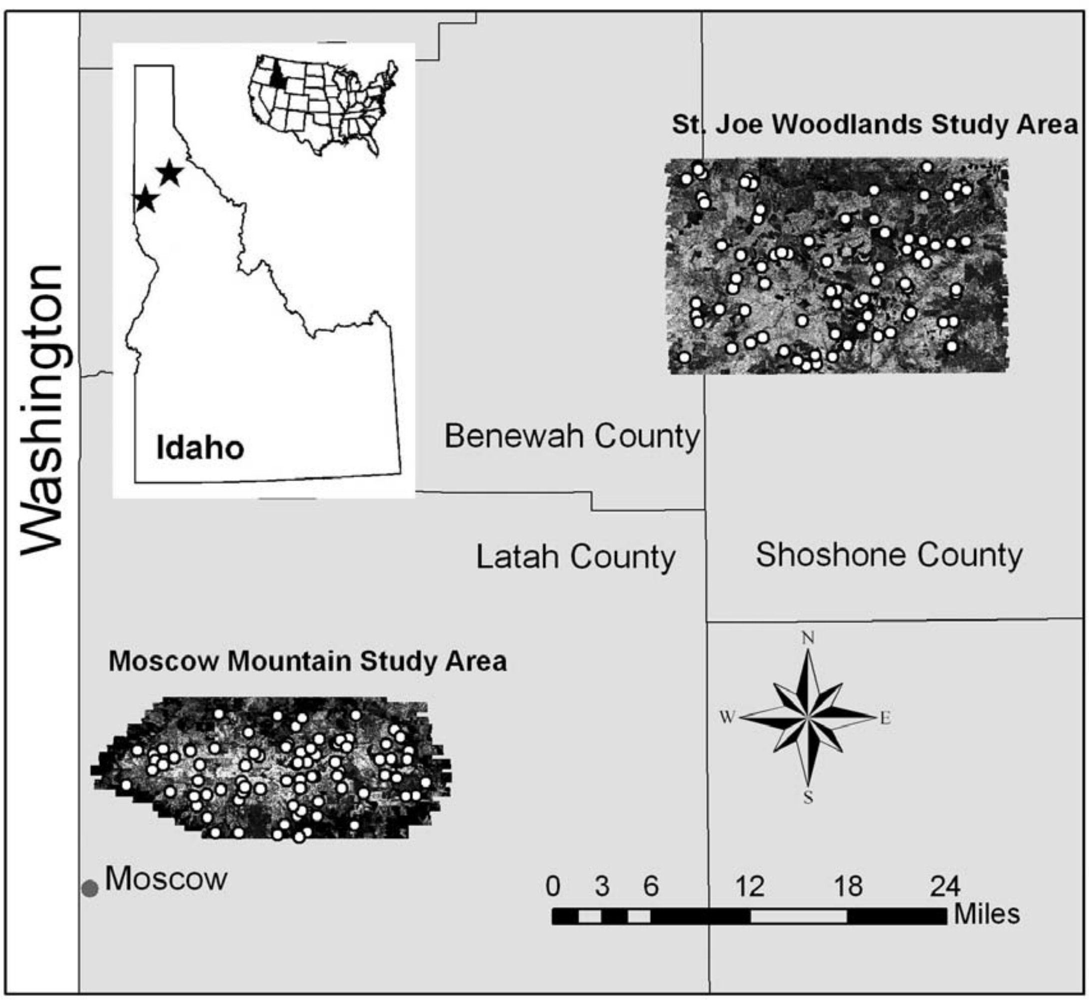


Figure 2—-Study areas in north-central Idaho, with basal area per acre (BAA) predicted by Model 1 mapped in grey scale. Maps of BAA predicted by the other three models presented in this paper appear the same. The white dots represent field plot locations (N = 165).

occidentalis, *Pinus contorta*, *Abies grandis*, *Pinus monticola*, *Thuja plicata*, *Tsuga heterophylla*, *Picea engelmannii*, *Abies lasiocarpa*, and ending with *Pinus albicaulis* at the cool/wet end, or the highest elevations in the St. Joe Woodlands. More complex terrain at the St. Joe Woodlands (elevation range: 2,093–6,578 ft) than at Moscow Mountain (elevation range: 2,549–4,980 ft) produces longer and steeper gradients that drive more diverse species composition in the St. Joe Woodlands.

Field Sampling

Field sample plot locations were selected using a stratified random design. The stratification variables were elevation from a 30 m USGS digital elevation model (DEM), solar insolation (Fu and Rich 2000), and a mid-infrared corrected normalized difference vegetation index (NDVIc) (Nemani and others 1993) calculated from an Landsat ETM+ scene (18 August 2002). The NDVIc has been found to be superior to NDVI for estimating leaf area index in mixed-conifer forests of northern Idaho (Pocewicz and others 2004). Plots were geolocated with a Trimble Pro-XR Global Positioning System (GPS). A minimum of 150 points were recorded on the ground surface at plot center, and later differentially corrected and averaged for a final three-dimensional (3D) point position with ±2.6 ft horizontal and ±3.6 ft vertical accuracy (Trimble Pathfinder Office). Plots were 1/10 acre at Moscow Mountain and 1/5 acre at the St. Joe Woodlands and of fixed radius, with all trees ≥5 inches diameter at breast height (dbh) tallied. The sampling design failed to capture rare, late successional conditions, so two plots were randomly located within two old-growth stands (one in each study area) to capture the high end of the BAA gradient, for a total of 165 plots.

Measured tree diameters (N = 5240) were converted to tree basal areas, summed, and divided by the plot area to estimate BAA for modeling. Eleven plots at Moscow Mountain lacked trees ≥5 inches dbh but were assigned negligible values of 0.4356 ft^2/acre (0.1 m^2/ha), to enable their inclusion in the analysis when a natural logarithm (ln) transform was applied.

LiDAR Sampling

Horizons, Inc. (Rapid City, SD) flew the Light Distance And Range (LiDAR) survey at an altitude of 8,000 ft above mean terrain during the summer of 2003, using an ALS40 system operating at 1,064 nm and a pulse rate of 20 KHz. Data were delivered in the form of unclassified point data. Evans and Hudak (2007) developed a Multiscale Curvature Classification algorithm in ArcInfo Macro Language (AML) to classify the returns as either ground or non-ground. The classified ground returns were interpolated into a 2-m DEM, from which several topographic predictor variables were derived (table 1).

Subtracting the 2-m DEM from the unclassified LiDAR returns produced a canopy height layer normalized for topography. By definition, returns classified as ground returns equaled 0 m in height. Returns greater than 0 m in height were considered non-ground returns. Returns greater than 1 m in height were considered vegetation returns. Distributional statistics (min, max, mean, percentiles, variance, skewness, kurtosis, and so on) were calculated from the height and intensity values of the vegetation returns. Vegetation density was calculated as the percentage of total returns that were vegetation returns. The percentage of vegetation returns occurring within each of six defined canopy height strata was also calculated. All of these metrics were derived from the LiDAR data in 30-m bins. The Universal Transverse Mercator (UTM, Zone 11) Easting and Northing coordinates were added to produce 60 candidate variables for modeling (table 1).

Modeling

This analysis compares BAA predictions from four alternative models, as described below.

Model 1—For forestry applications, Y variables are typically measured in plots (for example, BAA in this study), while X variables are environmental variables typically measured by remote sensing (for example, LiDAR in this study). The field sampled plots have both X and Y variables and all map units have X variables. Hudak and others (2008) pruned the list of 60 candidate predictor variables (table 1) down to 12 for pre-

Table 1—Candidate predictor variables and those selected for the four models compared.

Variable	Description	Models 1 and 2	Models 3 and 4
EAST	UTM Easting (meters)		
NORTH	UTM Northing (meters)		
ELEV	Elevation (meters)	X	X
SLP	Slope (degrees)		
TSRAI	Topographic solar radiation aspect index (Roberts and Cooper 1989)	X	X
SCOSA	Percent slope*cos(aspect) transformation (Stage 1976)		
SSINA	Percent slope*sin(aspect) transformation (Stage 1976)		
INSOL	Solar insolation (HEMI 2000)		
CRR	Canopy relief ratio (Pike and Wilson 1971)		
HMIN	Heights minimum		
HMAX	Heights maximum		
HRANGE	Heights range	X	
HMEAN	Heights mean		
HAAD	Heights average absolute deviation	X	
HMAD	Heights median absolute deviation		
HSTD	Heights standard deviation		
HVAR	Heights variance		
HSKEW	Heights skewness		
HKURT	Heights kurtosis		
HCV	Heights coefficient of variation	X	X
H05PCT	Heights 5th percentile	X	
H10PCT	Heights 10th percentile		
H25PCT	Heights 25th percentile	X	
H50PCT	Heights 50th percentile (median)		
H75PCT	Heights 75th percentile		
H90PCT	Heights 90th percentile		
H95PCT	Heights 95th percentile		
HIQR	Heights interquartile range		
IMIN	Intensity minimum		
IMAX	Intensity maximum		
IRANGE	Intensity range		
IMEAN	Intensity mean		X
IAAD	Intensity average absolute deviation		
IMAD	Intensity median absolute deviation		
ISTD	Intensity standard deviation		
IVAR	Intensity variance	X	
ISKEW	Intensity skewness	X	
IKURT	Intensity kurtosis		X
ICV	Intensity coefficient of variation		
I05PCT	Intensity 5th percentile		
I10PCT	Intensity 10th percentile		
I25PCT	Intensity 25th percentile		
I50PCT	Intensity 50th percentile (median)		
I75PCT	Intensity 75th percentile		
I90PCT	Intensity 90th percentile		
I95PCT	Intensity 95th percentile		
IIQR	Intensity interquartile range		
DENSITY	Canopy density (vegetation returns/total returns * 100)	X	X
STRATUM0	Percentage of ground returns = 0 m		
STRATUM1	Percentage of non-ground returns > 0 m and <= 1 m in height	X	
STRATUM2	Percentage of vegetation returns > 1 m and <= 2.5 m in height		
STRATUM3	Percentage of vegetation returns > 2.5 m and <= 10 m in height		X
STRATUM4	Percentage of vegetation returns > 10 m and <= 20 m in height		X
STRATUM5	Percentage of vegetation returns > 20 m and <= 30 m in height		X
STRATUM6	Percentage of vegetation returns > 30 m in height		X
TEXTURE	Standard deviation of non-ground returns > 0 m and <= 1 m		
PCT1	Percentage 1st returns		
PCT2	Percentage 2nd returns	X	X
PCT3	Percentage 3rd returns		X
NOTFIRST	Percentage 2nd or 3rd returns		

dicting species-level basal areas and tree densities of 11 conifer species (in other words, 22 Y variables). In that analysis, the RF classification method produced more accurate results than seven more traditional imputation methods available in yaImpute. The RF classification model used to map species-level basal areas and tree densities was applied to map BAA as an auxiliary variable, using $k = 1$ nearest neighbor, and constitutes the first map considered in this analysis.

Model 2—The RF algorithm can also be employed as a regression tool, for predicting a single Y variable of interest. For this analysis, that variable of interest was BAA, across all tree species. The same 12 predictor variables used in Model 1 to impute a BAA map using RF in classification mode (Hudak and others, 2008) were also used to map BAA using RF in regression mode.

Model 3—A multiple linear regression model was developed for comparison because it is the predictive modeling technique most broadly used for relating field and remotely sensed data, and has been successfully applied for mapping BAA in this landscape (Hudak and others 2006). Regression is much more vulnerable to colinearity problems than nonparametric methods such as RF, so the maximum Pearson correlation allowed between predictor variables was 0.8. (The maximum Pearson correlation between predictor variables included in Model 1 was 0.9; Hudak and others, 2008.) Although RF is resistant to problems of colinearity and overfitting in either classification or regression mode, it is neither helpful nor instructive to include highly correlated predictor variables in the same model. The best subset of twelve predictor variables that satisfied this constraint was selected for predicting BAA, after ln transformation to correct the positive skew. This necessitated a bias correction (Baskerville 1976) to correct for the bias introduced by back-transforming predicted ln (BAA) to the natural scale, following Hudak and others (2006).

Model 4—The twelve predictor variables selected as the best subset for multiple linear regression were used in another RF model run in regression mode.

In summary, the output from four alternative models for predicting BAA were compared: (1) RF in classification mode based on 12 predictor variables used in an imputation model (yaImpute) from a prior analysis; (2) RF in regression mode based on the same 12 variables as in Model 1; (3) multiple linear regression based on a best subset of 12 new predictor variables; and (4) RF in regression mode based on these same 12 variables as in Model 3.

Mapping

Raster layers of the predictor variables selected by the models were generated for both study areas at a 30 m resolution using the fishnet command in ArcInfo. The intersect command was used to assign the corresponding cell ID to each LiDAR point. The LiDAR points then were exported from ArcInfo as a comma-delimited (csv) file containing six attributes: bin-ID, bin centroid X coordinate, bin centroid Y coordinate, height (Z coordinate), intensity, and return level. The csv file of LiDAR points was sorted on the Bin-Id using the DOS SORT command, then input into a Perl program developed to iteratively subset the LiDAR point data by bin-id and calculated the LiDAR metrics within each bin. Metrics were calculated within each bin and written to an output csv file. A batch file was written in R that looped through each output csv file, creating ArcInfo ASCII grids of the metrics selected as predictor variables in R.

The yaImpute package (Crookston and Finley 2008) also includes functions to assign values of the response variable(s) to target cells across the landscape, whether by imputation, regression or some other predictive model, wherever data for the predictor variables exist. A 30-m mapping resolution was used for this analysis.

Validation

Predictions of BAA at the 30 m pixel level were aggregated within stand boundaries delineated by industry partners Potlatch Forest Holdings, Inc., and Bennett Lumber Products, Inc., who also provided stand exam data for 1,024 and 177 stands, respectively. Tree growth in the stand exam data was projected forward from the time of inventory until July 2003, when the LiDAR survey was conducted. Thus, only the spring growing season was included in the 2003 projection. The updated stand projections were then used to validate our predictions aggregated to the stand level using the ZONALMEAN function in ArcMap.

The regression-based method of equivalence tests (Robinson and Froese 2004; Robinson and others 2005) was used to validate predictions extracted from the four maps of BAA. Traditionally, models are validated under the null hypothesis of no difference between predictions and observations, or that the model is acceptable. However this approach is more likely to validate a model with low power (Robinson and Froese 2004). Equivalence tests begin with the null hypothesis that the model is unacceptable, thus shifting the burden of proof on to the model to demonstrate validity (Robinson and Froese 2004; Robinson and others 2005). The equivalence package in R regresses observations on to predictions, and uses bootstrapping to not only test between the similarity of means, but the similarity of individual predictions and observations, thus increasing statistical power for more robust model validation (Robinson and others 2005).

Results

The LiDAR predictor variables selected by Hudak and others (2008) for Model 1 included several height distributional metrics (for example, range, average absolute deviation, 5th and 25th percentiles) (table 1), for which Model 2 assigned importance values (fig. 3a). The best subset of LiDAR predictors selected for Model 3 included several upper canopy density metrics (canopy density in 3rd, 4th, 5th, and 6th strata) (table 1), for which Model 4 assigned importance values (figure 3b). The influential topographic predictors of elevation and topographic solar radiation aspect index were selected in both cases, as was density, coefficient of variation in height, and percentage of second returns (table 1; fig. 3). Two predictor variables derived from the intensity values were included in the subsets of both the imputation predictors (variance and skewness) and regression predictors (mean and kurtosis) (table 1; fig. 3).

All four models tended towards overprediction of BAA relative to the independent stand exams, although prediction residuals indicate BAA could be overpredicted greatly in some stands and underpredicted greatly in some others (fig. 4). The mean BAA from the imputation model (Model 1) was the least biased, while the mean predicted by multiple linear regression (Model 3) was most biased. The interquartile range of values predicted by the imputation and regression models was unrealistically larger than the interquartile range predicted by the two RF models in regression mode (Models 2 and 4), which closely matches the interquartile range of the stand exams (fig. 4).

Equivalence tests were used to validate the pixel-level predictions aggregated to the stand level with the stand-based inventories, updated with FVS to the July 2003 time of LiDAR acquisition. Each equivalence test regresses observations (stand exams) on predictions (aggregated pixels), then bootstraps the data to test the significance of both the intercept and slope terms of these simple linear regression models. Results are indicated graphically (fig. 5). The intercept test (gray error bars plotted around the mean value, but largely hidden by the black error bars) in each of the equivalence regressions does not significantly differ from its expected range (gray shaded region) for any of the models, as would be the case if the gray error bars were located outside the shaded region (fig. 5). The slope test (black error bars plotted around the solid diagonal line) in each of the equivalence regressions does significantly differ from its expected range (dotted diagonal lines) in the case of the imputation and regression models (Models 1 and 3), but not the two RF models run in regression mode (Models 2 and 4).

Discussion

Breiman (2001) found that RF did not incorporate randomness into the model quite as effectively in regression mode as in classification mode. One could associate non-randomness with bias, which might help explain why BAA imputed as an auxiliary variable by RF in classification mode (Model 1) was the least biased of the four models presented in this study (figs. 4 and 5). However, BAA predictions from the two RF models run in regression mode (Models 2 and 4) were not significantly biased either. In fact, the bias was only significant in the case of the multiple linear regression model (Model 3) (fig. 5). Although not presented in this paper, Hudak and others (2006) also overpredicted BAA using a multiple linear regression model, to an even larger degree than Model 3 in this study. The consistently positive and significant bias of these multiple linear regression

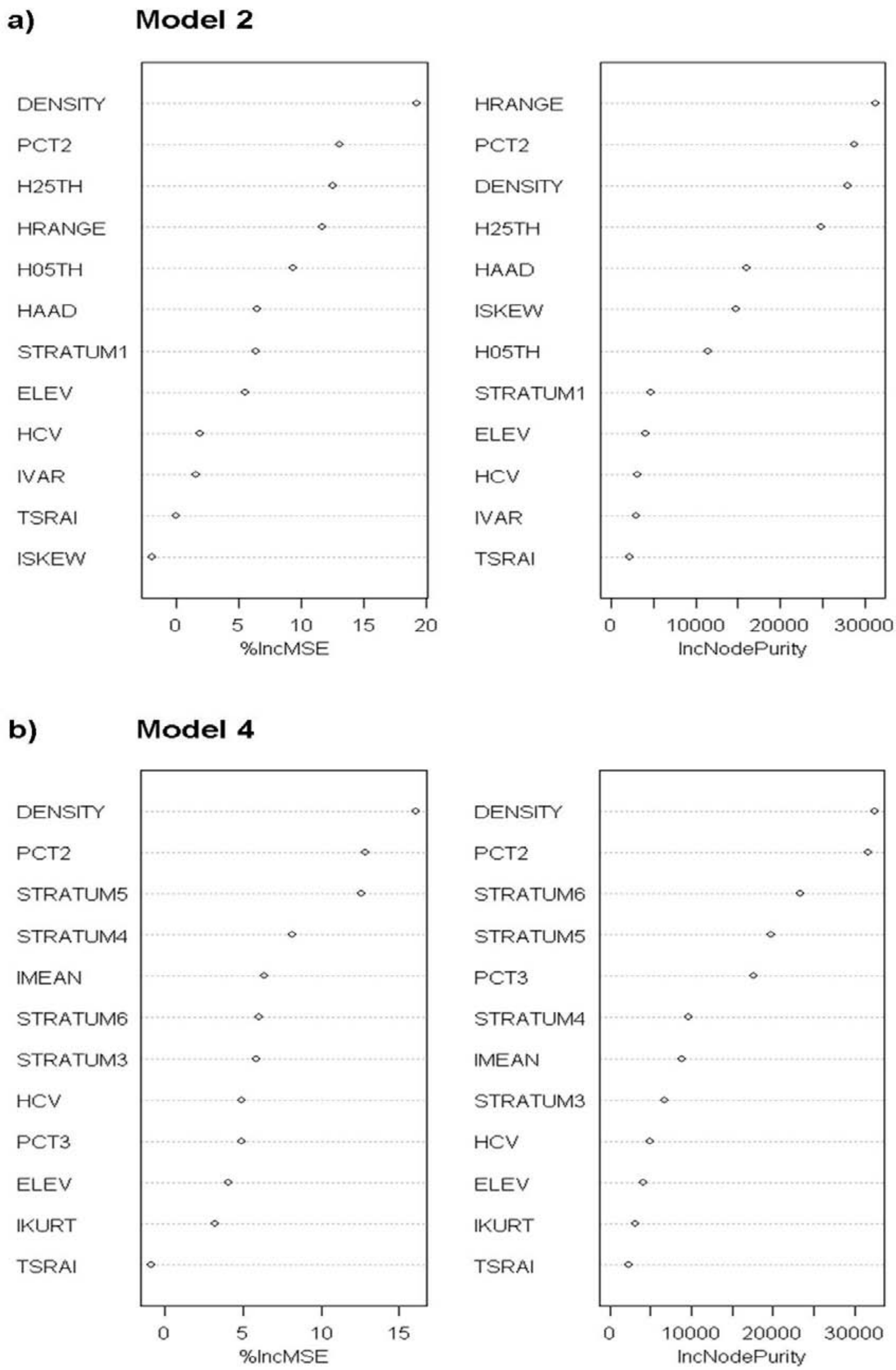


Figure 3—Importance plots from the randomForest models run in regression mode (Models 2 and 4) using a) 12 predictor variables selected for imputation (Model 1), and b) 12 predictor variables selected for multiple linear regression (Model 3). Two measures of relative importance are indicated in each case: influence on the mean squared error, and influence on node purity. Variables are plotted from the top with importance values in descending order.

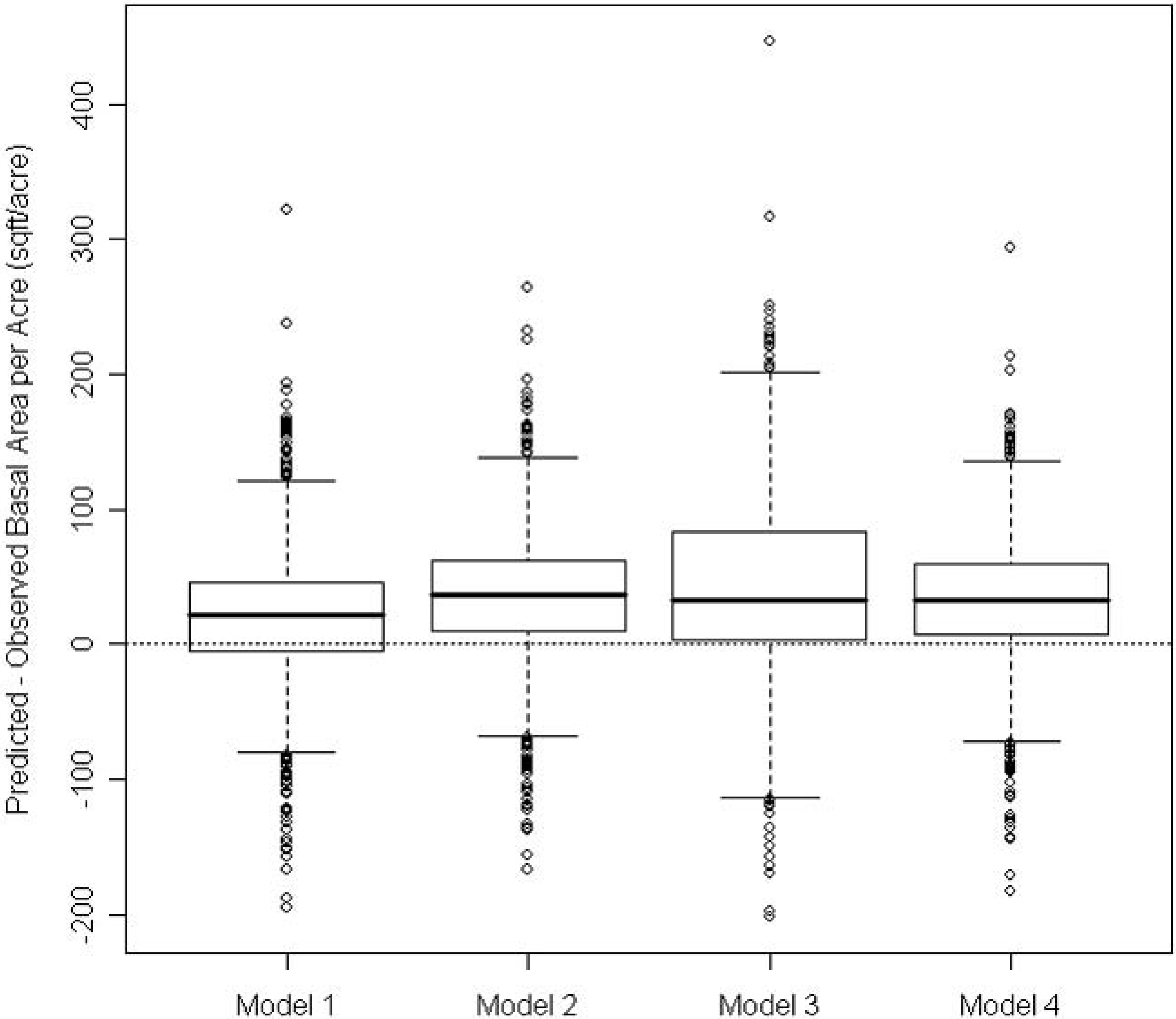


Figure 4—Boxplots comparing paired residuals, quantifying the difference between predicted pixel-level BAA aggregated within 1201 industry stands and observed stand-level BAA, for the four predictive models. Thick horizontal lines mark the medians, box ends represent lower and upper quartiles, line ends indicate the 5th and 95th percentiles, and dots show stands beyond the 5th and 95th percentiles. The dotted horizontal line indicates where model bias equals zero.

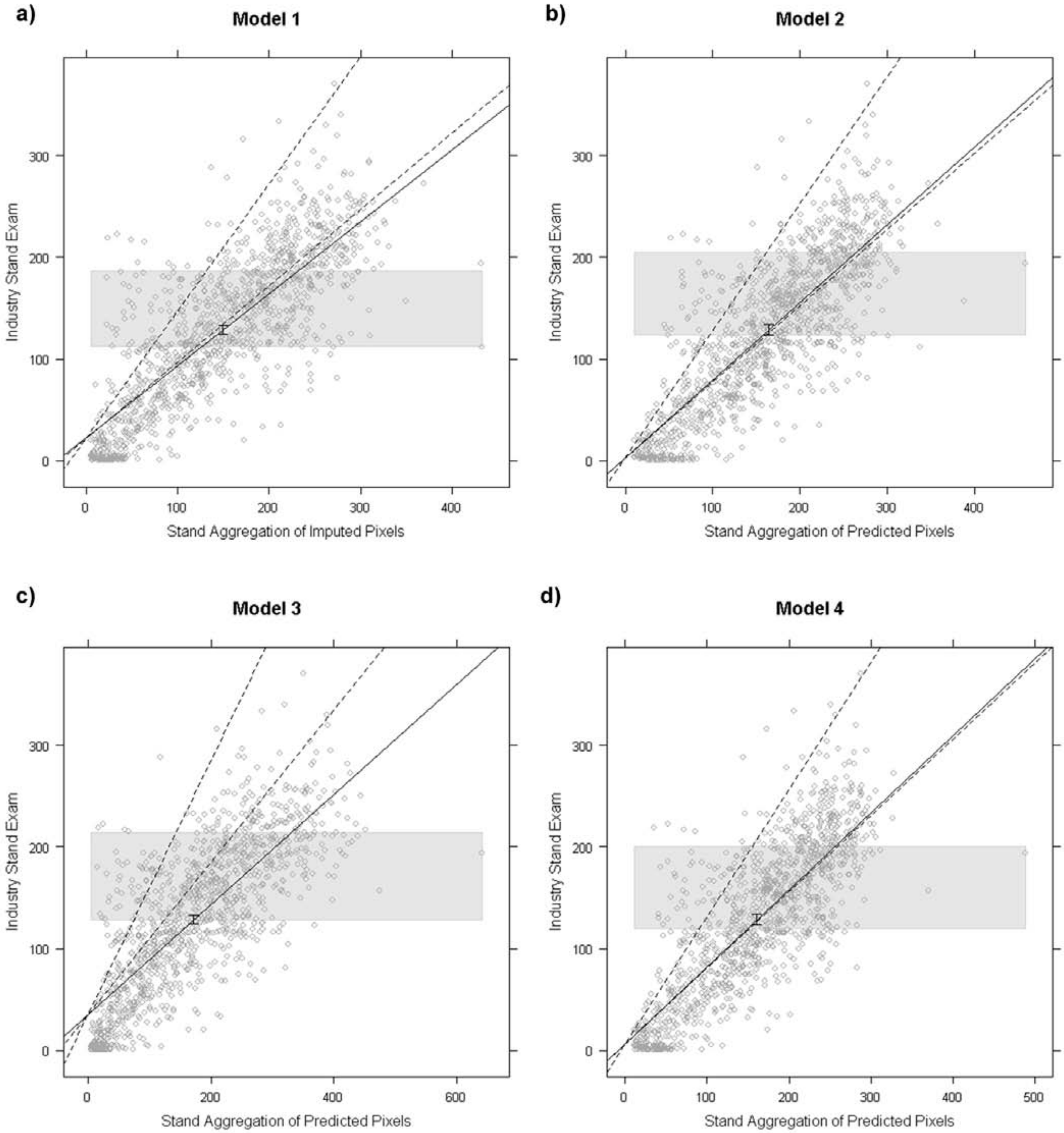


Figure 5—Equivalence plots that graphically indicate whether pixel-level BAA predictions aggregated to the stand level significantly differ from stand exams, based on the four models as labeled. The equivalence test regresses observations (stand exams) on predictions (aggregated pixels) in a simple linear regression, while bootstrapping the data. If the gray error bar (largely hidden by the black error bar) falls within the shaded gray region, then the intercept of the linear model does not significantly differ from its range of expected values. If the black error bar falls between the dotted lines, then the slope term of the linear model does not significantly differ from its range of expected values

models may be an artifact of the ln transformation and subsequent back-transformations, which warrants consideration of other methods for adjusting retransformation bias (e.g., Duan 2002). More likely, the stand-based inventories themselves are not an unbiased representation of the variation in BAA that formed the basis of our sampling design across our two study landscapes. BAA may be higher on the non-industrial forest lands within our study areas, which would be represented in the sample plots but not the stand exam data. We would need to limit the plots used to develop our models to only those occurring in industrial forest stands for which we have inventory data, to determine to what degree the models may be biased.

The three RF models also more satisfactorily reproduced the range of variability in the stand exams than the regression model (figs. 4 and 5). The random element of RF causes output to vary slightly between separate model runs, while multiple linear regression output is invariant. However, several runs of the RF models, each consisting of 500 classification trees, were found to produce very consistent results, so these differences were too negligible to alter our results to a degree that would change our interpretation or conclusions.

Hudak and others (2006) also considered the ten Advanced Land Imager (ALI) reflectance bands as candidate variables to predict basal area and tree density using multiple linear regression, but these spectral variables contributed little to the model. Similarly, Hudak and others (2008) found that these spectral variables, along with three simple vegetation indices, contributed only negligibly to imputation of basal area and tree density of 11 individual conifer species. Therefore, we did not pursue using spectral imagery in this analysis. Multispectral or hyperspectral imagery could aid discrimination between coniferous and deciduous species, or habitat types with variable phenologies. However, in the mixed conifer forest within our two study areas, LiDAR data alone appears to be sufficient for modeling structural attributes at the species level (Hudak and others, 2008). This is important because species can change timber value by a factor of 4 or 5 (Dennis Murphy, personal communication). Elevation and aspect play an obviously important role in determining vegetation structure and composition in these topographically complex landscapes, and can be mapped with unprecedented detail with LiDAR surveys. This paper further demonstrates that useful canopy metrics can be obtained from LiDAR intensity and density metrics, not just height metrics. In particular, vegetation density, or the proportion of total returns that are vegetation returns, is consistently a powerful predictor variable (fig. 3).

It is interesting that such similar predictions were obtained from the two RF models run in regression mode (Models 2 and 4; figs. 4 and 5). The predictor variables selected for imputation consisted of several height distribution metrics, some from the lower canopy, while the predictor variables selected for multiple linear regression were mostly density metrics from the upper canopy. We conclude that the canopy structure variation in these coniferous forests can be characterized equally well by different variable combinations. The 60 candidate variables considered for our models are likely many more than are necessary to develop a satisfactory model. Future research will test this suite of candidate variables in other forest types, to evaluate empirically which structural metrics have the greatest general utility.

LiDAR may prove essential in future forest inventory design. LiDAR data can provide the detailed height data that correlate well with tree diameter, basal area, and volume. Significantly fewer field plots may be required to build the empirical relationships necessary for predicting these and other attributes of interest to forest managers. Imputation of diameter distributions (i.e., tree lists) from independent LiDAR height, density, and intensity distributional metrics could provide spatially gridded inputs into FVS. This could change inventory designs from being based on stand (polygon) units to being based on cell (pixel) units (fig. 1). LiDAR-derived canopy structure layers could provide a more objective data source than aerial photos for delineating stands, for the purpose of aggregating gridded map outputs (e.g., BAA) to stand units for managers. Further research is needed to quantify the degree to which this may impact overall accuracy, efficiency, and cost of managing forested landscapes.

Conclusion

We found that applying randomForest in either classification or regression mode can consistently predict BAA from LiDAR-derived predictor variables. Mean BAA of pixels aggregated to the stand level did not significantly differ from independent stand based inventories. We recommend that forest industry invest in LiDAR and associated field plot surveys for improved forest management. These results move us another step closer to our goal of predicting tree lists from LiDAR structure metrics, so that FVS projections might be generated within map units across forested landscapes, for more precise forest inventory and management.

Acknowledgments

This research was funded through the Sustainable Forestry component of Agenda 2020, a joint effort of USDA Forest Service Research & Development and the American Forest and Paper Association. We thank David Hall for his programming assistance. We thank technical reviewers Dennis Ferguson and Dennis Murphy, and statistician Rudy King, for their helpful comments.

References

Breiman, L. 2001. Random forests. Machine Learning. 45:5–32.

Crookston, N.L.; Finley, A. 2008. yaImpute: an R package for k-NN imputation. Journal of Statistical Software. 28(10). Online: http://www.fs.fed.us/rm/pubs_other/rmrs_2008_crookston_n001.html. Package URL: http://cran.r-project.org/src/contrib/Descriptions/yaImpute.html.

Daubenmire, R. 1966. Vegetation: identification of typal communities. Science. 151:291–298.

Dixon, G.E., comp. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.

Duan, N. 2002. Smearing estimate: a nonparametric retransformation method. Journal of the American Statistical Association. 78:605–610.

Evans, J.S.; Hudak, A.T. 2007. A multiscale curvature algorithm for classifying discrete return lidar in forested environments. IEEE Transactions on Geoscience and Remote Sensing. 45:1029–1038.

Fu, P.; Rich, P.M. 2000. The Solar Analyst 1.0 User Manual. Lawrence, KS: Helios Environmental Modeling Institute (HEMI), LLC.

Hudak, A.T.; Crookston, N.L.; Evans, J.S.; Falkowski, M.J.; Smith, A.M.S.; Gessler, P.; Morgan, P. 2006. Regression modeling and mapping of coniferous forest basal area and tree density from discrete-return lidar and multispectral satellite data. Canadian Journal of Remote Sensing. 32:126–138.

Hudak, A.T.; Crookston, N.L.; Evans, J.S.; Hall D.E.; Falkowski, M.J. 2008. Nearest neighbor imputation of species-level, plot-scale forest structure attributes from LiDAR data. Remote Sensing of Environment. 112(5): 2232–2245.

Lefsky, M.A.; Cohen, W.B.; Spies, T.A. 2001. An evaluation of alternate remote sensing products for forest inventory, monitoring, and mapping of Douglas-fir forests in western Oregon. Canadian Journal of Forest Research. 31:78–87.

Lefsky, M.A.; Cohen, W.B.; Parker, G.G.; Harding, D.J. 2002. Lidar remote sensing for ecosystem studies. BioScience. 52:19–30.

Lefsky, M.A.; Hudak, A.T.; Cohen, W.B.; Acker, S.A. 2005a. Geographic variability in lidar predictions of forest stand structure in the Pacific Northwest. Remote Sensing of Environment. 95:532–548.

Lefsky, M.A.; Hudak, A.T.; Cohen, W.B.; Acker, S.A. 2005b. Patterns of covariance between forest stand and canopy structure in the Pacific Northwest. Remote Sensing of Environment. 95:517–531.

Liaw, A.; Wiener, M. 2002. Classification and regression by randomForest. R News. 2:18–22.

Moeur, M.; Stage, A.R. 1995. Most similar neighbor: an improved sampling inference procedure for natural resource planning. Forest Science. 41:337–359.

Ohmann, J.L.; Gregory, M.J. 2002. Predictive mapping of forest composition and structure with direct gradient analysis and nearest neighbor imputation in coastal Oregon, U.S.A. Canadian Journal of Forest Research. 32:725–741.

Pike, R.J.; Wilson, S.E. 1971. Elevation relief ratio, hypsometric integral, and geomorphic area altitude analysis. Geological Society of America Bulletin. 82:1079–1084.

R Development Core Team. 2004. R: A language and environment for statistical computing. ISBN 3-900051-07-0. Vienna, Austria: R Foundation for Statistical Computing. Online: http://www.R-project.org.

Roberts, D.W.; Cooper, S.V. 1989. Concepts and techniques of vegetation mapping. In: Land classifications based on vegetation: Applications for resource management. Gen. Tech. Rep. GTR-INT-257. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 90–96.

Robinson, A.P.; Froese, R.E. 2004. Model validation using equivalence tests. Ecological Modelling. 176:349–358.

Robinson, A.P.; Duursma, R.A.; Marshall, J.D. 2005. A regression-based equivalence test for model validation: shifting the burden of proof. Tree Physiology. 25:903–913.

Stage, A.R. 1973. Prognosis model for stand development. Res. Pap. INT-137. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Stage, A.R. 1976. An expression of the effects of aspect, slope, and habitat type on tree growth. Forest Science. 22:457–460.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Model Development I

Inventory-Based Sensitivity Analysis of the Large Tree Diameter Growth Submodel of the Southern Variant of the Forest Vegetation Simulator

Giorgio Vacchiano[1]
John D. Shaw[2]
R. Justin DeRose[3]
James N. Long[3]

Abstract—Diameter increment is an important variable in modeling tree growth. Most facets of predicted tree development are dependent in part on diameter or diameter increment, the most commonly measured stand variable. The behavior of the Forest Vegetation Simulator (FVS) largely relies on the performance of the diameter increment model and the subsequent use of predicted dbh in forecasting tree attributes.

Previous research has shown the efficacy of localized inventory data in calibrating model parameters when better predictions of individual and stand growth in focal geographic areas are sought. A sample-based sensitivity analysis (SA) is proposed as a preliminary step to model calibration, in order to identify which variables are most influential in determining predicted outcomes. SIMLab software was used for SA of the default dbh increment submodel in FVS-SN; samples were obtained from a recent inventory of longleaf pine stands in Fort Bragg, NC. Preliminary results show that dbh is by far the most important variable, followed by site index and competition-related predictors. Topographical and other site variables were largely non-influential. Before calibration and re-engineering of the submodel, variables conveying redundant or non-influential information may be considered for elimination.

Introduction

Project Background

The Fort Bragg military installation is located 10 miles northwest of Fayetteville, North Carolina, in the Sandhills Region. Of the 161,597 total acres, an estimated 65,000 are covered by longleaf pine (*Pinus palustris* Mill.) dominated forests. Habitat recovery efforts for the endangered red-cockaded woodpecker (*Picoides borealis*) currently are a priority at Fort Bragg (Blythe and others 2001). Forest inventory and monitoring are needed to assess suitability of forest conditions to the species' habitat requirements (U.S. Fish and Wildlife Service 2003), as well as to provide indicators of overall ecosystem integrity and capability of lands to support military training operations.

A 10-year forest inventory program is currently implemented throughout the installation; in addition, forest stands are annually monitored to update changes resulting from natural growth and silviculture treatments. In order to plan for future growth of the forest and development of military facilities, 10-year growth projections at the stand level were formulated for the entire installation at the time of the first inventory. However, model-based simulations provided unrealistically high stocking levels, and preliminary testing of the Southern Variant (Donnelly and others 2001) of FVS (FVS-SN) showed a similar tendency.

The main reason for such discrepancy has been speculated as being related to an erroneous representation of the inherent maximum size-density boundary for key forest species (Shaw and Long 2007). This issue cannot be adequately solved by standard model re-fitting techniques; DeRose and others (this proceedings) proposed a modification to FVS program logic that would yield more accurate survival predictions, in accordance with the findings by Shaw and Long (2007). However, Fort Bragg spans over an area much smaller than the one referenced by developers of FVS-SN (see after). For this reason, we put into question the validity of all components of the SN model, under the hypothesis that discrepancies between local growing conditions and the more general relationships outlined by the variant might prompt growth prediction errors at the

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Graduate Student, Dipartimento Agroselviter, Università di Torino, Grugliasco, Italy; e-mail: giorgio.vacchiano@unito.it.

[2] Analyst, USDA Forest Service, Rocky Mountain Research Station, Forest Inventory and Analysis, Ogden, UT; e-mail: jdshaw@fs.fed.us.

[3] Graduate student, and Professor, respectively, Utah State University, Department of Wildland Resources, Logan, UT; e-mail rjderose@cc.usu.edu; fakpb@cc.usu.edu.

individual tree scale. A research effort is currently underway which aims to evaluate and refit FVS-SN using forest inventory data collected on Fort Bragg (Shaw and others 2006). This paper represents a first step using the base FVS-SN submodels in order to establish how Fort Bragg data look in relation to the submodels specified in SN over a much wider geographic range, and thus calibrated over a much different dataset.

The Southern Variant: Features and Challenges

FVS-SN was developed from Forest Inventory and Analysis (FIA) data, Forest Service research data, and data from the Bureau of Indian Affairs. Its geographic coverage spans most of the southeastern United States (Donnelly and others 2001). Growth relationships for such a wide area are refined with the help of species-specific coefficients for each submodel equation. All submodels portray average growing conditions and allometric relationship throughout the southern states. Additionally, diameter increment and standing volume computations also include location codes accounting for the region, National Forest, and Ranger District where the stand is situated, and Ecological Unit Codes (Keys and others 1995) at the province level as a mean of distinguishing between major geographic areas within the region.

Even if the model includes a self-calibration feature, allowing it to adjust diameter and height growth predictions based on field increment data (Dixon 2002) there are grounds to suspect that local variability is not adequately reflected. Developers of FVS-SN stated that "If further research and/or evidence shows that tree growth differences are distinguishable at finer scales, such results can be fit into the growth relationships" at subsequent time (Donnelly and others 2001). Therefore, ecological subdivisions at a scale smaller than Province level may in some cases be proven to have an effect on diameter change computations.

Since the first version of Prognosis (Stage 1973), diameter growth prediction has represented the key modeling function, upon which other submodels depend, at least in part, for their inputs. In FVS-SN the diameter growth submodel for large trees, i.e., those with a diameter at breast height (dbh) greater than 3 inches, uses a 14-coefficient equation with a mixture of categorical and continuous variables (table 1). The dependent variable is the logarithm of the predicted periodic change in squared inside-bark diameter (Wykoff and others 1982).

When this equation was fitted to the Fort Bragg data in its complete form, three potential problems emerged. First, the regression yielded relatively low R^2 values. Second, some coefficients were found to have unrealistic signs, for example, competition-related variables with a positive effect on growth. Both anomalies have been previously related to correlation problems and the degree of variability in a given data set (Neter and others 1990); nevertheless, FVS-SN developers stated that "detection of multicollinearity was a major effort in picking independent variables for the diameter increment submodel of FVS-SN" (D. Donnelly, personal communication), which rules out interconnected distributions of independent variables as a source of error. Third, since the ranges of some variables are relatively small on Fort Bragg as compared to the variability found within the geographic range encompassed by FVS-SN, we anticipated that some input factors might be redundant or even unnecessary components of the submodel at the local scale.

Sensitivity Analysis of Model Output

In order to assess and rank the role of each independent variable in predicting diameter increment of longleaf pine on Fort Bragg, we carried out a sensitivity analysis (SA) of model output on the diameter increment submodel of FVS-SN. Innis (1979) defined SA as "the systematic search for those model entities to which the model is most sensitive"; the terms "model entities" refers to the measurement accuracy of input factors, the value of the parameters used by the model (Herring 2007), as well as the model form itself. The effect of incremental inclusion of independent variables and the effect of changes in functional relationships may be assessed both at the submodel and at the model superstructure level. However, the most general use of SA is concerned with model simplification (Saltelli and others 2008). The objective is to identify the factor or the subset of input factors that can be fixed at any given value over their range of uncertainty without reducing significantly the output variance. Regardless of their contribution to model predictions, insensitive model components need neither to be measured with great

Table 1—Variables and description in the FVS diameter growth submodel (from Donnelly and others 2001). Input variables account for the growth potential of individual trees, the influence of the tree's neighbors and the site's ability to support growth.

	Variable	Description
ln(dds)[a] =	b_0	intercept
	$+ b_1 \cdot \ln \text{dbh}$	log of dbh (at beginning of estimation period)
	$+ b_2 \cdot \text{dbh}^2$	squared dbh
	$+ b_3 \cdot \ln \text{crwn}$	log of percent crown ratio
	$+ b_4 \cdot \text{hrel}$	relative height
	$+ b_5 \cdot \text{SI}$	site index for the species
	$+ b_6 \cdot \text{plttba}$	plot basal area
	$+ b_7 \cdot \text{pntbal}$	plot basal area in trees larger than subject tree
	$+ b_8 \cdot \tan \text{slp}$	tangent of slope in degrees
	$+ b_9 \cdot \text{f cos}$	tangent of slope, cosine of aspect
	$+ b_{10} \cdot \text{f sin}$	tangent of slope, sine of aspect
	$+ b_{11} \cdot \text{fortype}$	categorical variable for forest type group
	$+ b_{12} \cdot \text{ecounit}$	categorical variable for ecological unit group
	$+ b_{13} \cdot \text{plant}$	categorical variable for planted stands

[a] dds = (diameter inside bark at time_0 + periodic diameter growth)^2 – diameter inside bark^2 (Wykoff and others 1982).

precision nor to be scrutinized during refitting of the model. Since their behavior is closer to that of constants than of variables, they might be omitted for the sake of parsimony should the model be reworked under a different form. Conversely, it is useful to know about model components with high sensitivity, because these have the greatest impact on model predictions (Vanclay and Skovsgaard 1997) and might need to be measured or assessed with greater care.

Most SA approaches to date have relied on local SA, i.e., the evaluation of the effect exerted on model outputs by individually varying only one of the model inputs across its entire range of plausible values, while holding all other inputs constant (Cullen and Frey 1999). A major drawback of this method is that interactions between input variables cannot be computationally taken into account. Thus, the results of nominal range sensitivity analysis are potentially misleading, especially for multilinear and nonlinear models (Frey and Patil 2002).

Hamilton (1997) proposed what he called "sensitivity analysis" of the FVS suite as a whole. His method was based on *a priori* alteration of submodel output, by means of FVS keywords such as BAIMULT, HTGMULT and MORTMULT (Van Dyck 2001). The percent difference in selected stand descriptors at the end of the modeling time step, resulting from the introduction of fixed perturbations in each of the submodels, represented the author's chosen sensitivity metric. However, this approach was affected by limitations similar to one-factor-at-a-time analysis.

We propose the use of first-order sensitivity indices, which assess the variance of model output Y due to model input X_i (Saltelli and others 2004). Our specific aim is to assess which of the input factors are most influential on the large-tree diameter growth submodel.

Methods

Although several techniques have been proposed (Frey and Patil 2002), sampling-based approaches to uncertainty and sensitivity analysis are both effective and widely used. Analyses of this type involve generating, via Monte Carlo simulations, a set of model evaluations Y_i (i = 1… N), corresponding to N different sampled values X_i of the vector $X = f(X_1, X_{2,\dots} X_k)$ of *k* input factors, and subsequently mapping uncertain analysis inputs to uncertain analysis results. The steps involved in conducting such an effort are the following (Helton 2005):

- Definition of probability distributions to characterize uncertainty in analysis inputs;
- Generation of samples from uncertain analysis inputs;
- Propagation of sampled inputs through model simulation;

- Assessment of uncertainty analysis results; and
- Determination of sensitivity analysis results.

Since we were interested in model parsimony, rather than in assessing error propagation through the model, we chose to consider only stochastic uncertainty, i.e., that arising from the behavioral properties of the system under study. Therefore, we adopted the default FVS-SN dbh increment submodel as the function to evaluate, retaining its original parameterization and evaluating uncertainty of each input factor across its potential variability in the inventory.

Growth data from 7,302 individual longleaf pines were available from Fort Bragg forest inventory and were used to infer the shape, statistical properties (estimates of population mean and standard deviation) and range of each factor's probability density function (PDF) (table 2). PDFs of sample variables were positively tested for normality by means of one-variable Kolmogorov-Smirnov test ($p < 0.05$) and truncated to minima and maxima measured in the field to avoid sampling outliers. Variables such as slope and forest type coding were assigned a discrete PDF with classes and weights inferred from sample frequencies. Biologically relevant correlations between input factors (tree dbh and height, tree height and crown ratio, crown ratio and stand basal area, and between stand basal area and plot basal area) were computed by means of Pearson's coefficients and their value entered in a dependence tree structure (Meeuwissen and Cooke 1994) (table 3).

Next, we generated an iterated sample of elements from the distribution of the inputs previously specified. Latin hypercube, or n-dimension stratified sampling, was chosen because of its efficient stratification properties allowing for the extraction of a large amount of uncertainty and sensitivity information with a relatively small sample size (Helton and Davis 2003). Moreover, this technique performs better than simple random sampling when the output is dominated by a few input factors (Iman and others 1981).

SIMLab software (EU IPSC 2004) was used for all steps of SA; the software architecture is represented in figure 1. The randomized sample is generated in SIMLab using an iterative function based on a user-defined seed number. We instructed the software to generate 10,000 samples, a number close to the number of tree records used for the default parameterization of FVS-SN in longleaf pine (Donnelly and others 2001) but much higher than the suggested minimum (McKay and others 1979). The generated sample served as a starting point for Monte Carlo-based model runs; in the model execution

Table 2—Characterization of the input factors for sensitivity analysis of the diameter increment submodel.

Input	Definition	PDF shape	Range	Units	Notes
D	Diameter at breast height	Normal	2–30	inches	
CR	Live crown ratio	Normal	1–00	percent	
H	Tree height	Normal	10–101	feet	For relative height computation
H40	Height of 40 thickest trees ac^{-1}	Normal	40–103	feet	
SI	Site Index	Normal	44–132	feet	
BA	Basal area (stand)	Normal	5.5–158	$feet^2\ ac^{-1}$	
pointBA	Basal area (plot)	Normal	10–270	$feet^2\ ac^{-1}$	For point BA in larger trees computation
rank	percentile of tree's dbh in plot	Uniform	0–1	-	
slope	plot mean slope	Discrete	0–0.8	rad	
aspect	plot mean aspect	Uniform	0–2π	rad	
EUC	Ecological unit code	Constant	0	categ.	PVP232
forcode	Forest cover type	Discrete	0–1	categ.	From Donnelly and others (2001)l
plant	Plantation origin	Constant	0	binary	None in Fort Bragg

Table 3—Correlation between input factors as measured from Fort Bragg inventory data.

Variable 1	Variable 2	Pearson's R
dbh (inches)	Height (feet)	0.69
Height (feet)	Live crown ratio	–0.34
Live crown ratio	Stand basal area ($feet^2\ ac^{-1}$)	0.35
Stand basal area ($feet^2\ ac^{-1}$)	Plot basal area ($feet^2\ ac^{-1}$)	0.56

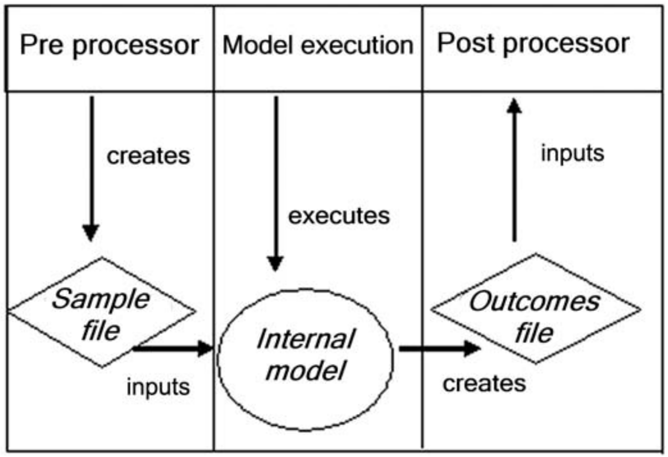


Figure 1—Internal model execution process in SIMLab (modified from EU IPSC 2004).

phase, each element of the sample is supplied to the model as input, and the corresponding model predictions are saved for lat uncertainty and sensitivity analyses, performed by the statistical post processor.

Uncertainty analysis aimed at comparing the PDF of generated diameter increment values with the ones measured in the field. Field measurements, inventory protocols and data treatment are described by Shaw and others (2006).

The outputs whose sensitivity was evaluated were both *dds*, the change in squared inside-bark diameter (in^2) during the estimation period, and d_g, the value of inside-bark diameter increment after a 5-year simulation cycle, as computed by the following:

$$d_g\,(inches) = \sqrt{dib^2 + dds} - dib \qquad [1]$$

where *dib* is tree dbh inside bark at the beginning of the modeling period (inches). A constant ratio of 1.15 has been adopted as the bark thickness coefficient for longleaf pine on Fort Bragg, independent of tree size or age (R.J. DeRose, unpublished data).

Sensitivity indicators were represented by standardized regression coefficients (SRC), that quantify the change in Y associated with a unit of change in a given parameter X_i, all other parameters remaining constant (Draper and Smith 1988; Helton 1993). The rank-based version of the index was used in order to account for nonlinearity in the model (Saltelli and others 2000). Finally, sensitivity tests based on data partitioning such as the Smirnov two-sample test (Conover 1980) helped assess the importance of each input factor. The test splits the sample space for factor X_i into two subsamples according to the quantiles of the output distribution Y. If the distributions of the two subsamples can be proven different (index values closer to 1) then the factor X_i is considerer influential. The influence of input factors on model output was computed separately for four different dbh size classes. Independent variables were entered in the model in base rather than composite form (for example, relative height has been split to tree height and height of the 40 largest trees per acre).

Results and Discussion

Mean modeled d_g was 0.54 ± 0.11 inches (modeling step: 5 years), a value statistically different (two-sample t-test, $p < 0.0001$) but close to the average 5-year dbh increment measured on longleaf pine increment cores in the 2000 inventory (0.60 ± 0.30 inches). Nevertheless, modeled output is characterized by a much lower uncertainty than measured data (fig. 2), the latter having a wider and more skewed distribution (range: 0.08 to 2.58 inches, skewness = +1.565). We hypothesized the lower variability of modeled growth was due to a higher homogeneity of tree measurements used for original FVS-SN calibration. However, this was inconsistent with the fact that the default model presents a much better goodness-of-fit to SIMLab-generated Fort Bragg data than to the original calibration dataset (R^2: 0.94 and 0.52 respectively).

A certain degree of model-induced simplification was not unexpected. The slight over-prediction at the lower end of the dbh increment range is not likely to be problematic,

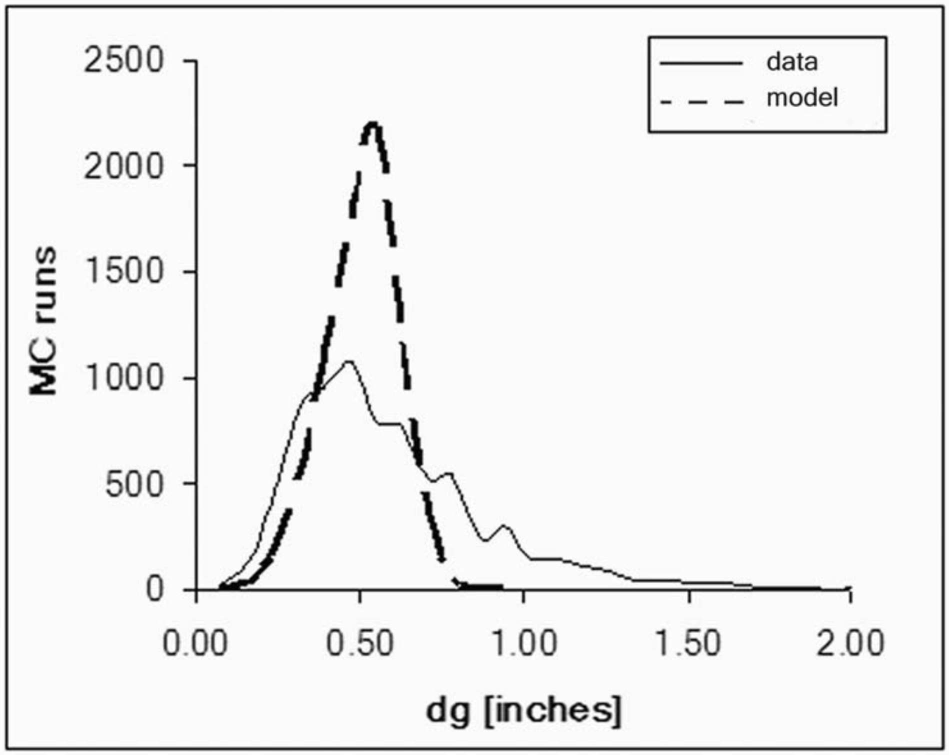


Figure 2—Probability density function of variable d_g (5-year diameter growth) resulting from uncertainty analysis (10,000 Monte Carlo simulations) as compared to that measured in the field.

and may be explained by the presence of a few old trees (ages ≥ 100 years), that likely represent leftovers from past management operations and might be characterized by much lower growth rates than would be predicted given their actual size (fig. 3).

To better understand what model component might be responsible for both the observed variance reduction and for underestimation of the higher end of growth range, we re-ran the Monte Carlo analysis on simulated data apportioned into dbh size classes (fig. 4). All classes showed significant differences from their real data counterparts (two-sample t test); while growth was usually overpredicted in medium-sized trees, it was underpredicted in both small and large trees, with the bias in the first category being the most severe (table 4).

The calibration and randomization routines embedded in FVS should partially resolve this issue (Dixon 2002; Stage 1973), but they were not applied here. Our main scope was to suggest SA as a means of preliminary model screening, underlining the inaccuracies of the FVS-SN base growth model when applied to a local dataset. Such framework should be applicable to all cases, and not only for those submodels that may benefit from the thorough calibration routines referenced by Dixon (2002). Moreover, FVS developers themselves later acknowledged as "unreasonable to assume that growth responses in locations with substantially different environmental limitations will be the same. It is more likely the shape of the response surface in these locations, relative to the selected set of predictor variables, will be different. When this is the case, the models should be refit" (Dixon 2002).

Underestimation of diameter growth might affect the final simulation result, both at the individual and at the stand level. For example, density-dependent mortality is triggered by a threshold relative density value (DeRose and others, this proceedings), and in turn mortality intensity depends on simulated relative density of the stand. Underestimation of individual dbh and thus quadratic mean diameter of the stand possibly will result in overpredictions of mean size and density combinations and therefore underpredict competition-induced mortality.

Diameter growth underprediction may be driven by a number of factors, including both assuming excessively severe competition, and a disproportionate influence

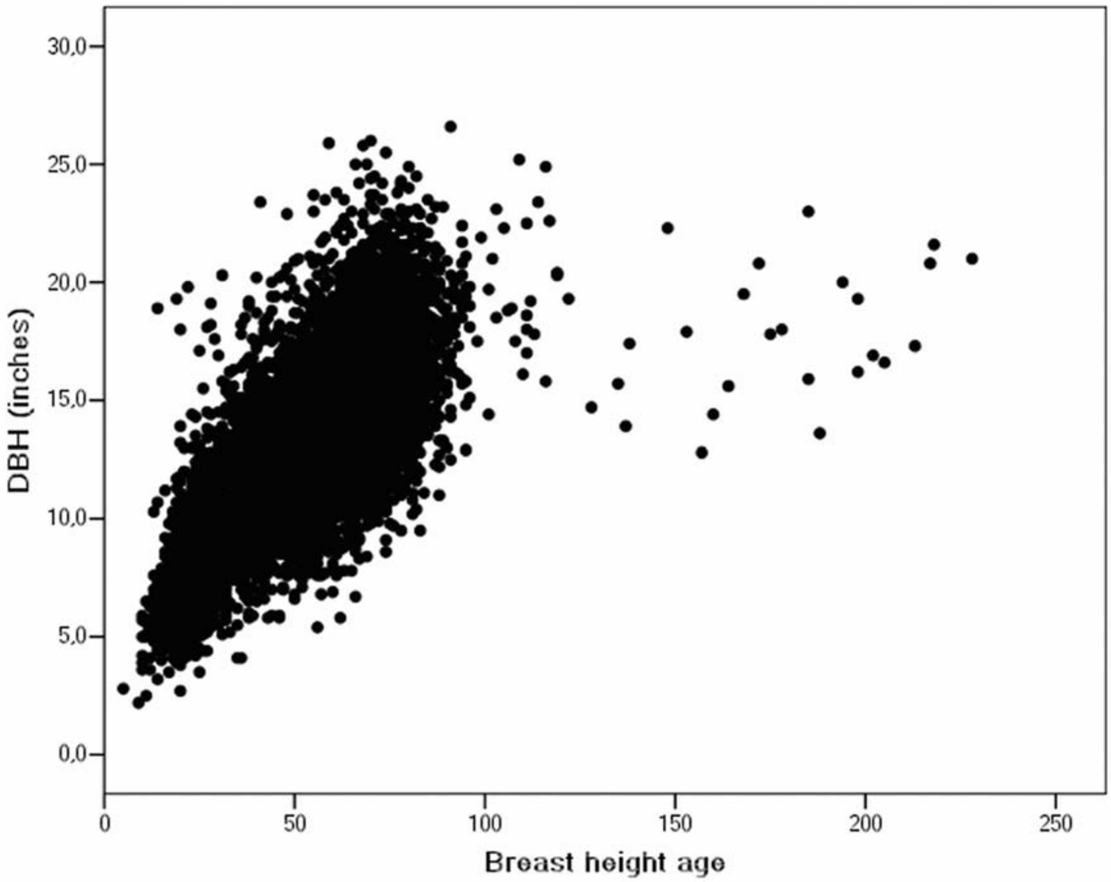


Figure 3—Breast height diameter to breast height age relationship in the sample.

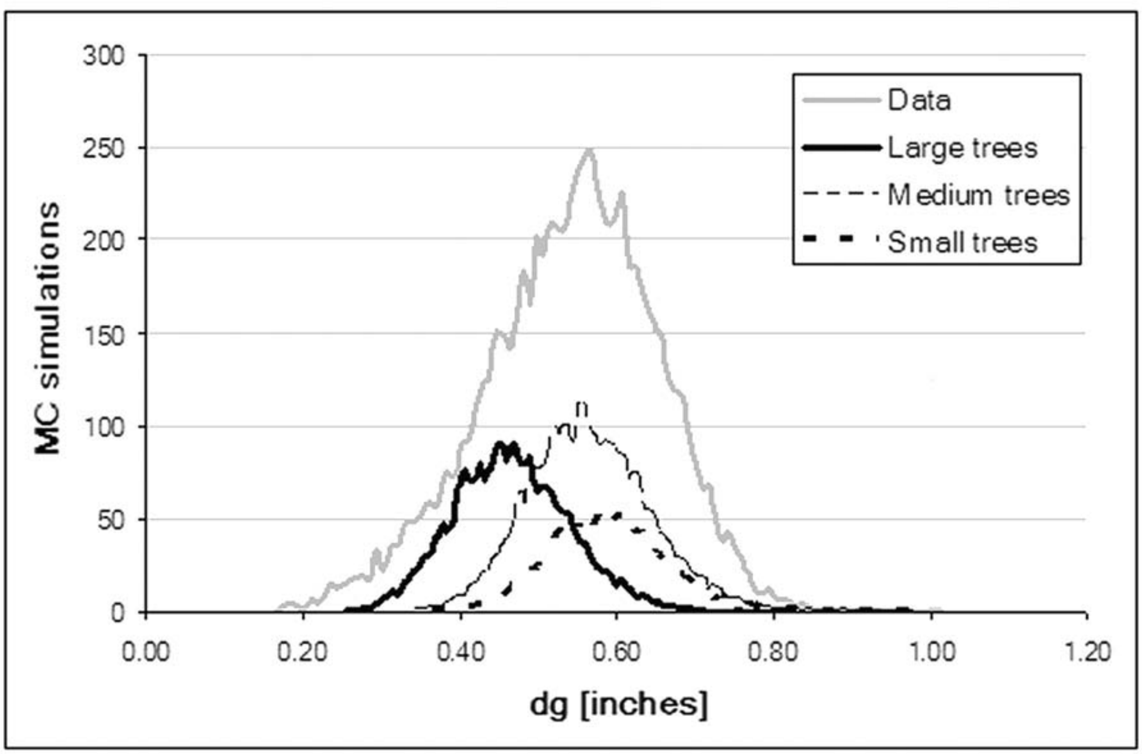


Figure 4—Uncertainty analysis of simulated 5-year diameter increment apportioned into the three dbh size classes (see text for description of size classes), as compared to that measured in the field.

Table 4—Mean and range of 5-year diameter growth (inches) for sample-based simulations (10,000 Monte Carlo runs per size class) as compared to field data. Very small trees: dbh 3 to 5 inches; small: 5 to 10 inches; medium: 10 to 15 inches; large: higher than 15 inches.

Size classes	Simulated data			Fort Bragg inventory	
	Mean	Range	R^2	Mean	Range
	inches	*inches*		*inches*	*inches*
Very small	0.82	0.39–2.58	0.85	0.66	0.16–1.89
Small	0.59	0.36–0.99	0.95	0.75	0.08–2.28
Medium	0.57	0.34–0.98	0.96	0.55	0.08–2.36
Large	0.47	0.25–0.82	0.96	0.50	0.08–1.57

of age-related decline as expressed by the dbh-squared factor. Since the most severe bias affects high increment values of small and medium trees, we hypothesize that the cumulate effect of many competition-related variables in the model could excessively hamper modeled growth.

Sensitivity indices ranking the importance and effect of each input factor are shown by standardized rank regression coefficients (SRRCs; fig. 5) and the Smirnov test index (fig. 6). The signs of all SRRCs (fig. 5) were consistent with expectations for growth behavior. If we exclude the role of forest type coding, which is capable of a large influence on growth prediction in a limited number of cases (when different from longleaf pine type; fig. 6), the most important variable is tree diameter. This is consistent with evidence from the growth modeling literature (see for example Trasobares and Pukkala 2004. Similarly, the FVS-SN variant manual states: "DBH at the beginning of each projection cycle is usually the strongest single statistical determinant of diameter growth during the cycle" (Donnelly and others 2001). However, the role of starting dbh, always preeminent in predicting basal area increment (data not shown), is differentiated when growth output is back-transformed to inside-bark inches of increment.

Large trees showed a very strong negative influence of dbh on increment prediction, an apparent result of the senescence-related dbh-squared term (fig. 5). This is not unexpected, since large trees would mostly be unaffected by competition from neighbors,

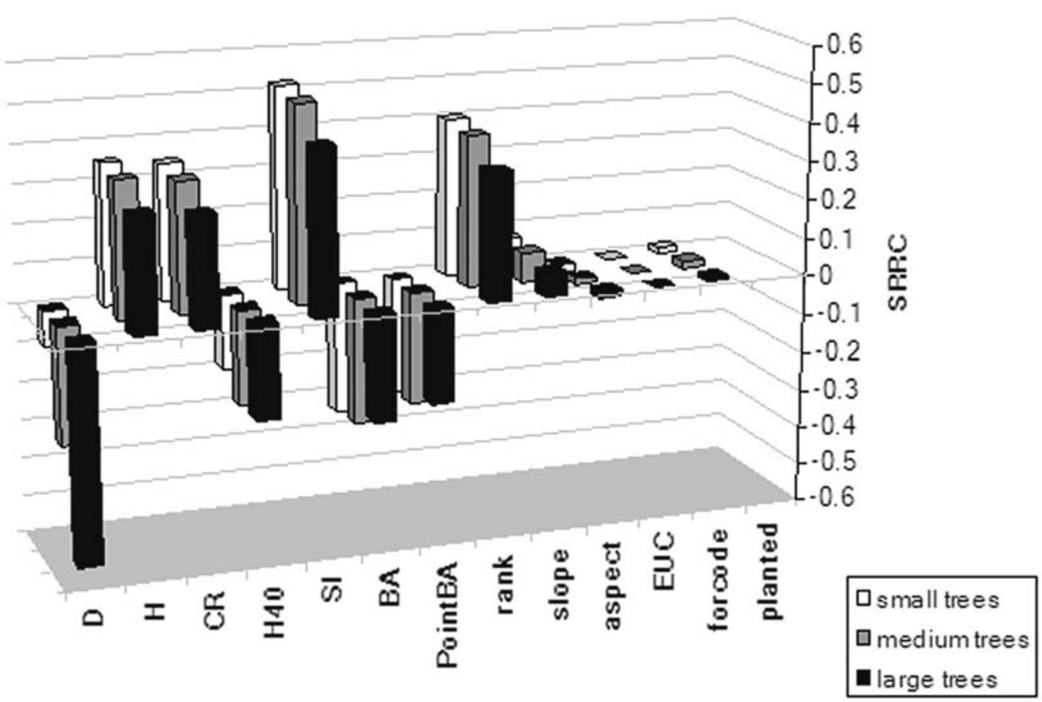


Figure 5—Sensitivity analysis. Standardized rank regression coefficient (SRRC) for input factors of the FVS-SN large tree dbh increment submodel, computed for each dbh size class.

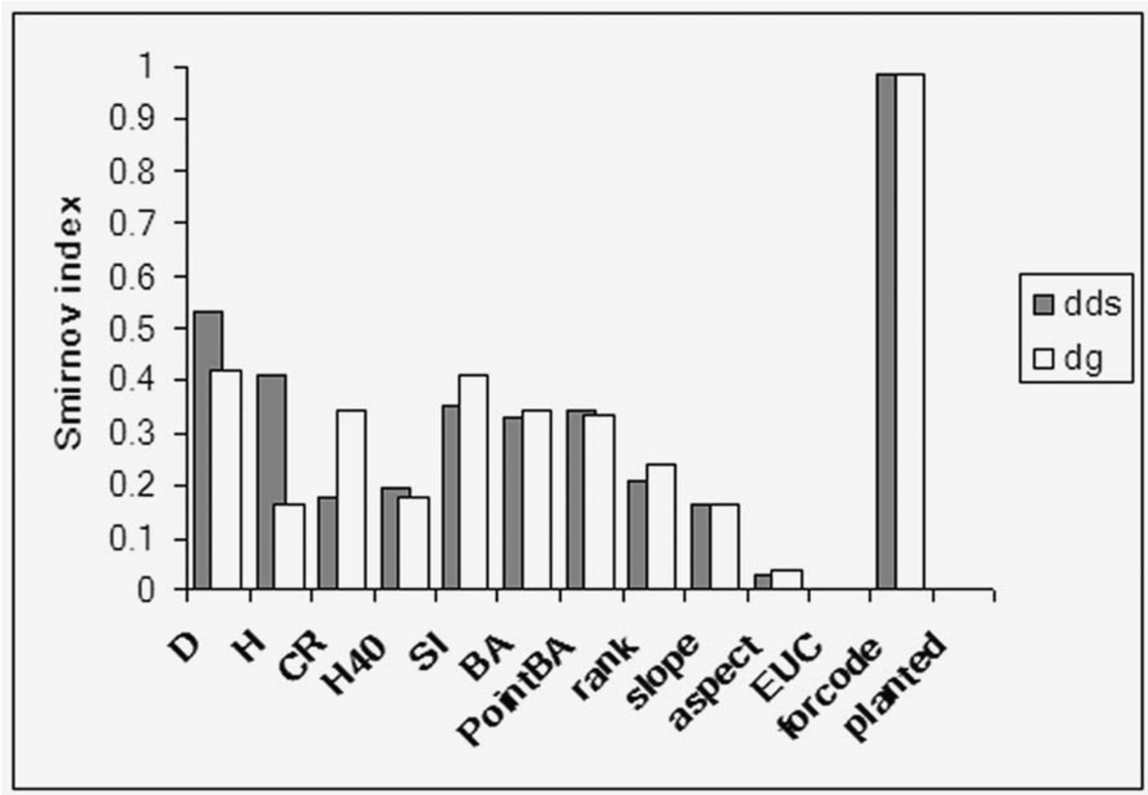


Figure 6—Sensitivity analysis. Smirnov test index for input factors of the FVS-SN large tree dbh increment submodel

and even a more fertile site could not adequately compensate growth decline caused by senescence. Growth of medium and small trees is driven to a greater extent by factors expressing tree and site potential and by competition-related variables. Among factors related to growth potential, site index always took the leading role, with tree height and live crown ratio somewhat less influential (and inherently correlated to tree diameter). If we assumed that the simultaneous action of several competition-related factors in the model is the main reason for growth underpredictions, the ranking operated by SA might be useful to leave out the least important drivers. For example, if just one individual and one stand-scale variable were to be retained, the choice would respectively fall upon individual dbh ranking and stand basal area, which are capable of determining the largest influence on model output among the competitive-related group of predictors.

Topographically related predictor variables such as slope unexpectedly showed a small but significant proportionality to growth, an effect that may be related to site morphology and inherent characteristics of longleaf pine sites. Fort Bragg has rolling terrain and the effects of slope and aspect on forest growth are not readily apparent. Slope position—for example, moist bottomlands vs. dry ridges—is far more likely to influence stand growth than steepness or aspect. Because both high and low moisture extremes are found on sites with relatively low slope values, any effect of slope on growth is likely to be confounded during equation fitting and evaluation.

Conclusions

We propose sensitivity analysis as a preliminary tool to model calibration, and suggest the use of sample-based global sensitivity analysis as a means of ranking the importance of input factors in determining the magnitude of modeled tree growth. Sensitivity analysis can be used to explore model behavior in specific portions of the input space to evaluate biologically sound growth dynamics of different stand components (e.g., partitioning data into size or density classes), and to compare the behavior of alternate model formulations. The analysis could have been done with any submodel of any variant; the flexibility of

SIMLab software represents a strong support to sensitivity analysis of individual FVS submodels and potentially the entire simulation chain.

Once the factors have been ranked in order of importance and the prediction biases have been detected, model developers may simplify model forms in the interest of parsimony or formulate sampling recommendations in order to focus measurement efforts on the most crucial variables. An importance-based ranking of input variables may prove useful in designing complex equations, such as in stepwise approaches to model calibration. After setting up calibrated model runs, a similar analysis to that described in this paper would be useful to show how well the calibrated model performs. Should major model validity problems still exist after a comprehensive calibration, local users would need to look into a refit of the model for local conditions.

References

Blythe, J.R.; Dickinson, R.S.; Trousil, G.J.; Webb, P.J. 2001. Integrated natural resources management plan 2001–2005, Fort Bragg and Camp Mackall. Fort Bragg: Environment and Natural Resources Division. 473 p.

Conover, W.J. 1980. Practical nonparametric statistics. New York: Wiley. 512 p.

Cullen, A.C.; Frey, H.C. 1999. Probabilistic techniques in exposure assessment: A handbook for dealing with variability and uncertainty in models and inputs. New York: Plenum Press. 352 p.

Dixon, G.E. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Report. Fort Collins CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 193 p.

Donnelly, D.; Lilly, B.; Smith, E. 2001. The Southern Variant of the Forest Vegetation Simulator. [online]. Available: http://www.fs.fed.us/fmsc/ftp/fvs/docs/overviews/snvar.pdf [March 16, 2007].

Draper, N.R.; Smith, H. 1998. Applied regression analysis. New York: Wiley. 736 p.

EU IPSC. 2004. Version 2.2. Simulation environment for uncertainty and sensitivity analysis, developed by the Joint Research Centre of the European Commission [online]. Available: http://simlab.jrc.it [March 16, 2007].

Frey, H.C.; Patil, S.R. 2002. Identification and review of sensitivity analysis methods. Risk Analysis. 22(3): 553–578.

Hamilton, D.A. 1997. Guidelines for sensitivity analysis of FVS. In: Teck, R.; Moeur, M.; Adams, J., eds. Proceedings: Forest Vegetation Simulator conference; 1997 February 3–7; Fort Collins, CO. Gen. Tech. Rep. INT-GTR-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 33–38.

Helton, J.C. 1993. Uncertainty and sensitivity analysis techniques for use in performance assessment for radioactive waste disposal. Reliability Engineering and System Safety. 42(2–3): 327–367.

Helton, J.C. 2005. Sampling-based methods for uncertainty and sensitivity analysis. In: Hanson, K.M.; Hemez, F.M., eds. Sensitivity analysis of model output. Los Alamos: Los Alamos National Laboratory: 221–29. [online]. Available: http://library.lanl.gov [August 20, 2006].

Helton, J.C.; Davis, F.J. 2003. Latin hypercube sampling and the propagation of uncertainty in analyses of complex systems. Reliability Engineering and System Safety. 81(1):23–69.

Herring, N.D. 2007. Sensitivity analysis of the Forest Vegetation Simulator Southern Variant (FVS-SN) for southern Appalachian hardwoods. Blacksburg, VA: Virginia Polytechnic Institute, Department of Forestry. 112 p. Dissertation.

Iman, R.L.; Helton, J.C.; Campbell, J.C. 1981. An approach to sensitivity analysis of computer models: Part I—Introduction, input variable selection and preliminary variable assessment. Journal of Quality Technology. 13(3):174–183.

Innis, G. S. 1979. A spiral approach to ecosystem simulation. In: Innis, G.S.; O'Neill, R.V., eds. Systems analysis of ecosystems. Fairland, MA: International Co-operative Publishing House: 211–386.

Keys, J.E.; Carpenter, C.A.; Hooks, S.L.; Koenig, F.G.; McNab, W.H.; Russell, W.E.; Smith, M.L. 1995. Ecological units of the Eastern United States: A first approximation. Tech. Publ. R8-TP 21. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region.

McKay, M.D.; Beckman, R.J.; Conover, W.J. 1979. A comparison of three methods for selecting values on input variables in the analysis of output from a computer code. Technometrics. 21:239–245.

Meeuwissen, A.M.H.; Cooke, R.M. 1994. Tree dependent random variables. Tech. Rep. 94-28. Delft, The Netherlands: Delft University of Technology, Department of Mathematics.

Neter, J.; Wasserman, W.; Kutner, M.H. 1990. Applied linear statistical models: Regression, analysis of variance, and experimental designs. Homewood, IL: Richard D. Irwin, Inc. 1181 p.

Saltelli, A.; Ratto, M.; Andres, T.; Campolongo, F.; Cariboni, J.; Gatelli, D.; Saisana, M.; Tarantola, S. 2008. Global sensitivity analysis—The primer. Chichester: Wiley. 292 p.

Saltelli, A.; Tarantola, S.; Campolongo, F. 2000. Sensitivity analysis as an ingredient of modeling. Statistical Science. 15(4):377–395.

Shaw, J.D.; Long, J.N. 2007. A density management diagram for longleaf pine stands with application to red-cockaded woodpecker habitat. Southern Journal of Applied Forestry. 31(1):28–38.

Shaw, J.D.; Vacchiano, G.; DeRose, R.J.; Brough, A.; Kusbach, A., Long, J.N. 2006. Local calibration of the Forest Vegetation Simulator (FVS) using custom inventory data. In: Society of American Foresters 2006 National Convention [electronic resource]: Pittsburgh, PA; 2006 October 25–29.

Bethesda, MD: Society of American Foresters. [CD-ROM]. [Online] Available: http://www.treesearch.fs.fed.us/pubs/24973 [April 21, 2008].

Stage, A.R. 1973. Prognosis model for stand development. Res.Pap. INT-137. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Trasobares, A.; Pukkala, T. 2004. Using past growth to improve individual-tree diameter growth models for uneven-aged mixtures of *Pinus sylvestris* L. and *Pinus nigra* Arn. in Catalonia, north-east Spain. Annals of Forest Science. 61:409–417.

U.S. Fish and Wildlife Service. 2003. Recovery plan for the red-cockaded woodpecker (*Picoides borealis*): Second revision. Atlanta, GA: U.S. Fish and Wildlife Service. 296 p.

Van Dyck, M.G. 2001. Keyword reference guide for the Forest Vegetation Simulator. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 128 p.

Vanclay, J.K.; Skovsgaard, J.P. 1997. Evaluating forest growth models. Ecological Modeling. 98:1–12.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Improving Longleaf Pine Mortality Predictions in the Southern Variant of the Forest Vegetation Simulator

R. Justin DeRose[1]
John D. Shaw[2]
Giorgio Vacchiano[3]
James N. Long[1]

Abstract—The Southern Variant of the Forest Vegetation Simulator (FVS-SN) is made up of individual submodels that predict tree growth, recruitment and mortality. Forest managers on Ft. Bragg, North Carolina, discovered biologically unrealistic longleaf pine (*Pinus palustris*) size-density predictions at large diameters when using FVS-SN to project red-cockaded woodpecker (Picoides borealis) habitat. Inventory data from Ft. Bragg indicated the mortality submodel was responsible for the over-predictions. Three approaches to remedy longleaf pine mortality predictions in FVS-SN were explored: (1) using stand density modifier keywords, (2) using a tree size cap to influence mortality rates but not growth, and (3) iteratively invoking a mortality rate based on empirical data. Results showed the third approach was the only viable alternative. Details of this approach are described so that an FVS-SN user can effectively constrain predicted longleaf pine size-density combinations at realistic levels. Although the approach was successful, it required advanced knowledge of size-density relationships for longleaf pine. It also demands an advanced understanding of FVS-SN from the user. We suggest over-prediction of size-density relations at large diameters will be evident in any growth and yield model using similar mortality logic. Therefore our results provide a general framework for improving the accuracy of mortality predictions in FVS.

Introduction

Forest growth and yield models such as the Southern Variant of the Forest Vegetation Simulator (FVS-SN) (Donnelly and others 2001) typically consist of component submodels that describe tree growth, recruitment (sprouting), establishment (seeding), and mortality. The extent to which submodel predictions realistically portray natural and managed stand dynamics should be routinely evaluated. Recently, as part of a larger study, FVS-SN was found to over-predict growth and yield in mature longleaf pine (*Pinus palustris* Mill.) stands on the Ft. Bragg military installation in North Carolina (Shaw and others 2006). Realistic predictions of stand dynamics for longleaf pine forests are a necessary component of habitat recovery efforts currently underway for the endangered red-cockaded woodpecker (*Picoides borealis*) (Blythe and others 2001). FVS-SN simulations of pure longleaf pine stands by forest managers revealed unrealistic size—density combinations for large (greater than 10 inches) diameter stands on Ft. Bragg (Pat Wefel, personal communication). Over-prediction of size-density relationships is likely due to erroneous mortality rates, which implicates the mortality submodel. In this study, we used a density management diagram (DMD) for longleaf pine (Shaw and Long 2007) to explore the deficiencies of the FVS-SN mortality model and developed possible approaches for its correction.

Currently, two types of mortality occur in FVS-SN: (1) background and (2) density-related. **Background mortality** is estimated when stands are below 55 percent of forest type-dictated maximum stand density index (SDIMax). For this mortality type it is assumed there is no density-dependent mortality and an annual compound interest formula is used to calculate mortality. Furthermore, disturbance agents such as insects, fire, and pathogens are assumed to be exclusive of background mortality (Dixon 2002). **Density-related mortality** is estimated when stands are above 55 percent SDIMax and below 85 percent SDIMax, (SDIMax mortality), presumably as a result of competition and self-thinning. Ninety percent of SDIMax is considered an upper limit to stand density and if the current inventory SDI exceeds 90 percent, then SDI is reset so that current SDI is 85 percent of the maximum. If SDI is between 85 percent and 90 percent, it is reduced to 85 percent SDIMax. Stand dynamics throughout the simulation are determined by the relationship between current inventory SDI and SDIMax (Dixon 2002). Background mortality stops once SDIMax mortality begins.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Graduate student, and Professor, respectively, Department of Wildland Resources and Ecology Center, Utah State University, Logan, UT; e-mail: rjderose@cc.usu.edu; fakpb@cc.usu.edu.

[2] Analyst, USDA Forest Service, Rocky Mountain Research Station, Forest Inventory and Analysis, Ogden, UT; e-mail: jdshaw@fs.fed.

[3] Graduate student, Dipartimento Agroselviter, Università di Torino, Grugliasco Italy; e-mail: gvacchiano@inwind.it.

The DMD, developed using range-wide empirical data from both managed and unmanaged longleaf pine stands, is a conceptual model useful for evaluating stand dynamics (Shaw and Long 2007). The 'mature stand boundary' (MSB) displayed on the DMD represents an empirical ceiling to possible size - density combinations for natural and managed stands of longleaf pine (Shaw and Long 2007). FVS-SN mortality logic tends to maintain stands within 55 percent and 85 percent of SDIMax after they reach the 55 percent threshold (Dixon 2002). In contrast, the MSB indicates size-density combinations cannot be maintained within this range of densities. The non-linear MSB (in log-log space) suggests mortality actually proceeds at a constant rate relative to SDIMax mortality, indicating less efficient use of growing space by larger diameter (Dq) stands. The biological mechanisms for less efficient occupancy of growing space by larger trees are not well known but, a number have been postulated. First, it is possible that as trees increase in size mortality proceeds but with an increasing chance of density-independent mortality (in other words, lightning or pathogens). Second, Zeide (1985) suggested 'self-tolerance,' or the intra-specific ability to coexist, might decrease with increasing density where 'self-tolerance' is not necessarily related to shade tolerance. Similarly, Assmann (1970) observed 'crown disengagement' in even-aged forest stands which has been attributed to increased height growth resulting in physical crown interaction, removing leaf area and subsequently reducing growth (Long and Smith 1992). The over-prediction of size-density relationships could result in unrealistic management scenarios and, regardless of the mechanisms, more realistic estimates of longleaf pine mortality are needed.

To assess FVS-SN mortality predictions, we used stand data to examine the effect the mortality submodel has on predicting size-density combinations. We then explored three potential approaches to modifying and improving mortality rates: (1) using stand density modifier keywords, (2) using a tree size cap which affects mortality but not growth, and (3) iteratively invoking a mortality rate based on empirical data (in other words the MSB). We evaluated our results graphically against the MSB on the DMD (Shaw and Long 2007) because it represents the most detailed quantification of the 'ceiling' to size-density combinations for longleaf pine. Conceptually, we aimed to maintain stand dynamics below the empirical MSB threshold.

Methods

Data for this study came from the Ft. Bragg military installation in North Carolina. An intensive forest inventory was designed to collect information necessary for FVS-SN submodel testing and calibration. Details of the study design, data collection, and model calibration have been described (Shaw and others 2006). For the purposes of this study relatively pure longleaf pine stands (greater than 70 percent total basal area, table 1) were chosen from the Ft. Bragg forest inventory database (table 1) and run using the current southern variant file (revision date: 7-31-07, downloaded from http://www.fs.fed.us/fmsc/fvs/software/varfiles.php) in Suppose 2.0, the graphical user interface

Table 1—Stand number, number of plots per stand, percentage basal area in longleaf pine, trees per acre (TPA), mean stand diameter (QMD), stand density index (SDI), and site index (SI) for the sample stands.

Stand number	Number of plots	Percent longleaf pine	TPA	QMD(in)	SDI	SI (ft)
1032	15	86	89	10.2	92	62
2157	15	100	215	7.2	127	69
3089	10	70	226	8.1	161	67
4012	20	78	75	11.0	87	65
5046	5	96	340	7.0	194	91
5088	9	95	138	10.3	145	70
6014	15	82	178	6.0	78	65
7064	10	85	269	6.7	140	87
8045	10	99	173	8.8	141	66
8090	10	75	142	8.4	108	55
9051	10	89	195	8.5	149	59
10001	15	71	454	5.6	178	65

of FVS. The default cycle length of five years was used. Three approaches to simulate empirically observed size-density patterns were explored:

1. Stand density modifier keywords (SDIMax / BAMax) were used to emulate the MSB. The default SDIMax (390) in FVS-SN was reset to 350 as an example and simulations from each stand were graphically examined on the DMD.

2. The TreeSzCp keyword was used to adjust mortality to 10 percent for longleaf pine above 10 inches DBH and this size cap was set to effect mortality predictions only (Van Dyck 2005). An SDIMax of 390 (FVS-SN default) was used for this analysis.

3. We used the FixMort keyword in the Event Monitor to invoke approximately 2 percent annual mortality (Palik and Pederson 1996) when the stand approached the MSB (MSB-modified mortality). The Event Monitor program logic was:

```
1. IF
2. BADBH GT (18.68-20.63*Exp(-13.25*(BTPA)**(-0.503)))+2
3. THEN
4. FixMort  0  Parms(All, 1-(1-0.021751)**(CENDYEAR-YEAR), 0., 999., 0, 0)
5. ENDIF
```

This effectively iterated a mortality rate of approximately 10 percent (line 4) per cycle when the beginning cycle Dq was greater than the fitted MSB equation (line 2). We then re-ran FVS-SN with relatively pure longleaf pine stands (table 1) and compared the original with the modified output.

Size-density trajectories were inspected on the longleaf pine DMD to compare the differences in projected size-density relationships for each approach and assess how well they corresponded to the MSB. For illustration only three of the 12 sample stands were randomly chosen (3089, 4012, and 10001) to display in the figures.

Results

Unrealistic combinations of size and density were predicted in simulations of longleaf pine (fig. 1) using the default FVS-SN, which suggested inadequate mortality predictions. The southern variant projected size-density combinations above the MSB approximately 80 to 100 years into each simulation. The predicted linear nature (in log-log space) of the trajectory for each stand, presumably a result of SDIMax mortality logic, approached and surpassed the MSB. This resulted in over-predictions of stand growth and yield.

The SDIMax (or BAMax = SDI x 0.5454154) keyword approach, which lowered the maximum stand density, changed simulation output based on our arbitrarily chosen SDIMax of 350. However, over-predictions were still apparent, albeit at lower relative densities (fig. 2). If a larger SDIMax had been chosen it is likely larger over-predictions would have occurred. Regardless of the chosen SDIMax, FVS-SN size-density combinations will eventually cross the MSB due to their linear (in log-log space) nature. The SDIMax for longleaf pine across its geographic range has been quantified; therefore, there is little ecological rationale for modification of SDIMax in FVS-SN.

The TreeSzCp keyword approach appeared to increase mortality rates compared to the default model (fig. 3). Although we set the keyword to affect mortality only and not diameter growth, as there is no evidence to support diameter increment reduction of large DBH longleaf pine on Ft. Bragg (mean ± std. dev. for five-yr diameter growth of trees greater than 20 inches = 0.553 inches ± 0.195, n = 272), the mortality rate was not sufficient to maintain size-density combinations below the MSB.

The FixMort keyword modification resulted in size-density combinations consistent with the MSB. The greater mortality rate (approximately 10 percent per cycle) thus appeared to most closely mimic the MSB. Although mortality was greater in the MSB-modified trajectory than in the baseline simulation, mean stand diameters were similar during both simulations (figure 4).

Discussion

Density-independent mortality, or annual background mortality, is likely underestimated in FVS-SN. Palik and Pederson (1996) reported 1.9 percent annual background mortality for longleaf pine in mature, second-growth stands of longleaf pine. We calculated a range of background mortality of 0.19–0.2 percent, for 4 and 20 inch dbh

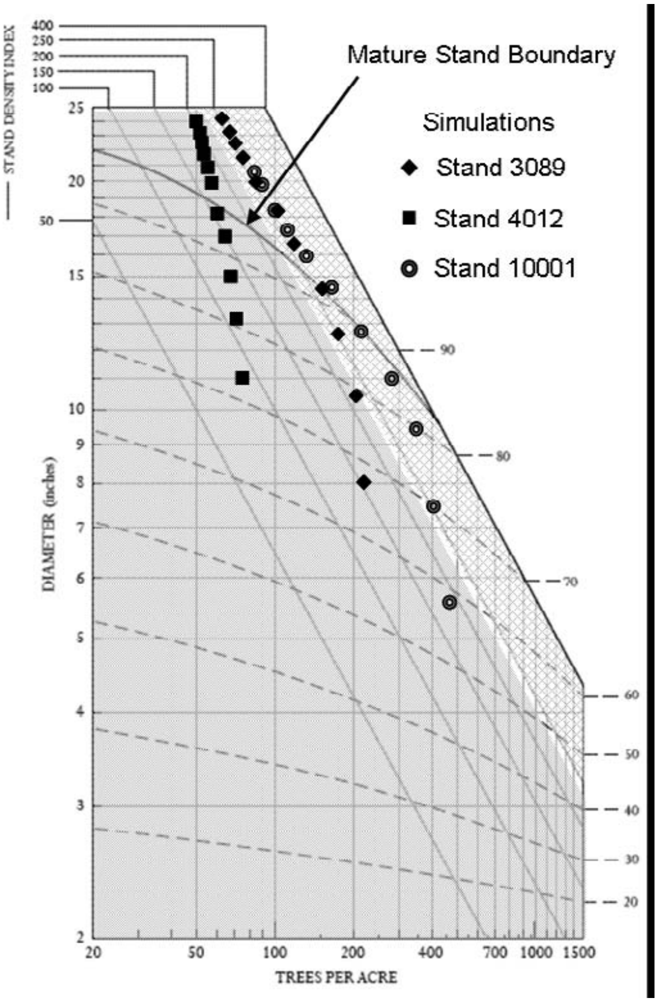


Figure 1—Trajectories of three of the sample stands (table 1), projected with the default southern variant and plotted on the density management diagram, showing size—density combinations well above the mature stand boundary. Symbols are plotted every 20 years for clarity. Grey area shows where background mortality occurs, hatched area indicates density-dependent mortality.

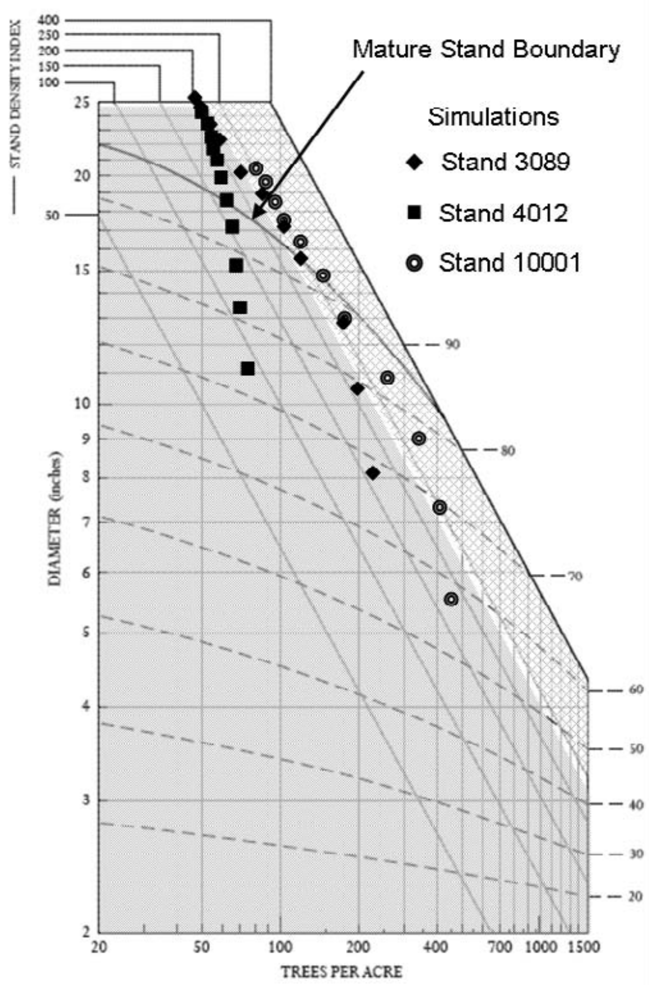


Figure 2—Trajectories of three of the sample stands (table 1) plotted on the density management diagram showing the effect of adjusting the SDIMax keyword from 390 to 350 on mortality predictions. Symbols are plotted every 20 years for clarity. Grey area shows where background mortality occurs, hatched area indicates density-dependent mortality.

trees respectively using the default values in FVS-SN (Dixon 2002; Donnelly 2001). The assumption that density-dependent mortality begins at 55 percent of SDIMax is consistent with the literature (Drew and Flewelling 1979; Long 1985) and likely accurately describes the 'zone of imminent competition mortality'. It is probably unrealistic however, that background mortality no longer operates after density-dependent mortality (SDIMax) is invoked as is currently done in FVS-SN. Background mortality emulates natural mortality agents that are operating concurrently as stands increase in relative density (for example lightning). Therefore both density-independent and dependent factors should be simultaneously considered when SDIMax exceeds 55 percent. The SDIMax ceiling of 85 percent (Dixon 2002) appeared effective for predicting self-thinning (for example stand 10001) (fig. 1). However, maintenance of a stand greater than 55 percent but less than 85 percent SDI, when Dq is large, appears to be the major problem with FVS-SN mortality logic (fig. 1). Therefore, an SDI-based approach to mortality seems adequate as long as consideration for an increasing rate of mortality is given at larger diameters.

The TreeSzCp keyword approach failed to maintain realistic size-density combinations (fig. 3). We increased mortality for longleaf pine 10 inches dbh and greater but this was not sufficient to limit size-density combinations below the MSB. There is no evidence to suggest that large diameter longleaf pine would die faster than a background mortality rate of approximately 1.9 percent (Palik and Perderson 1996). In fact, our five-yr diameter

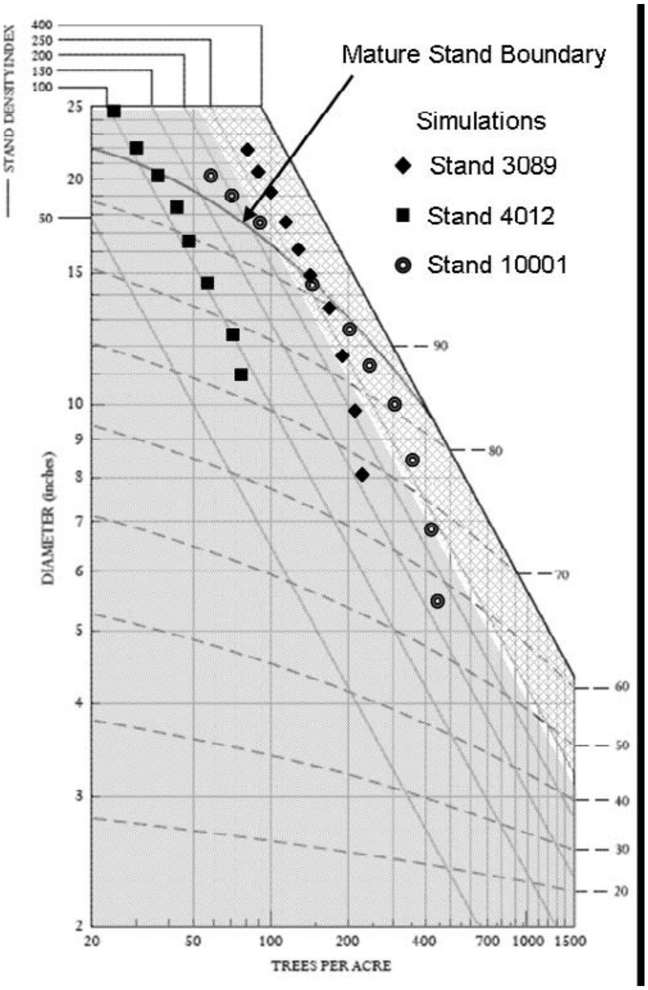


Figure 3—Trajectories of three of the sample stands (table 1) plotted on the density management diagram showing the effect of using the TreeSzCp keyword on mortality predictions. Symbols are plotted every 20 years for clarity. Grey area shows where background mortality occurs, hatched area indicates density-dependent mortality.

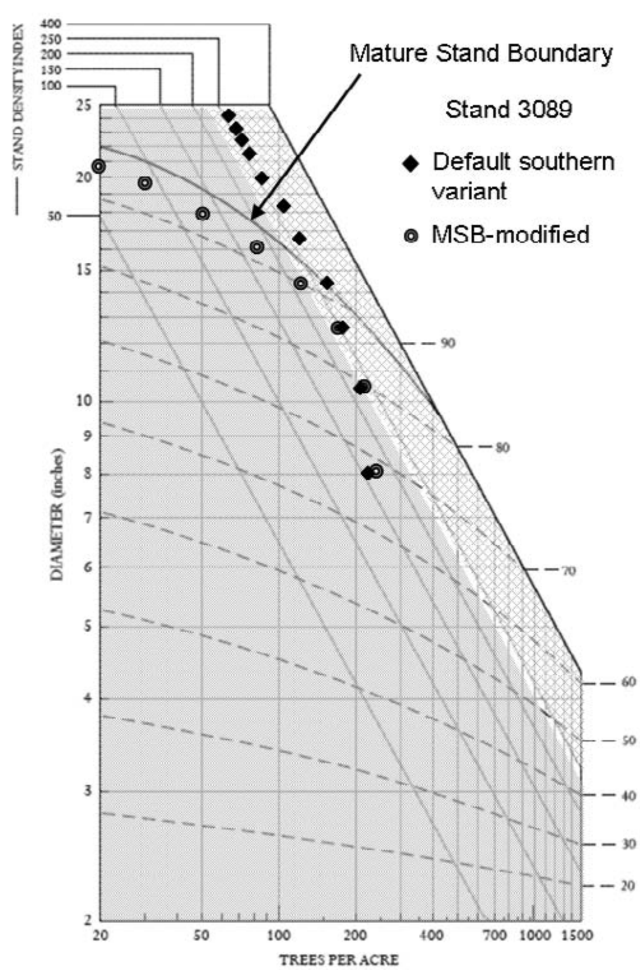


Figure 4—Longleaf pine stand 3089 projected for 200 years using the default southern variant and the FixMort mortality logic showing a divergence in mortality rates. Symbols are plotted every 20 years for clarity. Grey area shows where background mortality occurs, hatched area indicates density-dependent mortality.

growth measurements suggested larger trees (greater than 20 inches dbh) are vigorous and adding substantial increment. The TreeSzCp approach also resulted in size-density combinations for some stands that fell near 25 percent of SDI (fig. 3) where vacant growing space might promote undesirable understory species, specifically turkey oak (*Quercus laevis* Walt.) on Ft. Bragg, in the absence of fire. Understory fire was a ubiquitous force in natural longleaf pine forests (Van Lear and others 2005) and is maintained through prescribed burning on Ft. Bragg. Modeling stands with size—density combinations below the 25 percent threshold, a conventional threshold for predicting the availability of growing space for understory trees (Long 1985), might realistically incorporate regenerating understory species. However, in this study it was not necessary to include regeneration in model simulations because we were focused on mortality of the mature overstory. Palik and Pederson (1996) suggested mortality rates in longleaf pine proceed so slowly that openings for longleaf pine regeneration develop very slowly without hurricanes, which corroborates our decision to ignore regeneration in this study.

By invoking a higher mortality rate (approximately 10 percent per cycle) in large diameter longleaf pine stands, realistic size-density combinations were achieved. As indicated in the FixMort keyword coding logic, maintaining size-density combinations below the MSB requires redefining the mortality rate such that density is reduced at a much greater rate as trees increase in Dq. Our MSB-predicted mortality rate was approximately double that of default FVS-SN. It is realistic to expect the predicted size-density combinations to fall below the MSB, which describes the ceiling and not average, size-density relationships. Further sophistication of projected size-density relationships is possible by fine-tuning our Event Monitor logic by increasing or decreasing the intercept (+2 in our example); however, this is not recommended unless based on detailed stand-level information. Such an adjustment would change projected size-density combinations relative to the MSB.

Although our FixMort approach created realistic projections of size-density combinations by bridging density-dependent and independent mortality, it is computationally difficult and likely not easily implemented by the many FVS users who may not, for example, be comfortable using the Event Monitor. Furthermore it requires the existence of an established MSB relationship for the species of interest. If fitted MSB relationships were known for enough commercial tree species, their incorporation into FVS would greatly facilitate more accurate size-density projections. Mimicking the MSB required FVS-SN to eliminate trees well above the rate of mortality currently predicted in large Dq stands (approximately 10 inches) using SDIMax. Incorporating mortality mediated by the MSB in place of SDIMax in FVS-SN would require relaxing the current assumption that as stands increase in Dq basal area stays constant. Realistically, basal area and SDI should be allowed to decrease as Dq increases.

Increasingly in forest management, the creation and maintenance of large, mature trees is a priority. For example, on Ft. Bragg maintaining large diameter longleaf pines at low densities is a primary forest management goal as this is a critical component of red-cockaded woodpecker nesting and foraging habitat (U.S. Fish and Wildlife Service 2003). Management for a few large diameter trees focuses stand dynamics modeling on unconventional areas of size-density combinations (in other words, low densities). This highlights the importance of effective simulation of forest stand dynamics.

Conclusions

Density-dependent (SDIMax) mortality was responsible for the over-prediction of size-density combinations in mature stand simulations. We found the longleaf pine DMD useful as a graphical tool to display and evaluate mortality predictions. We suggest that any growth and yield model incorporating the same mortality logic as FVS-SN will also produce unrealistic combinations of size and density for mature stands. Our alternative, based on the longleaf pine MSB, effectively simulated realistic size-density combinations when the stand neared the MSB. Managers of relatively pure longleaf pine stands should incorporate the FixMort logic from approach three into their FVS-SN simulations. This approach bridges density-dependent (SDIMax) and density-independent (background mortality) factors for mortality predictions. While our analysis was restricted to longleaf pine, we suggest our results may be broadly relevant and provide a general framework for assessing and improving the accuracy of mortality predictions.

Acknowledgments

We thank the Forestry Branch of the Fort Bragg Natural Resources Division and the U.S. army Environmental Center for funding this project. We extend special thanks to P. Wefel and J. Stancar for their continuing support and D. Donnelly for initial project help. The comments of two anonymous reviewers helped to substantially improve this work.

References

Assmann, E. 1970. The principles of forest yield study: Studies in the organic production, structure, increment and yield of forest stands. Oxford, U.K., Pergamon Press. 505 p.

Blythe, J.R.; Dickinson, R.S.; Trousil, G.J.; Webb, P.J. 2001. Integrated natural resources management plan 2001–2005, Fort Bragg and Camp Mackall. Fort Bragg: Environment and Natural Resources Division. 473 p.

Crookston, N.L. 1990. User's guide to the Event Monitor: Part of Prognosis model version 6. Gen. Tech. Rep. GTR-INT-275. Ogden, UT; U.S. Department of Agriculture, Forest Service, Intermountain Research Station. (Last Revised: January 2000.)

Dixon, G. E., comp. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 208 p. (Last Revised: February 2007).

Donnelly, D.; Lilly, B.; Smith, E. 2001. The southern variant of the Forest Vegetation Simulator. [Online] http://www.fs.fed.us/fmsc/ftp/fvs/docs/overviews/snvar.pdf]

Drew, T.J.; Flewelling, J.W. 1979.Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science. 25:518–532.

Long, J.N. 1985. A practical approach to density management. Forestry Chronicle. 61(1):23–27.

Long, J.N.; Shaw, J.D. 2005. A density management diagram for even-aged ponderosa pine stands. Western Journal of Applied Forestry. 20:1–11.

Long, J.N.; Smith, F.W. 1992. Volume increment in *Pinus contorta* var. *latifolia*: the influence of stand development and crown dynamics. Forest Ecology and Management. 53(1–4):53–64.

Palik, B.J.; Pederson, N. 1996. Overstory mortality and canopy disturbances in longleaf pine ecosystems. Canadian Journal of Forest Research. 26:2035–2047.

Shaw, J.D.; Vacchiano, G.; DeRose, R.J.; Brough, A.; Kusbach, A.; Long, J.N. 2006. Local calibration of the Forest Vegetation Simulator (FVS) using custom inventory data. 2006 Society of American Foresters National Convention Conference Proceedings.

Shaw, J.D.; Long, J.N. 2007. A density management diagram for longleaf pine stands with application to red-cockaded woodpecker habitat. Southern Journal of Applied Forestry. 31(1): 28–38

U.S. Fish and Wildlife Service. 2003. Recovery plan for the red-cockaded woodpecker (*Picoides borealis*): Second revision. Atlanta, GA: U.S. Fish and Wildlife Service. 296 p.

Van Dyck, M.G. 2005. Keyword reference guide for the Forest Vegetation Simulator. U.S. Department of Agriculture, Forest Service. [available online at: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_keyword.php]

Van Lear, D.H.; Carroll, W.D.; Kapeluck, P.R.; Johnson, R. 2005. History and restoration of the longleaf pine-grassland ecosystem: Implications for species at risk. Forest Ecology and Management. 211:150–165.

Zeide, B. 1985. Tolerance and self-tolerance of trees. Forest Ecology and Management. 13(3/4): 149-166.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Evaluating Growth Models: A Case Study Using Prognosis^{BC}

Peter Marshall[1]
Pablo Parysow[2]
Shadrach Akindele[3]

Abstract—The ability of the Prognosis^{BC} (Version 3.0) growth model to predict tree and stand growth was assessed against a series of remeasured permanent sample plots, including some which had been precommercially thinned. In addition, the model was evaluated for logical consistency across a variety of stand structures using simulation. By the end of the evaluation process, we were pleased with the performance of the model. Some of the less obvious benefits of growth model evaluation and the value of using multiple approaches when evaluating growth models are discussed.

Introduction

Prognosis^{BC} is a growth and yield simulator adapted from the North Idaho version of the Forest Vegetation Simulator—FVS (Dixon 2002; Stage 1973; Wykoff and others 1982). Prognosis^{BC} is designed to forecast future stand conditions in mixed-species and/or multi-aged (complex) stands found in southeast and central British Columbia (BC). It retains much of the architecture of the original model; however, many of the internal equations have been reformulated and the remainder have been recalibrated. The habitat types required in the original model have been replaced by appropriate units within BC's Biogeoclimatic Ecosystem Classification (BEC) system and inputs and outputs have been converted to metric units (Snowdon 1997; Zumrawi and others 2002). Several different versions of Prognosis^{BC} applicable to various BEC zones or subzones have been developed.[1] This paper addresses Version 3.0 (released in 2003). Version 3.0 is applicable to the Interior Douglas-fir (IDF) BEC zone.

The accuracy of growth and yield model projections affects the quality of forest management decisions. Model validation (evaluation) is an integral part of model development (Scholten and Udink ten Cate 1995). It is aimed at determining the degree to which projections from the model are accurate representations of the real world. Rykiel (1996) identified three types of model validation: operational validation, conceptual validation and data-based validation. In empirical growth and yield modeling, these three validation types could be grouped into two categories: conceptual validation and data-based validation.

In this paper, we present both data-based and conceptual evaluations of Prognosis^{BC} (Version 3.0). The data-based validation examined the accuracy of the model in projecting re-measured data from two permanent sample plot installations not employed in the calibration of the model. The conceptual validation involved conducting a sensitivity analysis of the model relative to different initial stand structures. Sensitivity analysis (for example, Frey and Patil 2002; Kleijnen 2005) occupies a prominent place among forest model evaluation methods (Huang and others 2003; Vanclay and Skovsgaard 1997), since it facilitates assessing model behaviour under a broad range of conditions. Sensitivity analyses have been widely used to evaluate forest growth and yield models (for example, Gertner 1987; Mowrer 1991; Peng and others 2002). Recently, Lacerte and others (2004) used this technique to assess the Lakes States variant of FVS in Ontario under various levels of site index, stand density, and age.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Professor and Associate Dean, Faculty of Forestry, University of British Columbia, Vancouver, BC, Canada; e-mail: Peter.Marshall@ubc.ca.

[2] Associate Professor, School of Forestry, Northern Arizona University, Flagstaff, AZ.

[3] Associate Professor, Department of Forestry and Wood Technology, Federal University of Technology, Akure, Nigeria.

[1] Additional information on Prognosis^{BC} may be found at: http://www.for.gov.bc.ca/hre/gymodels/progbc/.

Methods

Evaluation Using Independent Data

Independent data were obtained from two permanent sample plot installations located in uneven-aged interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) stands in the Knife Creek Block of the Alex Fraser Research Forest, approximately 20 km southeast of Williams Lake, BC (52°05'N, 121°50W) (fig. 1). This area is located in the dk3 subzone of the Interior Douglas-Fir biogeoclimatic (BEC) zone (Hope and others 1991) in a gently rolling landscape at an elevation of approximately 1000 m.

The first installation, consisting of six plots, was established to follow stand dynamics under three different structural conditions: (1) predominance of large older trees (dbh > 30 cm)—two 0.1-ha plots; (2) predominance of pole-sized trees (dbh 15-30 cm)—two 0.1-ha plots; and (3) predominance of saplings (dbh < 15 cm)—two 0.05-ha plots. The trees on these plots were measured following the 1987, 1992, 1996, and 2003 growing seasons. The second installation, consisting of 24 0.05 ha plots, was set up as a pre-commercial thinning experiment in stands which were diameter-limit logged in the 1960s. Three blocks (replicates) were established, each consisting of three thinning treatments and a control, with two plots located in each block/treatment combination. Measurements of the trees on these plots were made following the 1992, 1996, and 2003 growing seasons. An 11 year growth period (1993 to 2003, inclusive) was used for this study since this period most closely matches the 10-year projection period used in Prognosis[BC].

Most of the plots are located on zonal (mesic) sites, with some plots on slightly drier sites. However, within-site variation is minimal and does not warrant any changes in site classification. Douglas-fir is by far the most prevalent species, accounting for approximately 90 percent of the trees in the plots. Other tree species present are lodgepole pine (*Pinus contorta* var. *latifolia* (Engel.)), spruce (*Picea glauca* (Moench), *Picea engelmanni* (Parry) and their crosses), white birch (*Betula papyrifera* (Marsh.)) and trembling aspen (*Populus tremuloides* (Michx.)). More detail on these installations is given in Marshall (1996) and Marshall and Wang (1996).

Tree variables used in the validation exercise included species, diameter at breast height (dbh) in cm, total tree height in m, height to base of live crown in m, and crown width in m. From these basic measurements, other tree variables such as crown ratio, basal area in trees larger than the subject tree, and crown competition factor were computed. Attributes projected were stems per ha, basal area per ha, total stand volume

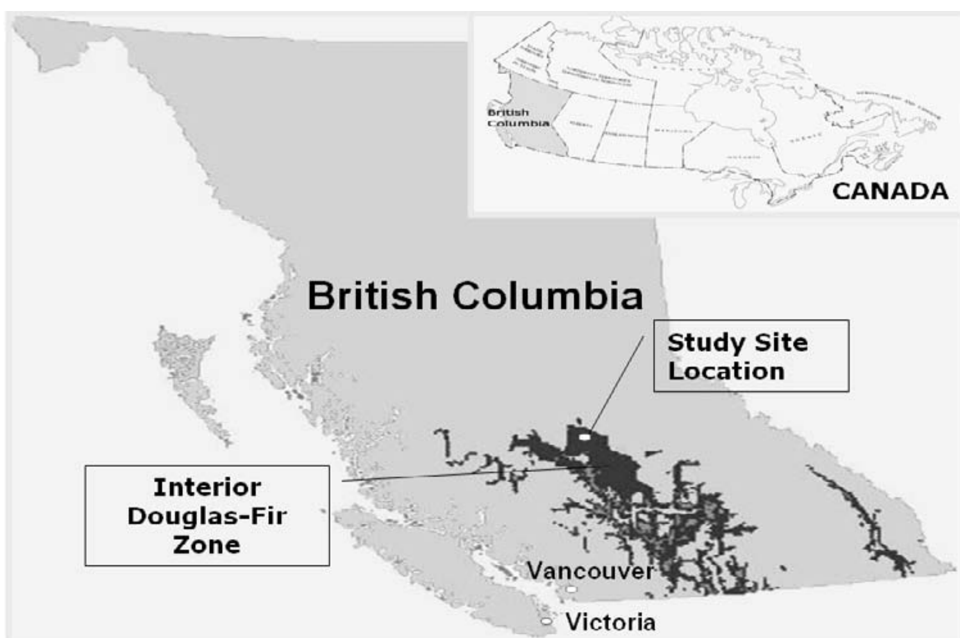


Figure 1—Location of the permanent sample plot installations.

per ha, merchantable stand volume per ha, tree dbh, and tree height. In the interests of space, only projections of stems per ha and dbh growth for trees larger than 7.5 cm dbh are reported here. Evaluations are presented in tabular form and via graphical presentations of regression-based equivalency tests (Robinson and others 2005)

Evaluation Using Simulation

Partial harvesting to produce and/or maintain uneven-aged stand structures has been successfully applied to many drier western interior North American forests (O'Hara 2002), including stands in the IDF zone. The rationale for this type of harvesting in the IDF zone includes maintaining and enhancing mule deer (*Odocoileus hemionus* Raf.) winter range, as well as meeting timber and other forest management goals (Armleder and Dawson 1992; Armleder and others 1986; BC Ministry of Forests 1992).

The BDq approach to specifying target structures for partially harvested stands has been implemented in numerous forest types (Fiedler 1995), including interior Douglas-fir forests (Day 1998). BDq is an acronym which represents target basal area (B), maximum dbh (D), and diminution quotient[2] (q, the tree-frequency ratio between successive diameter classes). These three components together characterize a target structure for a stand.

In this study, we produced a wide range of initial stand structures for pure Douglas-fir stands. These structures resulted from a factorial combination of the three components of the BDq approach. Each component was assigned four levels: basal area (B): 10, 30, 50, 70 m^2/ha; maximum dbh (D): 20, 40, 60, 80 cm; and diminution quotient (q): 1.5, 2.0, 2.5, 3.0. The resulting total number of combinations equalled 64 ($4 \times 4 \times 4$). Using 5 cm dbh classes and a minimum class midpoint of 5 cm, we generated dbh distributions (trees/ha per dbh class) corresponding to each BDq combination, as described by Fiedler (1995). Tree class frequencies were initially allocated to the dbh class midpoints. Any combination that generated a frequency of less than one tree/ha for the largest dbh class resulted in the entire combination being considered infeasible and dropped from the analysis. The combinations included in the analysis are shown in table 1.

To allow for a smoother growth simulation among successive dbh classes, we divided each class frequency among the five 1-cm dbh values within each class. To insure that class frequency and basal area would be the same as having allocated the entire frequency only to the class midpoint, we assigned a decreasing tree frequency to each successive larger dbh within each class. This frequency allocation was accomplished as follows: (1) the dbh matching the class midpoint received one-fifth of the class frequency; (2) the dbhs 1 cm and 2 cm larger than the midpoint received frequencies that were 10% and 20% lower than the midpoint frequency, respectively; and 3) the dbhs 1 cm and 2 cm smaller than the midpoint received frequencies that were 10 and 20 percent higher than the midpoint frequency, respectively.

A computer program was written to generate the dbh distributions corresponding to each feasible BDq combination. Those dbh distributions were formatted as Prognosis^{BC} input tree list files. We ran each dbh distribution for a 50-year period, assuming no interventions. For each simulated BDq combination, we forecasted stand-level variables such as basal area (ba—m^2/ha) and quadratic mean diameter (qmd—cm), as well as the following variables by dbh class: live trees/ha, ba/ha (m^2), dbh growth (cm), and mortality

Table 1—Feasible (✓) and infeasible (×) combinations of BDq for the simulation analysis.

B[a]	10				30				50				70			
q[b]	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0	1.5	2.0	2.5	3.0
D[c] = 20	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
D = 40	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
D = 60	✓	×	×	×	✓	×	×	×	✓	✓	×	×	✓	✓	×	×
D = 80	×	×	×	×	×	×	×	×	✓	×	×	×	✓	×	×	×

[a] Initial basal area per ha in m^2.
[b] Diminution quotient (tree-frequency ratio between successive dbh classes).
[c] Initial maximum dbh class in cm.

[2] This coefficient is sometimes called de Liocourt's coefficient. Meyer (1952) identified de Liocourt (1898) as the first individual to publish a numerical study of growing stock distribution in uneven-aged forests.

(dead trees/ha). To report sensitivity analysis results, we first specified the level for B, then D, and finally q. For example, the combination B = 10 m^2/ha, D = 20 cm, and q = 1.5 is identified as 10-20-1.5.

Results

Evaluation Using Independent Data

Overall, the mean differences between predicted and observed dbh over the projection period were relatively small, except for the few trees greater than 60 cm dbh where the model overestimated 11-year dbh growth by an average of 0.9 cm (table 2). The mean differences for the thinning treatments (table 3) were also relatively small (<0.2 cm), indicating little bias in predicted dbh for any spacing treatment over the 11-year projection period.

These observations are supported by the graphical representations of the equivalence tests (figs. 2 and 3). In these figures, the solid line is the regression of observed on model-predicted dbh, the grey horizontal bar represents the equivalence region for the intercept, and the diagonal dotted lines represent the equivalence region for the slope. Both figures show that the two independent one-sided confidence intervals for the slope and intercept fall entirely within their specified equivalence regions (±10 percent for the intercept and ±20 percent for the slope), at a significance level (α) of 0.05. Thus, there was strong evidence to reject the null hypotheses of the dissimilarity of the observed and predicted dbh.

However, Prognosis^{BC} predicts periodic dbh growth, not future dbh. Future dbh is calculated as the original dbh plus the dbh growth. The equivalence test on dbh growth of trees in the thinning study indicated some overestimation of dbh growth by Prognosis^{BC} following thinning (fig. 4). This result is not surprising given that the dbh growth function was calibrated using data that did not incorporate recent cutting. Trees of a given dbh growing for a number of years at lower densities would tend to have larger crowns than would be found in trees of a similar size immediately following thinning to that density.

Future stems per ha (or its corollary, mortality level) appeared to be acceptably predicted overall (fig. 5). There was a slight underestimate of future stems per ha, but the regression line and most of the observations fall well within the equivalence region. There were too few plots at each thinning level (6) to perform separate equivalence tests on predicted stems per ha for each of the thinned plots.

Table 2—Differences (cm) between actual and predicted dbh by dbh class (cm).

dbh Class	All	10	15	20	25	30	40	50	60	>60
Stems	3078	1467	969	398	113	41	49	28	9	4
Mean difference	–0.009	–0.154	0.126	0.211	0.048	0.066	–0.055	–0.036	–0.978	–0.925

Table 3—Differences (cm) between actual and predicted dbh by thinning treatment.

	C1[a]	C2[b]	STD[c]	CTRL[d]	N/A[e]
Stems	626	335	729	801	587
Mean difference	–0.135	0.064	–0.069	–0.018	0.168

[a] 3-m clumped thinning treatment. (See Marshall 1996 for a description of this treatment.)
[b] 5-m clumped thinning treatment. (See Marshall 1996 for a description of this treatment.)
[c] Standard thinning treatment. (See Marshall 1996 for a description of this treatment.)
[d] Trees growing in the control plots for the thinning installation.
[e] Trees growing in the 6 plots in the stand structure installation.

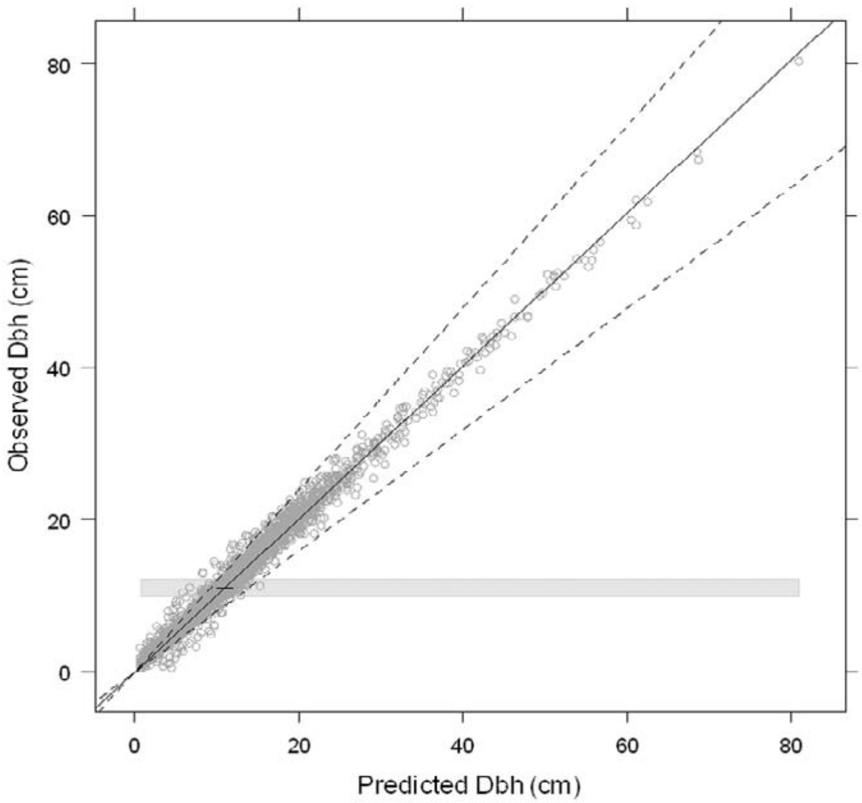


Figure 2—Observed dbh versus predicted dbh for all trees.

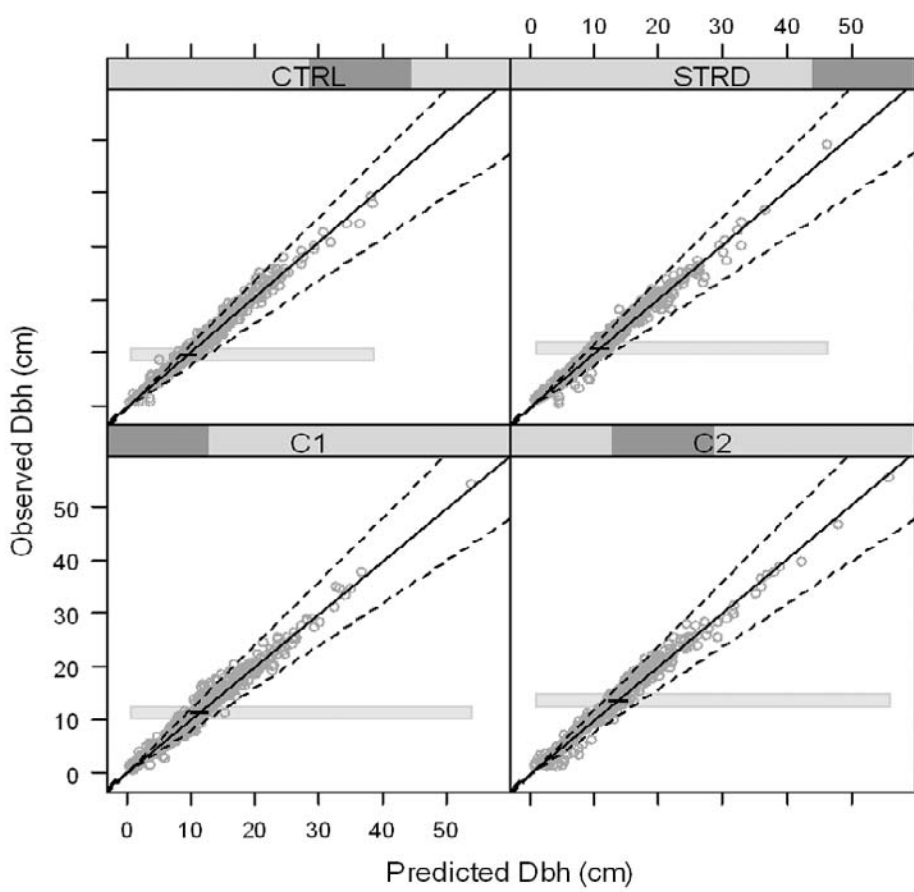


Figure 3—Observed dbh versus predicted dbh for trees in the pre-commercial thinning installation. CTRL represents trees in the control plots; STRD represents trees in the plots that received a standard thinning; C1 represents trees in the plots that received a 3 m clumped thinning; and C2 represents trees in the plots that received a 5 m clumped thinning.

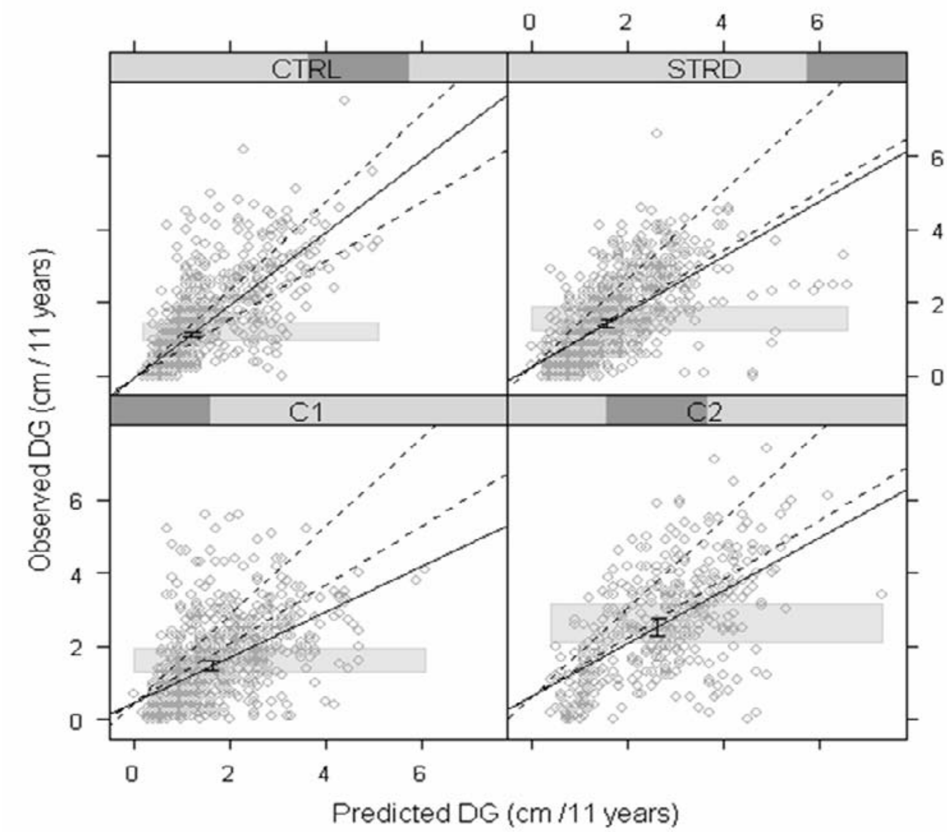


Figure 4—Observed 11-year dbh growth versus predicted 11-year dbh growth for trees in the precommercial thinning installation. CTRL represents trees in the control plots; STRD represents trees in the plots that received a standard thinning; C1 represents trees in the plots that received a 3 m clumped thinning; and C2 represents trees in the plots that received a 5 m clumped thinning.

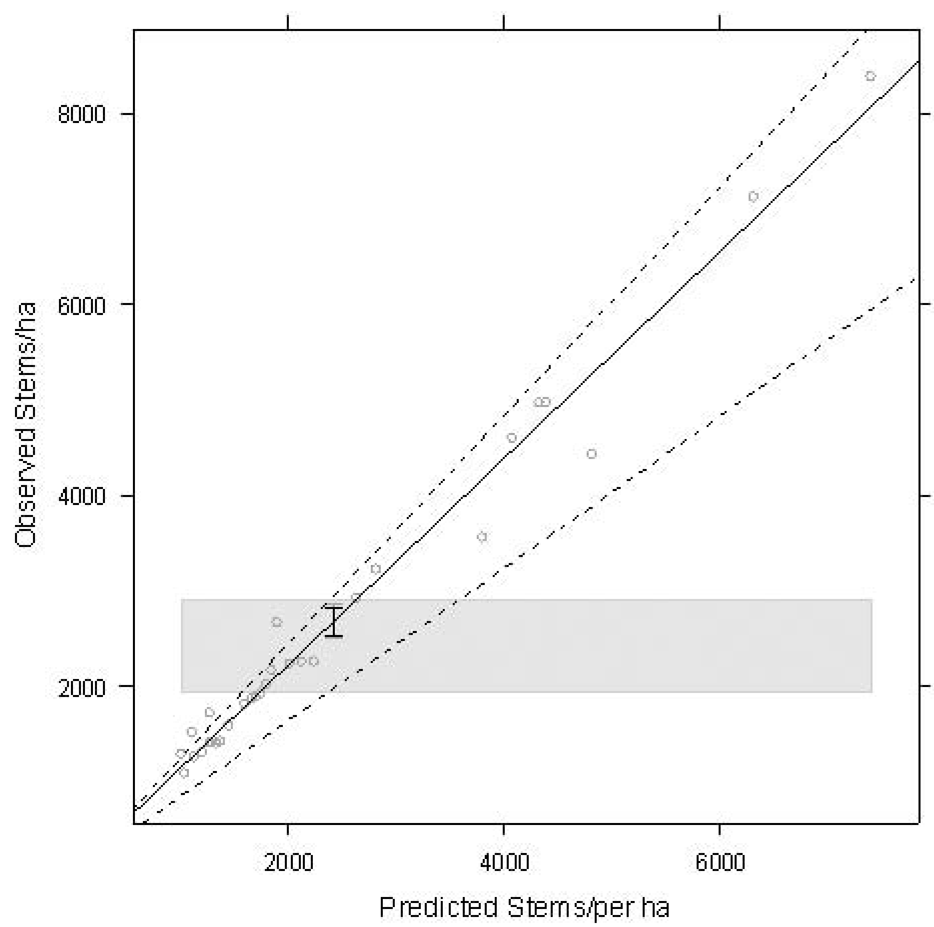


Figure 5—Observed stems per ha versus predicted stems per ha for all 30 plots used in this study.

Evaluation Using Simulation

Out of the 64 original BDq combinations, 25 resulted in a frequency of less than one tree/ha for the largest dbh class and were consequently considered infeasible. Therefore, 39 BDq combinations were analyzed in this study (table 1). Stand structures with a D of 80 cm were feasible only when B was at least 50 m^2/ha, and q was 1.5. Stand structures with a D of 60 cm were feasible for all levels of B only when q was 1.5. When q was 2.0, stand structures with a D of 60 cm were feasible only when B was at least 50 m^2/ha. Stand structures with a D of 60 cm were not feasible when q was 2.5 or 3.0. Stand structures with a D of 40 cm were feasible for all levels of B and q, except for a B of 10 m^2/ha and a q of 3.0. All of the stand structure combinations examined with a D of 20 cm were feasible.

Figure 6 displays forecasted basal area per ha under varying levels of BDq over the simulation period for a q of 1.5. The patterns for q values of 2, 2.5 and 3 were similar. Prognosis^{BC} has a limit on maximum basal area in this region of approximately 53 m^2/ha. Consequently, the projected basal area approached this limit from above (B = 70 m^2/ha) or below (B = 10 or 30 m^2/ha). The trend line for a B of 50 m^2/ha was essentially level.

The projected changes in qmd were almost straight lines, beginning at a particular value that was related to the initial maximum dbh (D) and the value of q. (See fig. 7 for an example using a q of 1.5). The starting qmd was independent of B. The higher the D for a given value of q, the higher the initial qmd. Higher values of q reflect more rapid decreases in tree numbers with increasing dbh class (i.e., relatively more small trees for a given initial basal area), and consequently lower initial values for qmd. As expected, those with lower initial basal areas showed more rapid increases in qmd than those with more dense initial basal areas. The highest level of qmd obtained was almost 35 cm for the 10-60-1.5 scenario (fig. 7c), while the lowest was just under 12 cm for the 70-20-2.5 scenario (fig. 7d). These scenarios also produced the greatest and least changes, respectively, in qmd over the simulation period.

Since the recruitment (regeneration) function of Prognosis^{BC} was not activated for this assessment, all scenarios showed a decrease in stems per ha with time (see fig. 8 for an example using a q of 1.5). Not unexpectedly, the amount of decrease increased as B increased. In both absolute and relative terms, the largest decrease in stems per ha occurred for the smallest D examined (fig. 8a). Increasing q for a given level of B and D, increased the number of stems initially (more small dbh stems required), and resulted in higher levels of mortality over the projection period.

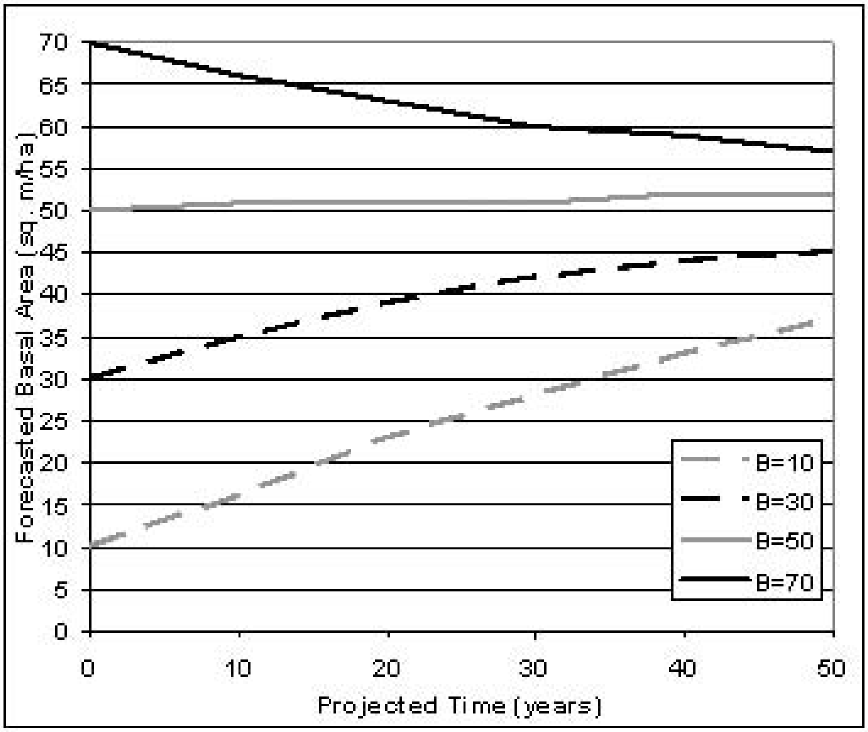
As expected, overall dbh growth was higher for stand structures with lower initial basal areas (fig. 9 vs. fig. 10). Dbh growth was similar when D was 20 and 40 cm, but decreased for a D of 60 cm (figs. 9a and b verses c, figs. 10a and b verses c). Increasing q for a given level of B and D had a slightly negative impact on the overall dbh growth (figs. 9a and b verses d and e, figs. 10a and b verses d and e).

A summary of the changes in stand dynamics associated with different stand structures predicted by the Prognosis^{BC} simulations is given in table 4. These were consistent and align with present biological understanding.

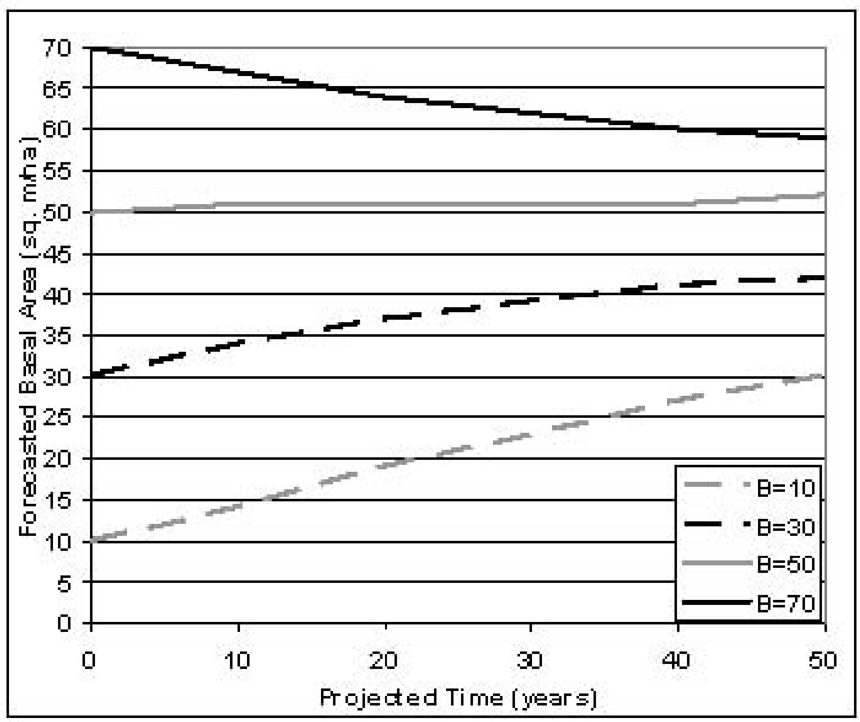
Discussion

Evaluation of any growth model provides several benefits. Documenting the performance of a model under a particular set of conditions provides benchmark information to potential model users as to the degree of trust that they ought to place in model outputs under similar conditions. The evaluation process also can bring specific components of the model under close scrutiny. It is usually beneficial if this scrutiny can be performed at more than one scale. In the case of Prognosis^{BC} (Version 3.0), we were able to identify anomalous behaviour in predictions of single tree attributes for a small subset of trees. This behaviour was traced back to a programming error which was then easily repaired. The impact of this error on stand level projections (for example, basal area per ha growth and future stems per ha) was sufficiently small that it was not previously identified.

We believe that model evaluation is more effective if more than one approach is used. In this study we combined a performance assessment conducted against independent data with a simulation study designed to assess the impact of changes in stand structure on model projections. The former approach allowed us to benchmark performance and the later provided an assessment of the consistency of model behaviour across a wide range

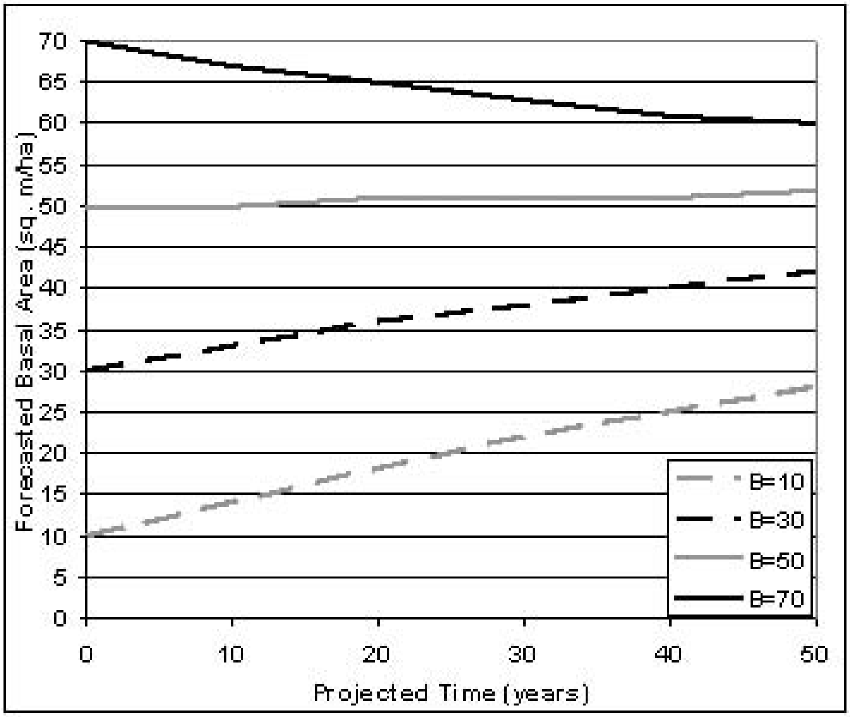


(a)

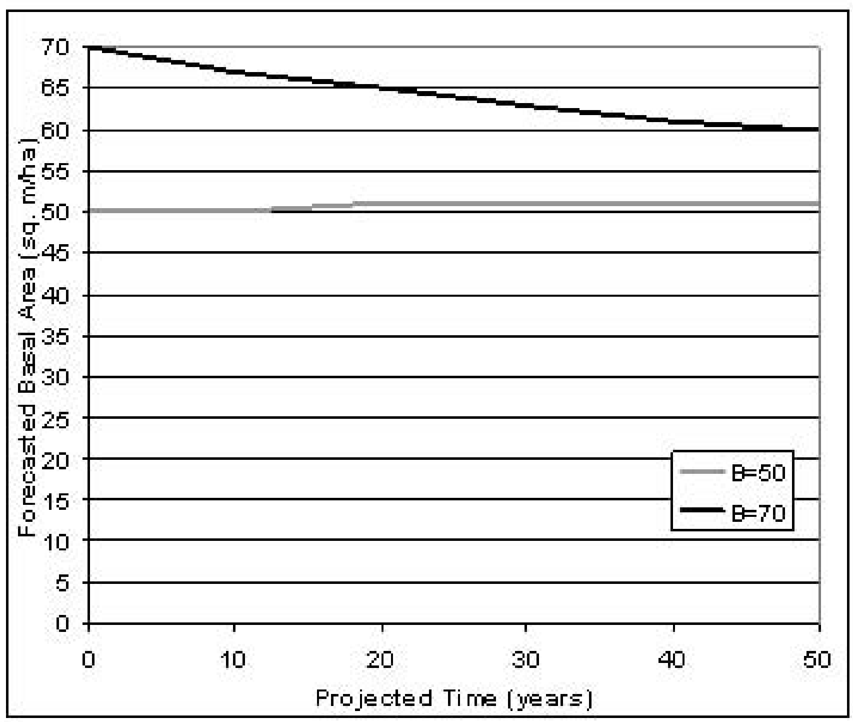


(b)

Figure 6 —Projected basal area for various initial levels of initial basal area (B) with q = 1.5 and maximum diameter (D) at (a) 20 cm; (b) 40 cm; (c) 60 cm; and (d) 80 cm.

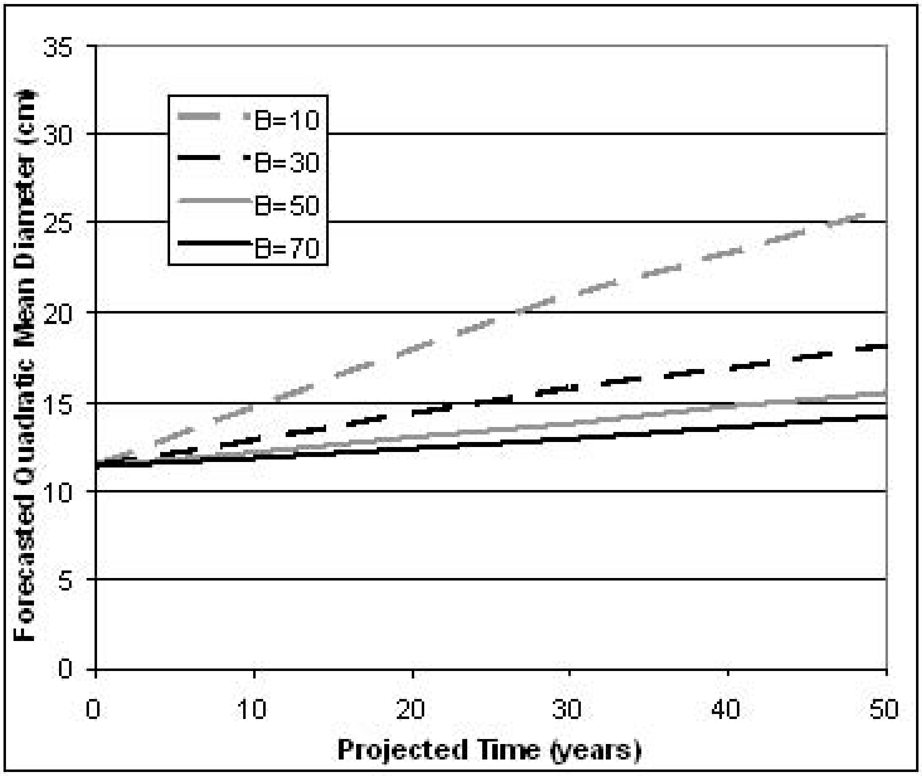


(c)

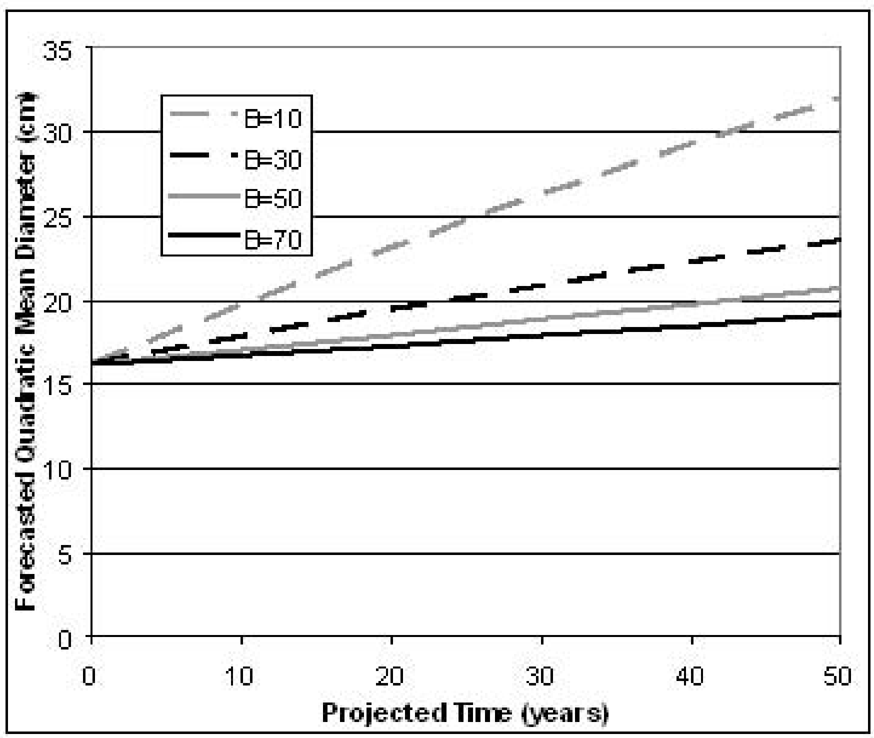


(d)

Figure 6 —(Continued.)

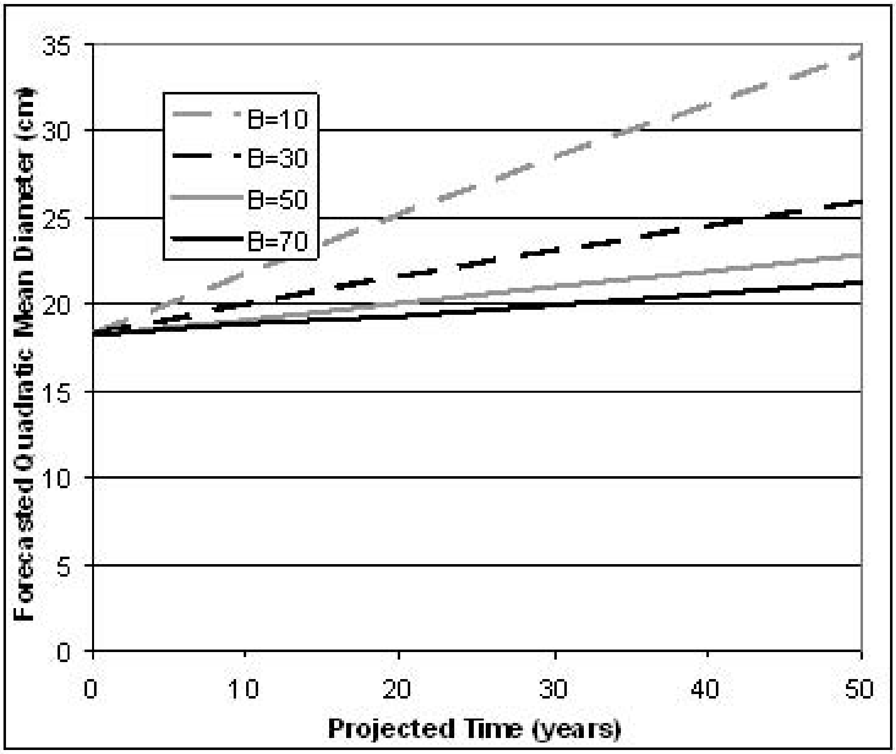


(a)

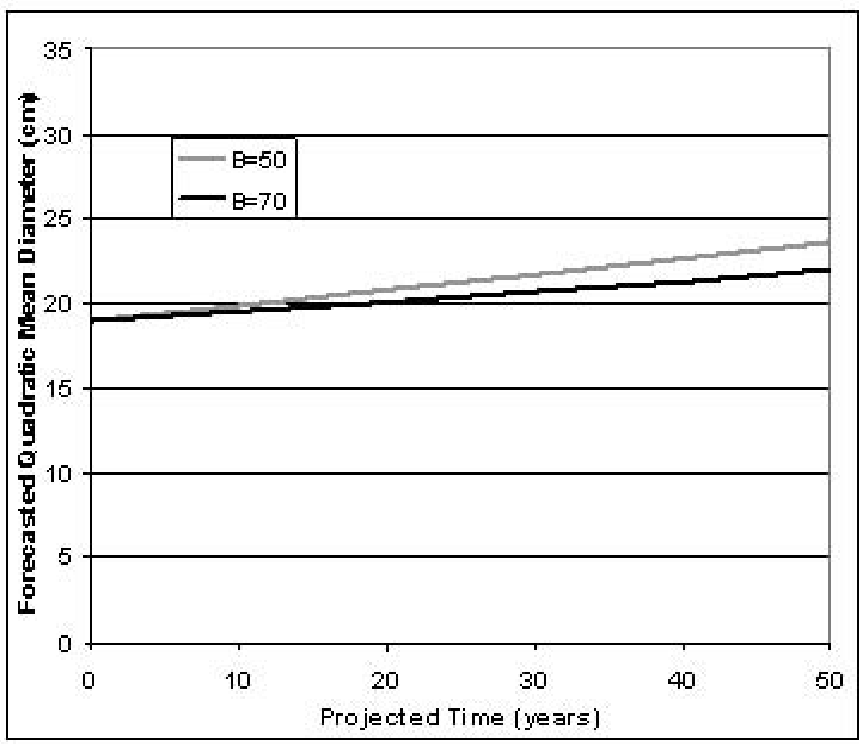


(b)

Figure 7—Projected quadratic mean diameter (qmd) for various initial levels of basal area (B) with q = 1.5 and maximum diameter (D) at (a) 20 cm; (b) 40 cm; (c) 60 cm; and (d) 80 cm.

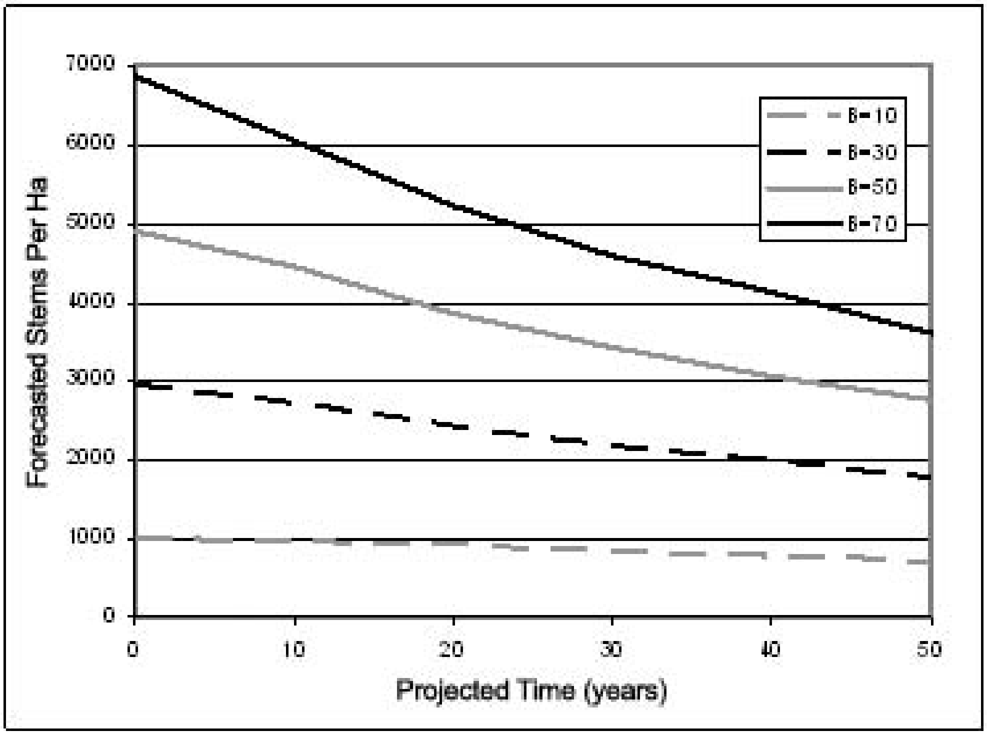


(c)

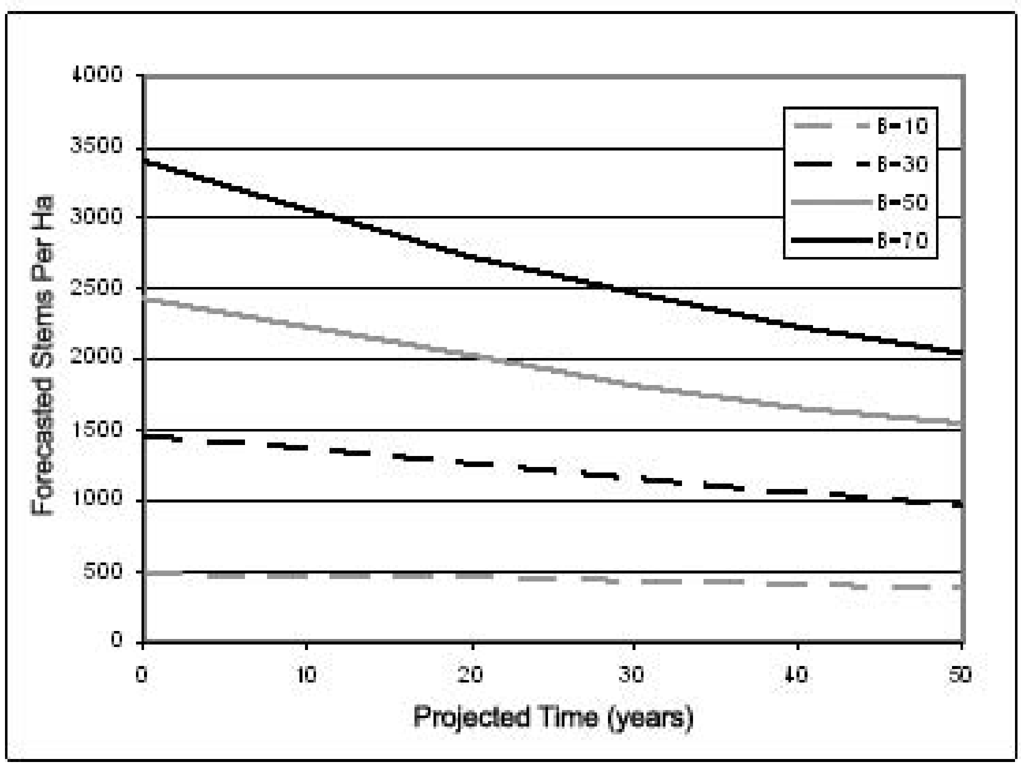


(d)

Figure 7—(Continued.)

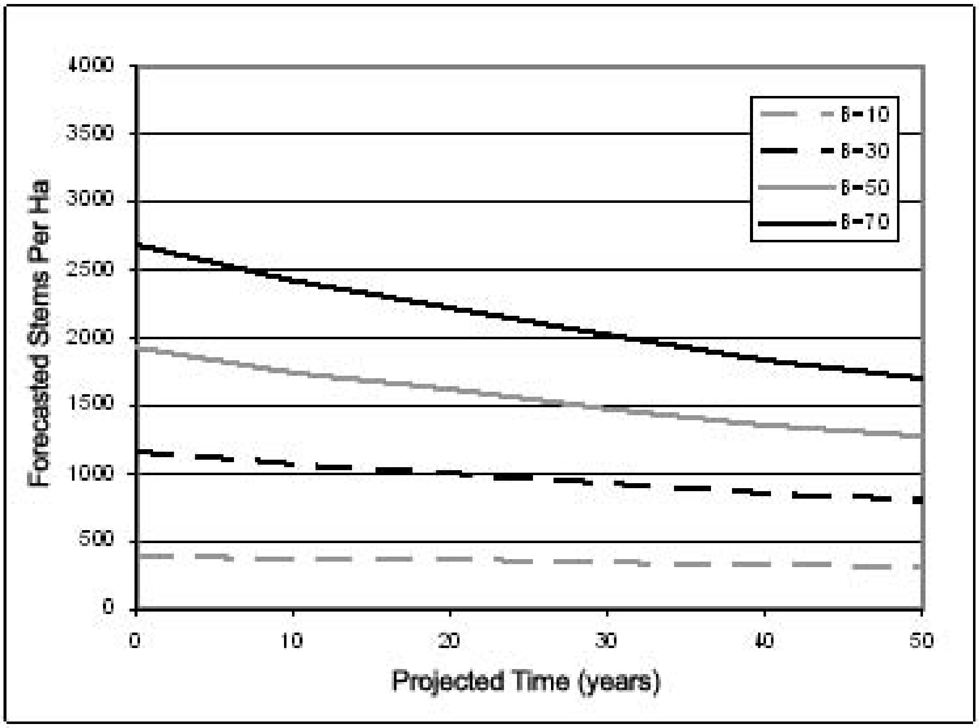


(a)



(b)

Figure 8—Projected change in stems per ha for various initial levels basal area (B) with q = 1.5 and maximum diameter (D) at (a) 20 cm; (b) 40 cm; (c) 60 cm; and (d) 80 cm.



(c)

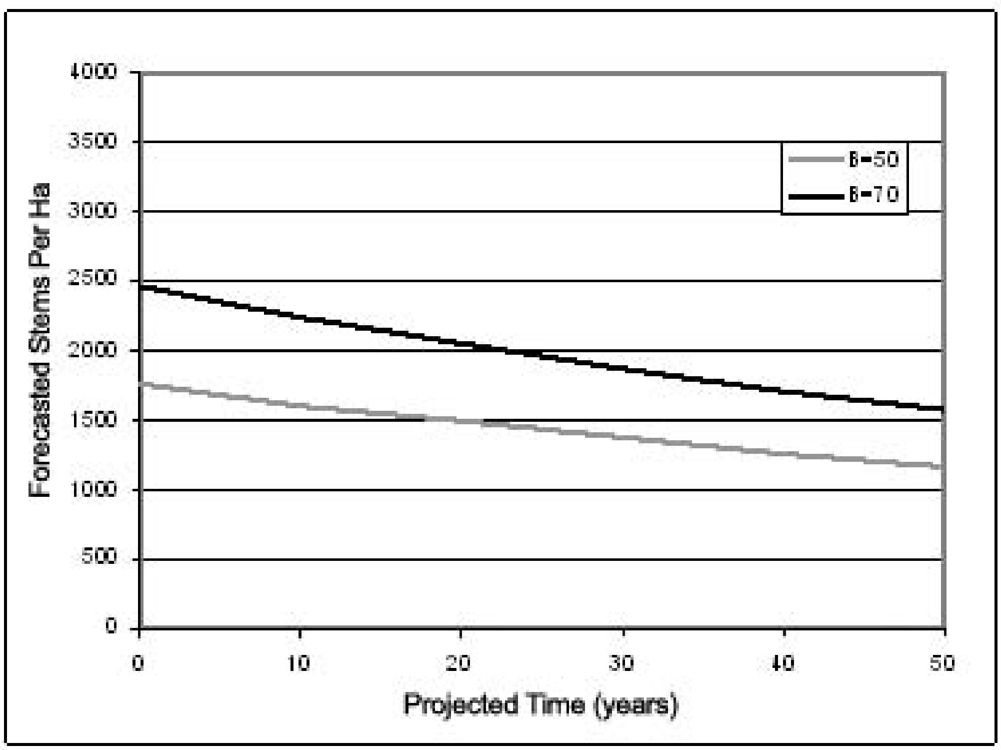
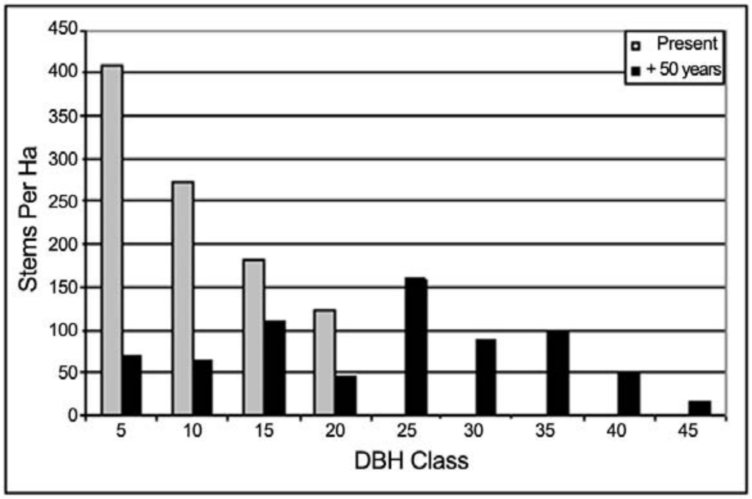
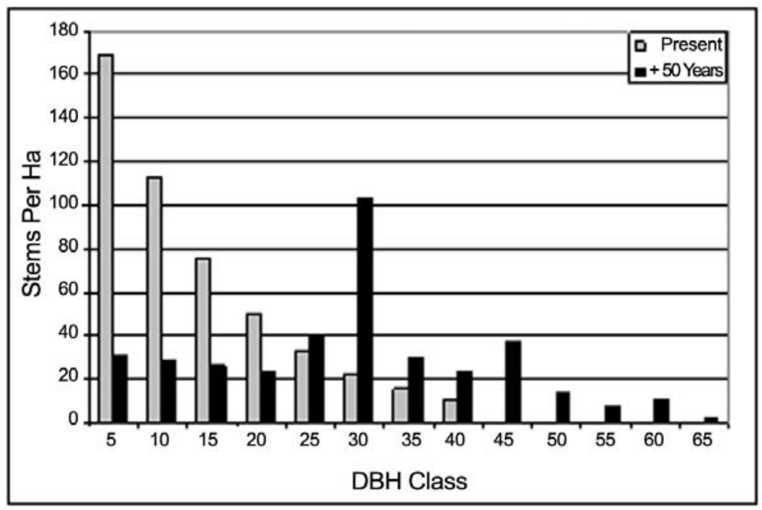


Figure 8—(Continued.)

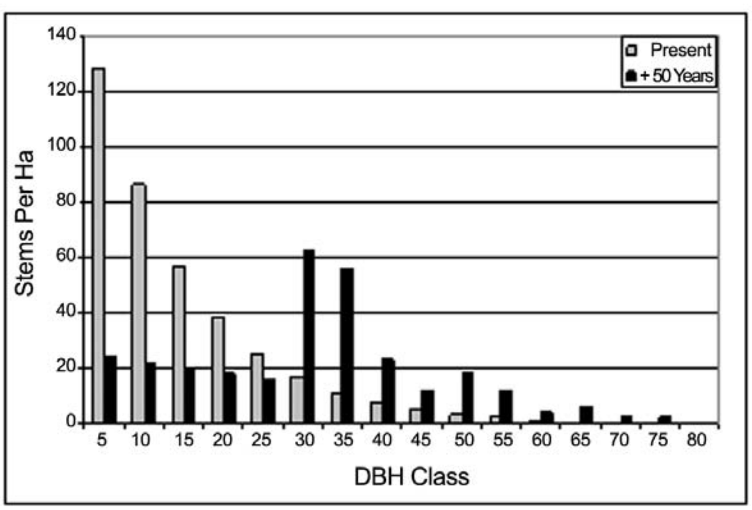
(d)



(a)

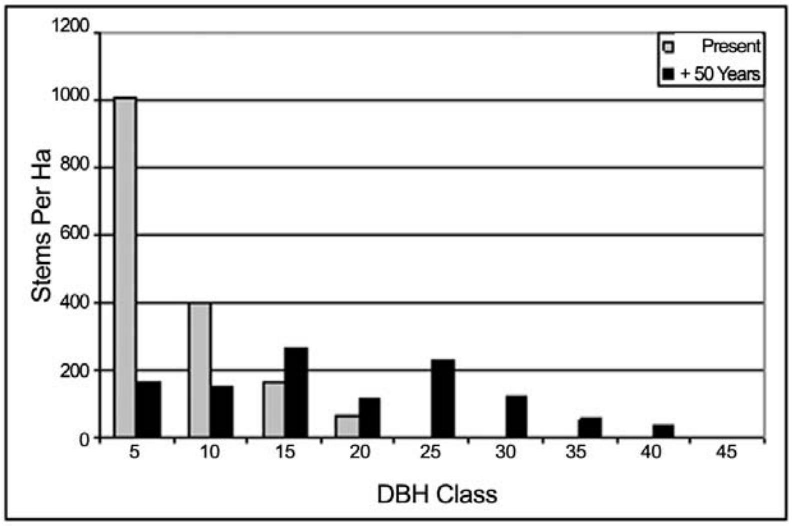


(b)

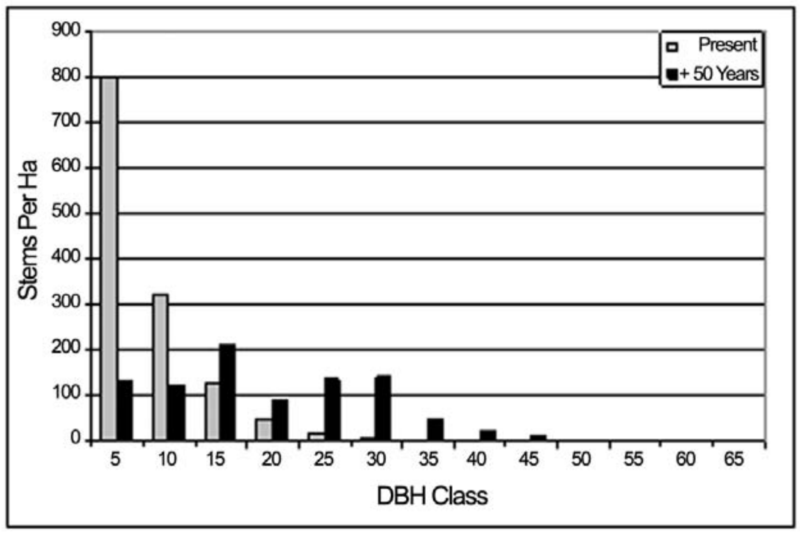


(c)

Figure 9—Dbh distributions at the onset of the simulation and after 50 years for an initial basal area (B) of 10 m2/ha at: (a) D = 20 cm and q = 1.5; (b) D = 40 cm and q = 1.5; (c) D = 60 cm and q = 1.5; (d) D = 20 cm and q = 2.5; and (e) D = 40 cm and q = 2.5.

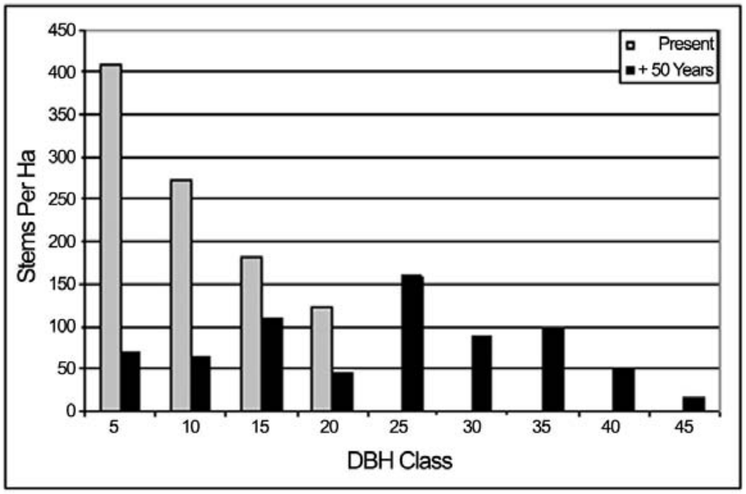


(d)

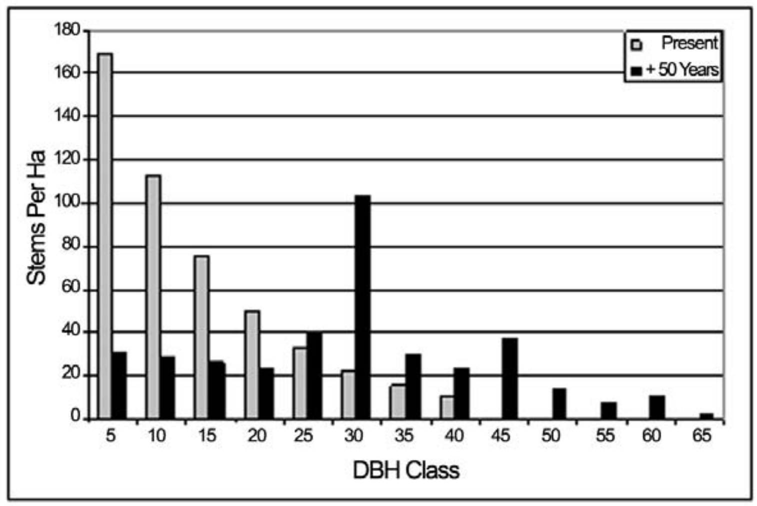


(e)

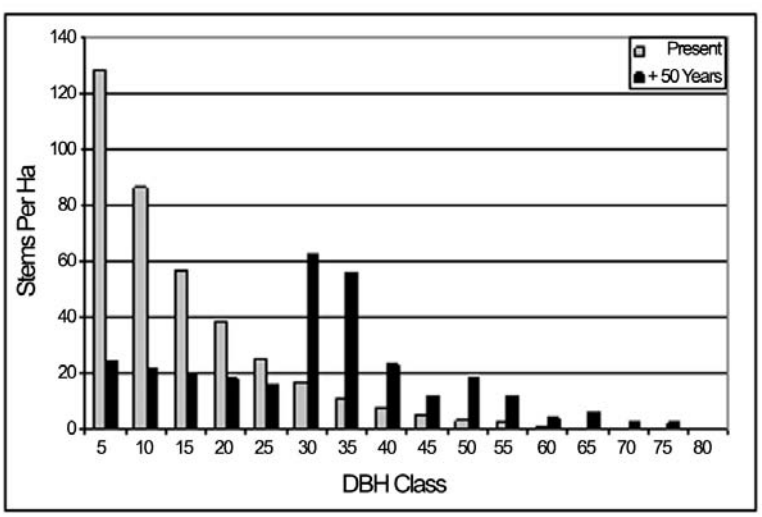
Figure 9—(Continued.)



(a)

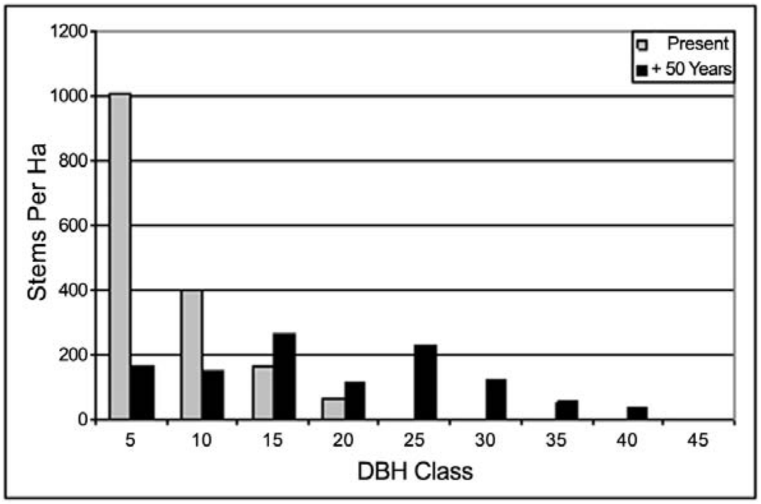


(b)

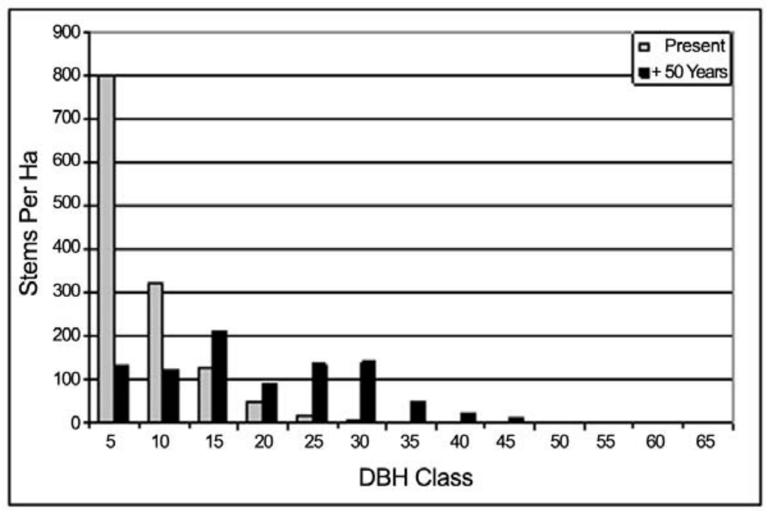


(c)

Figure 10—Dbh distributions at the onset of the simulation and after 50 years for an initial basal area (B) of 50 m2/ha at: (a) D = 20 cm and q = 1.5; (b) D = 40 cm and q = 1.5; (c) D = 60 cm and q = 1.5; (d) D = 20 cm and q = 2.5; and (e) D = 40 cm and q = 2.5.



(d)



(e)

Figure 10—(Continued.)

Table 4—Impact of initial stand structure on various stand attributes after 50 years of projected growth.

Attribute	Increase in stand structure component[a]		
	B[b]	D[c]	q[d]
Basal area per ha	Movement towards "carrying capacity." If B is ~53 or below, approaches from below; if B is >53 approaches from above.	Slightly slower increase (for lower values of B) or slightly slower decrease (for higher values of B).	Very slight increase (forr lower values of B) or very slight decrease (for higher values of B).
Quadratic mean dbh	Decrease in the rate of increase.	Higher initial value and higher final value after 50 years.	Lower initial and lower final value after 50 years.
Stems per ha	Higher initial value and final value after 50 years. Increase in the mortality rate.	Lower initial value and final value after 50 years. Decrease in the mortality rate.	Higher initial value and final value after 50 years. Increase in the mortality rate.
Dbh growth	Decrease in overall growth rate.	Slight decrease in growth rate.	Slight decrease in growth rate.

[a] The other stand structure components are assumed to remain constant.
[b] Initial basal area per ha (m^2).
[c] Largest dbh class present in the initial stand (cm).
[d] Diminution quotient (tree-frequency ratio between successive dbh classes).

of initial conditions. Both approaches provided information to potential model users on how well the model may perform under certain conditions.

It is important in conducting model evaluations and in interpreting the results of model evaluations to be clear on what is being tested and presented. For example, one could be led to entirely different conclusions about the ability of Prognosis^{BC} to make projections following thinning from viewing only figure 3 or only figure 4. The former shows the accuracy of predicting future dbh values over an 11-year period while the later shows the accuracy of predicting dbh growth over the 11-year period. From a modeller's perspective, it is dbh growth which is of primary interest since that is what is actually being predicted within Prognosis^{BC}. From the perspective of a practitioner interested in predicting future stand structures, it could well be the accuracy of future dbh values that is of interest.

It would have been useful if we could have provided a comparison of the data used in our evaluation with the data used in calibration of the model. There were obvious differences geographically, with the data used in the evaluation coming from a single local area and the calibration data coming from a much wider geographical region. Given this difference, the fact that the model projected tree and stand growth which was close to that observed in the unthinned plots was reassuring. More substantive differences between model projections and observed growth were apparent in the thinned plots. Given the scarcity of thinning in this region historically, it is likely that there was little to no data from thinned stands used in calibrating the model.

Conclusions

In the process of evaluating Prognosis^{BC} (Version 3.0) we discovered a few minor errors in the coding that affected individual tree projections. Once those errors were fixed, the model generally performed well against the test data at both the single tree and the stand level. Although predicted dbh values for individual trees appeared to match closely with actual values in an 11-year period following precommercial thinning, growth in dbh following thinning was clearly overestimated. The simulations performed produced results under a wide variety of stand structures which were consistent with our understanding of stand dynamics. Overall, we felt that Prognosis^{BC} proved to be acceptably robust for the range of conditions examined.

Acknowledgments

This project was funded by the BC Ministry of Forests and Range, using funds provided for continuing work on Prognosis^{BC} in the Forest Investment Account (FIA). We are grateful for this support. We also benefited greatly from help and advice provided by Dr. Abdel-Azim Zumrawi, BC Ministry of Forests and Range, Research Branch and Don Robinson, ESSA Technologies Ltd.

References

Armleder, H.M.; Dawson, R.J. 1992. Logging on mule deer winter range: An integrated management approach. Forestry Chronicle. 68:132–137.

Armleder, H.M.; Dawson, R.J.; Thomson, R.N. 1986. Handbook for timber and mule deer management coordination on winter ranges in the Cariboo Forest Region. Land Management Handbook 13. Victoria, BC: British Columbia Ministry of Forests. 98p.

BC Ministry of Forests. 1992. Correlated guidelines for management of uneven-aged drybelt Douglas-fir stands in British Columbia. Victoria, BC: British Columbia Ministry of Forestrs, Silviculture Branch. 44 p. + appendices.

Day, K. 1998. Stocking standards for uneven-aged interior Douglas-fir. In: Vyse, A.; Hollstedt, C.; Huggard, D., eds. Proceedings of the workshop on managing the dry Douglas-fir forests of the Southern Interior;. 1997 April 29–30; Kamloops, BC. Working Paper 34/1998. Victoria, BC: British Columbia Ministry of Forests, Research Branch: 37–52.

de Liocourt, F. 1898. De l'amenagement des sapinieres. Societe Forestiere de Franche-Compte et Belfort Bulletin. 6:396–405.

Dixon, G.E., comp. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. 208 p. (Last revised: February 2007)

Fiedler, C.E. 1995. The basal area-maximum diameter-q (BDq) approach to regulating uneven-aged stands. In: O'Hara, K., ed. Uneven-aged management: Opportunities, constraints, and methodologies. MFCES Miscellaneous Publication No. 56: 94–109.

Frey, H.C.; Patil, S.R. 2002. Identification and review of sensitivity analysis methods. Risk Analysis. 22:553–578.

Gertner, G. 1987. Approximating precision in simulation projections: an efficient alternative to Monte Carlo methods. Forest Science. 33:230–239.

Hope, G.D.; Mitchell, W.R.; Lloyd, D.A.; Erickson, W.R.; Harper, W.L.; Wikeem, B.M. 1991. Interior Douglas-fir zone. In: Meidinger, D.; Pojar, J., eds. Ecosystems of British Columbia. British Columbia Ministry of Forests, Research Branch: 153–165.

Huang S.; Yang, Y.; Wang, Y. 2003. A critical look at procedures for validating growth and yield models. In: Amaro A.; Reed, D.; Soares, P., eds. Modelling forest systems. Cambridge, MA: CABI Publishing: 271–294.

Kleijnen, J.P.C. 2005. An overview of the design and analysis of simulation experiments for sensitivity analysis. European Journal of Operational Research. 164:287–300.

Lacerte, V.; Larocque, G.R.; Woods, M.; Parton, W.J.; Penner, M. 2004. Testing the Lake States variant of FVS (Forest Vegetation Simulator) for the main forest types of northern Ontario. Forestry Chronicl. 80:495–506.

Marshall, P.L. 1996. Response of uneven-aged Douglas-fir to alternative spacing regimes: Analysis of the initial impact of the spacing regimes. Canada-British Columbia Joint Publication. FRDA II Rep. 242. 27 p.

Marshall, P.L.;Wang, Y. 1996. Growth of uneven-aged interior Douglas-fir stands as influenced by different stand structures. Canada-British Columbia Joint Publication. FRDA II Report 267. 20 p.

Meyer, H.A. 1952. Structure, growth, and drain in balanced uneven-aged forests. Journal of Forestry. 50:85–92.

Mowrer, H.T. 1991. Estimating components of propagated variance in growth simulation model projections. Canadian Journal of Forest Research 21: 379-386.

O'Hara, K. 2002. The historical development of uneven-aged silviculture in North America. Forestry. 75:339–346.

Peng, C.; Liu, J.; Dang, Q.; Apps, M.J.; Jiang, H. 2002. TRIPLEX: A generic hybrid model for predicting forest growth and carbon and nitrogen dynamics. Ecological Modelling. 153:109–130.

Robinson, A.P.; Duursma, R.A.; Marshall, J.D. 2005. A regression-based equivalence test for model validation: Shifting the burden of proof. Tree Physiology. 25:903–913.

Rykiel, E.J. Jr. 1996. Testing ecological models: The meaning of validation. Ecological Modeling. 90:229–244.

Scholten H.; Udink ten Cate, A.J. 1995. Testing simulation modeling quality. In: Mathematical modelling and simulation in agriculture and bio-industries. Volume I. Brussels, Belgium: IMACS/IFAC. II.A.3: 1–6.

Snowdon, B. 1997. British Columbia's Forest Vegetation Simulator application software. In: Teck, R.; Moeur, M.; Adams, J., tech. eds. Proceedings of Forest Vegetation Simulator Conference. 1997 February 3–7; Fort Collins, CO. Gen. Tech. Rep. INT-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Stage, A.R. 1973. Prognosis model for stand development. Res. Pap. INT-137, Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Vanclay, J.K.; Skovsgaard, J.P. 1997. Evaluating forest growth models. Ecological Modelling. 98:1–12.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

Zumrawi, A.; Stage A.; Snowdon, B. 2002. Stand level scaling of a single tree distance independent diameter growth model: Interim calibration of Prognosis in the south-eastern interior of British Columbia. In: Crookston, N.L; Havis, R.N., comps. Proceedings of second Forest Vegetation Simulator (FVS) Conference; 2002 February 12–14, Fort Collins, CO. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 151–157.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Predicting the Recruitment of Established Regeneration into the Sapling Size Class Following Partial Cutting in the Acadian Forest Region: Using Long-Term Observations to Assess the Performance of FVS-NE

David Ray[1]
Chad Keyser[2]
Robert Seymour[3]
John Brissette[4]

Abstract—Forest managers are increasingly called upon to provide long-term predictions of forest development. The dynamics of regeneration establishment, survival and subsequent recruitment of established seedlings to larger size classes is a critical component of these forecasts, yet remains a weak link in available models. To test the reliability of FVS-NE for simulating sapling (stems ≥ 0.5 in dbh) recruitment dynamics in stands subject to repeated partial harvests, we compared model predictions with long-term observations (n = 729 plots/5-yr interval combinations) from the Penobscot Experimental Forest (PEF) in central Maine. Two different parameterizations of FVS-NE were tested; the currently available production code and a yet to be released beta version that contains a number of structural changes. Because neither parameterization has a full-establishment model, regeneration composition and densities were from the research plots. Our analyses indicated that predicted rates of sapling recruitment were biased according to both models, averaging 47 percent (production) and 206 percent (beta) of the observed rate at the PEF (1.71 ± 0.25 ft2/ac/5-yr). Mortality rates among the newly recruited saplings were overestimated by both models, and species composition of the survivors did not closely match the observations. Correlation analysis on the residuals from the beta version pointed to a strong link between the overestimation of stems recruited to the sapling size class and the density of large regeneration input to the model. Limiting the density of regeneration entering the simulation to ≤1,800 TPA (~2 stems/milacre plot) largely eliminated the prediction bias, yet only modestly improved model accuracy (R^2 0.398 vs. 0.341).

Introduction

Reasonably accurate stand dynamic models are required in to assess the long-term consequences of different forest management scenarios. The Forest Vegetation Simulator (FVS) (Dixon 2002), developed and supported by the USDA Forest Service, is currently being used to provide evidence to support the sustainability of management plans developed for national forests across the United States. By definition, the terms *forest management* and *long-term* encompass the process of forest renewal, and suggest that prediction of regeneration is a requisite part of any such system (*sensu* Stage 1973). However, attempts to address this critical component remain problematic for developers. Among the 20 regional variants of FVS, only five support full establishment models. Users of variants lacking this functionality are required to specify measured or anticipated regeneration (with the exception of sprouting hardwoods) to obtain realistic long-term simulations following harvesting disturbances.

In the Northeastern United States, where rainfall is abundant and distributed fairly evenly throughout the year, growing season water deficits and associated regeneration failures are uncommon (Seymour 1992). In fact, regeneration is often viewed as overly dense and pre-commercial thinning is a common practice among landowners concerned with timber production in the conifer dominated forests of central and northern Maine (Seymour and Gadzik 1985). Evidence from a long-term USDA Forest Service compartment study at Penobscot Experimental Forest (PEF) in central Maine supports the hypothesis that abundant reproduction may be obtained following a broad range of silvicultural treatments (Brissette 1996). Under these conditions the imputation of regeneration to

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forestry Scientist, Tall Timbers Research Station, Tallahassee, FL. At the time of this conference, Graduate Research Assistant, School of Forest Resources, University of Maine, Orono, ME; e-mail: dray@ttrs.org.

[2] Forester, USDA Forest Service, Forest Management Service Centre, Fort Collins, CO.

[3] Curtis Hutchins Professor of Silviculture, School of Forest Resources, University of Main, Orono, ME.

[4] Project Leader/Research Forester, USDA Forest Service, Northern Research Station, Durham, NH.

the partial establishment model in FVS-NE following harvest may be justifiable, allowing it to develop under the influence of the residual overstory. Another generalization that may be drawn from the research carried out at the PEF is that heavier cutting results in a relative shift in species composition from shade-tolerant conifers to less tolerant hardwoods (Sendak and others 2003), which may allow users that lack specific regeneration data to impute a more realistic regeneration response based on the level of overstory disturbance.

Partial-cutting practices that give rise to multiaged stand structures have come to characterize contemporary forest management across much of the Northeast U.S. (Department of Conservation, Maine Forest Service 2005). Thus, newly regenerated cohorts typically develop under the influence of partial overstory shade before recruiting into the main canopy layer, or succumbing to competition induced mortality. A number of important regulators of stand development in FVS are based on quantitative relationships established in even-aged stands. Specifically, size-density relationships are constrained by Reineke's (1933) stand density index (SDI), and site quality is described by site index in the eastern TWIGS based variants. Both approaches are of questionable validity in the context of multiaged stand development.

In light of the issues laid out above, and in order to build on some recent validation work conducted with FVS-NE (Ray and others 2006), we sought to determine if the model would provide reasonably accurate and unbiased estimates of the rates of sapling recruitment observed under the range of partial-cutting treatments at the PEF. Specifically, we compared model predicted rates of ingrowth to the 1-in dbh class with observations from nested fixed-area plots remeasured at 5-yr intervals over a 25–30 yr period. Observed self-thinning within these cohorts was compared with model-predicted competition induced mortality. Results obtained from the currently available production code of FVS-NE were compared with those from an unreleased beta version that incorporates some major structural changes.

Methods

The Dataset

Penobscot Experimental Forest (PEF) is the location of a long-term silvicultural compartment study established as a collaborative effort between the U.S. Forest Service and the forest products industry in the early 1950s. The 4,000-ac property is located in central Maine, U.S.A (44˚52'N, 68˚38'W) within the Acadian Forest Region. Species composition is characterized by a mixture of shade-tolerant northern conifers, most notably red spruce (*Picea rubens*), balsam fir (*Abies balsamea*) and eastern hemlock (*Tsuga canadensis*); and faster growing hardwoods, primarily red maple (*Acer rubrum*), paper birch (*Betula papyrifera*) and aspen (*Populus* spp.). Precipitation averages 42 inches annually and is evenly distributed throughout the growing season. Soils are of glacial till origin and tend to be somewhat poorly drained, particularly in the flat areas where the compartment study is located. We estimate the average site index for balsam fir at 55 ft at a breast height age of 50 yrs.

The growth and development of individual trees in response to six partial-cutting treatments (2 reps/treat) has been documented before and after harvests and at about 5-yr intervals between harvests since the mid-1970s. Species, diameter at breast height (dbh, 4.5-ft), and status (i.e. ingrowth/ live/ dead/ harvested) were noted at each inventory. Stems ≥4.5-in dbh have consistently been tracked on circular 5th ac plots, while smaller stems (0.5 to 4.5-in dbh) were historically measured on nested 20th ac plots; beginning in year 2000 individual stems between 0.5 and 2.5-in dbh have been tallied on a nested 50th ac plot due to perceived over sampling within that size class. Counts of regeneration by species within four height classes (0.5 to 1 ft, 1 to 2 ft, 2 to 4.5 ft, and >4.5 ft tall but <0.5 in dbh) have taken place since the mid-1960s on three milacre plots distributed around the perimeter of the 20th ac plot.

In the context of this study, we take a broad view of partial cutting as encompassing commercial timber harvests that remove sufficient stocking of overstory trees to facilitate the establishment/recruitment of a new/existing cohort. The six partial-cutting approaches documented at the PEF vary widely, both in terms of silvicultural intensity (commercial clearcutting vs. single-tree selection) and frequency of application (table 1). For a more detailed description of the PEF study system, the reader is referred to Sendak and others (2003).

Table 1—Summary description of the partial-cutting treatments at the Penobscot Experimental Forest (PEF). Note that the treatment codes correspond to the figures.

Treatment	Code	Description	Cutting cycle (yrs)	Harvests	Total plot count (2-reps)
Selection system	S05	Single-tree/small groups	5	10	33
	S10	Single-tree/small groups	10	5	35
	S20	Single-tree/small groups	20	3	37
Diameter-limit	FDL	Fixed diameter-limit	20[a]	3	33
	MDL	Modified diameter-limit	20	3	32
Unregulated harvest	URH	Commercial clearcut	30[a]	2	41
Natural area	NAT	Reference stand	n/a	n/a	20

[a]Historical cutting cycle lengths are not sustainable in the more exploitative treatments.

The Forest Vegetation Simulator (FVS)

All simulations were carried out with FVS production code (FVS-NE$_P$, revision date of 12.27.06) and an unreleased beta version (FVS-NE$_B$) of the Northeastern Variant. A description of FVS-NE$_P$ is provided by Bush (1995), while FVS-NE$_B$ has yet to be documented. A summary of the major alterations implemented between versions is outlined in table 2. We used the recently available database extension (Crookston and others 2005) to manage data input and output streams.

Because FVS-NE does not support a full establishment model, we input regeneration measured on the milacre plots at the PEF. Only stems within the largest size class (4.5 ft tall to 0.5-in dbh, hereafter referred to as large regeneration) at the beginning of the projection interval were entered into the simulation. Large regeneration was generally well represented across treatments and remeasurement periods, and was considered the most likely pool of recruits to the 1-in dbh size class (i.e. sapling ingrowth). Large regeneration was added to the TREELIST after determining species specific dbh estimates based on the height/diameter (h/d) equations used in FVS-NE$_B$. This involved first calculating the height of a 0.5-in dbh tree, determining the midpoint value between that height and the 4.5 ft lower cutoff for the large regeneration size-class, and then back calculating the corresponding dbh based on the initial equation. On average, large regeneration of conifer and broadleaf species was 6.5 and 5.4-ft tall and 0.33 and 0.23-in dbh, respectively. Site index for all runs was set at 55 ft for balsam fir based on observations from the even-aged treatment compartments located on similar sites at the PEF.

Short-term simulations corresponding to the nominal 5-yr inventory period at the PEF were used to evaluate FVS predictions of recruitment dynamics on the study plots. Approximately 1,200 plots per 5-yr interval combinations were simulated, or about five runs/plot. We believe these short interval projections provided the most objective means of evaluating model performance in the context of sapling recruitment. Specifically, this approach was taken to minimize the influence of a growth overestimation bias revealed previously in the overstory model (Ray and others 2006) that would otherwise suppress growth and/or increase mortality within the subordinate cohort. To further limit this possibility, the available diameter increment measurements were used to calibrate the large tree diameter growth model during each model run.

In summary, each simulation involved projecting the initial conditions (post-cut in cases where a harvest had taken place during the interval) on an individual research plot over a 5-yr period and generating an output TREELIST. Large regeneration present at the beginning of the run was assigned a number ≥500 so they could easily be located on the output (there were typically <200 trees on a given plot). Large regeneration that grew above the 0.5-in dbh threshold by the end of the simulation was considered recruitment to the sapling size class and converted to units of basal area (BA; ft^2/ac/5-yr), which were then compared with observed rates on the same study plot. To be fair to the model, we did not include plots that lacked large regeneration at the beginning of a given measurement interval. Because the partial-establishment model in FVS requires that the user specify the regeneration, plots containing no regeneration have no chance of yielding ingrowth. Imposing this criterion resulted in a substantial reduction to the available plot by interval combinations, by approximately 35 percent, to 729 across all treatments.

Table 2—Comparison of changes to model components implemented between the production (FVS-NEP) and beta (FVS-NEB) versions of the model used in this study. A more complete description for FVS-NEP is available in Burke (1995).

Component	Production code	Beta code
Height-Diameter Allometry	Based on Ek's equations.	Based on Curtis-Arney or Wykoff equations.
Small Tree Model (<1-in dbh)		
Height	Uses aspen hg from UT variant (hardwoods) and conifer equations from NI variant (softwoods).	See large tree height growth (potential with a modifier value).
Diameter	Uses Wykoff h/d relationship to get growth.	Use h/d above to get DG.
Large Tree Model (>1-in dbh)		
Height	HG based on Ek's equations as. modified by GMOD from large tree diameter growth	HG based on potential HG from site index curves as modified by relative height and GMODa from large tree DG.
Diameter	Uses TWIGS potential growth with GMOD modifier, lower limit of GMOD is set to 0.15.	Uses TWIGS potential growth with GMODa modifier, lower limit of GMOD is set to 0.5.
Mortality		
Background (<55 percent maxSDI)	1/10 of TWIGS mortality rate (survival model).	Utilizes background mortality rate equations from the SE Variant.
Density dependent (>55 percent maxSDI)	SDI-based, distributed based on the TWIGS survival function rates.	SDI-based, distributed based on species tolerance and relative height.

[a]GMOD in the beta version is influenced by competitors in 2 1-in classes below the dbh of the subject tree.

Performance Criteria and Analyses

To get a sense of the suitability of the nested-plot design at the PEF for carrying out this analysis, we compared the occurrence of ingrowth on the larger 20th and 50th-ac plots to the presence/absence of large regeneration on the milacre plots; the assumption being that large regeneration is a prerequisite to recruitment over this timeframe. Alternatively, the patchy spatial distribution of stems of different sizes resulting from repeated partial cuts may result in poor correspondence between estimates from the two plot types. We also predicted a pre-recruitment dbh for saplings at the PEF by subtracting the average 5-yr post-recruitment diameter increment rate from their initial dbh (when they first appeared as saplings). This information was then used to assess the proportion of observed sapling recruitment that may have been smaller than our large regeneration category, and to identify stems that may have been overlooked during an earlier inventory (i.e. estimated dbh 5-yr prior >0.5-in).

To assess the performance of FVS-NE, we compared observed and predicted rates of sapling recruitment to the 1-in dbh class (≥0.5-in dbh) in units of BA. The Northeast TWIGS model (Teck and Hilt 1990, 1991) that underlies FVS-NE is based on basal area growth equations, providing the most direct link between model predictions and the observed values. Goodness of fit was assessed using reduced major axis regression to accommodate both measurement and prediction errors (Sokal and Rohlf 1981). We assessed mortality dynamics among the newly recruited stems by comparing the observed and predicted rates in these same units of measure. Finally, correlation analysis was used to relate residuals (observed-predicted recruitment rates) with various attributes of the remeasurement plots (i.e. large regeneration density, composition (broadleaf vs. conifer), Dq, SDI, etc.).

The sampling unit(s) employed in this study, in particular the use of individual plots to measure recruitment rates over 5-yr intervals, raise some concerns about pseudoreplication in the context of significance testing, e.g. the average plot was represented by three remeasurement intervals. Thus, the alpha level used to assess the P-values associated with the correlation analysis should be evaluated with this in mind, that is, P-values close to 0.05 are probably not significant. Note that our intent here was simply to identify important trends in relation to model bias. Averaging across plots within a compartment was done to minimize the influence of zero values, and is consistent with the stand-level estimates generated from a typical inventory driven FVS run.

Results

Assessing the Sampling Design

Nested fixed-area plots are commonly used to sample vegetation of substantially different stature (e.g. FIA). Establishing the cutoffs between the size classes sampled on smaller versus larger plots involves striking a compromise between sampling effort and variability. At the PEF, three, and more recently four different nested fixed-area plots have been used. Because recruitment to the sapling size class involves growth across one of these plot size cutoffs (i.e. from the milacre to the larger 20^{th} or 50^{th} (since 2000) ac plot), we were mindful of avoiding spurious conclusions based on an incompatibility between our research questions and the sampling design.

Observations from the six partial-cut treatments and an untreated reference stand indicated that sapling recruitment took place on more than half of the plot/interval combinations (653 of 1,182). Large regeneration was present at the beginning of a measurement interval on 68 percent of the total plot/interval combinations; thus, ingrowth 'appeared' on 32 percent of all plots. Among the 729 plot/interval combinations for which large regeneration was present (the dataset used for simulations in order to assess model performance), approximately 60 percent registered some sapling recruitment during the subsequent 5-yr interval. By comparison, the model(s) predicted sapling recruitment on 35 percent (FVS-NE_P) and 68 percent (FVS-NE_B) of these plots. Assessed across all plots that had large regeneration present, and on which sapling recruitment was recorded, model predictions of the presence or absence of sapling recruitment were consistent with observations for 29 percent (FVS-NE_P) and 56 percent (FVS-NE_B) of plot/interval combinations.

A total of 8,729 (28 percent of total records) saplings identified as recruits on the PEF plots had multiple dbh measurements allowing estimation of pre-recruitment diameters. The resulting backward extrapolations suggested that approximately 10 percent of the observed recruitment may have been shorter than 4.5-ft tall (i.e. resulted in negative dbh estimates). Stems in this category were primarily associated with fast growing broadleaf species in the commercial clearcutting treatment (URH; table 1). These backward projections also indicated that up to 44 percent of saplings that appeared as new recruits may have been overlooked during the first measurement interval when they crossed the ≥0.5-in dbh threshold. Assuming some of these saplings estimated to have been ≥0.6-in dbh or ≥0.7-in dbh were actually below the 0.5-in dbh threshold, then only 29 percent or 18 percent are implied to have been overlooked, respectively. The average initial diameters of 0.31-in (broadleafs) and 0.23-in (conifers) back calculated for the newly recruited saplings was very similar to predictions from the allometric equations in FVS-NE_B (see "Methods").

Perhaps more important in the context of evaluating model performance, however, was confirmation that large regeneration was sufficiently abundant on the milacre plots, and thus included in the TREELIST to account for the observed rates of sapling recruitment. Correspondence between nested plots was considerably better based on this criterion, with 96 percent of all simulated plot/interval combinations having at least as many large regeneration stems as recruited saplings. The percentage of plots with adequate large conifer regeneration was also 96 percent, whereas 92 percent of plots with large broadleaf regeneration were similarly represented.

Characteristics of the Simulation Plots

There was considerable overlap in the range of conditions present on the study plots with large regeneration (fig. 1). The overall average stem density of 1,810±207 (TPA; ≥0.5-in dbh) was highest on the reference plots (NAT; 2,577±416 TPA) and lowest for the 5-yr selection treatment (S05; 996±65 TPA). Basal area was highest on the reference plots (NAT; 120.7±5.4 ft^2/ac) and lowest in the commercial clearcuts (URH; 81.8±4.0 ft^2/ac), compared to the average across treatments of 100.3±6.0 ft^2/ac. Stand density index (SDI) ranged from 187.9±6.4 in the 10-yr selection treatment (S10) up to 262.7±13.4 on the reference plots, averaging 219.4±10.4 across treatments. The plot level values for SDI seldom exceeded the 55 percent of SDI_{max} threshold of 293 (determined as a weighted average value for red spruce/balsam fir/eastern hemlock) used to trigger density dependent mortality in FVS (Dixon 2002). Northern conifers, including red spruce, balsam fir, eastern hemlock, northern white-cedar, and eastern white pine (*Pinus strobus*), accounted

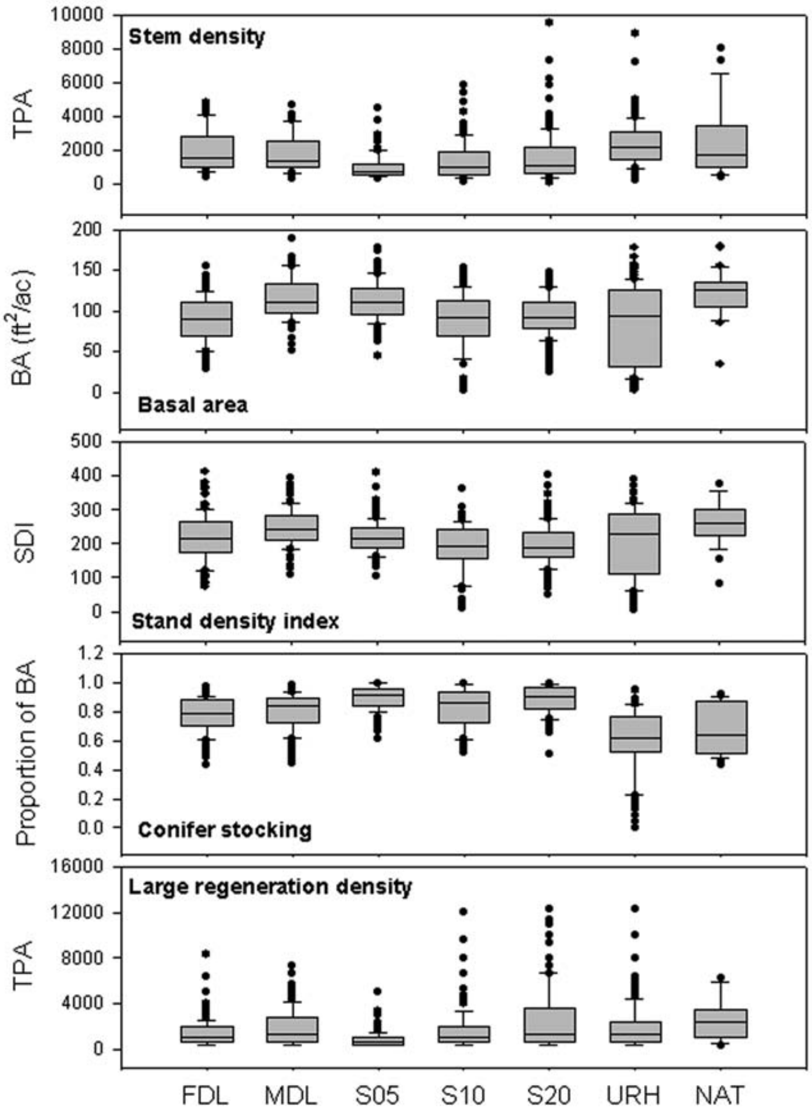


Figure 1—Summary of conditions on the partially cut and control plots at the PEF (treatment codes are in table 1). Variables presented in the top four panels are based on stems ≥0.5-in dbh. The large regeneration category (bottom panel) corresponds to stems between 4.5-ft tall and 0.5-in dbh.

for approximately 80 percent of the BA stocking on the research plots, being highest (90±1 percent) on the 5-yr selection and lowest on the commercially clearcut plots (60±2 percent). Large regeneration was abundant on the simulated plots, averaging 1,837±241 TPA across treatments, and ranging from a high of 2,639±345 TPA on the control plots down to 849±66 TPA in the 5-yr selection treatment. Note that large regeneration was only present on plots in one of the reference compartments. Although no harvesting has been carried out in the reference compartment since the study was established in the early 1950s, natural disturbance, i.e. the eastern spruce budworm outbreak extending from the mid 70s into the early 80s, differentially impacted the development of the reference compartment with large regeneration.

Calibration of Large Tree Diameter Growth

While a comprehensive evaluation of the performance of FVS-NE_P against FVS-NE_B is beyond the scope of this study, we used the large tree diameter growth calibration option on all runs and briefly summarize those results here (fig. 2). Fifteen species were sufficiently represented to provide calibrations (seven conifers, seven broadleafs and one misc. grouping), however, only two of the broadleafs (e.g. red maple and paper birch) were well represented. The summary READCORD factors were greater than 1.0 in most

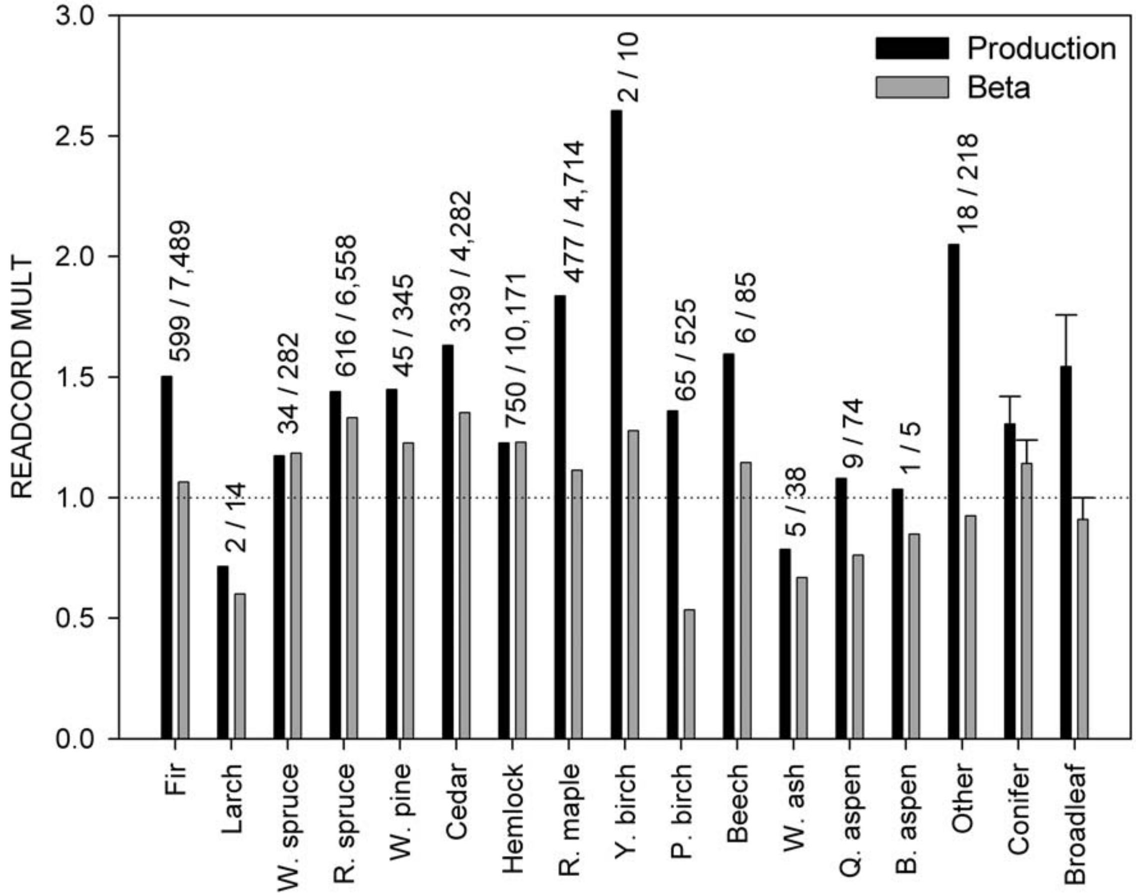


Figure 2--Comparison of summary calibration factors (READCORD MULT) obtained from the large tree diameter growth model running the production and beta coded versions of FVS-NE. The number of plot/interval combinations and individual tree records contributing information to the species level means, respectively, are presented above the bars. The mean and standard error are also presented for the conifer and broadleaf species groupings.

cases, suggesting that the uncalibrated model(s) tended to grow trees at the PEF too slowly. The multipliers were generally higher for the conifers than the broadleafs, and on average, estimates from FVS-NE_B were closer to the observed diameter growth rates than FVS-NE_P.

Sapling Recruitment and Mortality Rates

Recruitment to the sapling size class was systematically underestimated by FVS-NE_P and overestimated by FVS-NE_B relative to observations from the PEF (fig. 3). Fit statistics associated with the RMA regression models confirm that the correspondence between observed and predicted values was poor (table 3). Averaged across treatments and intervals, the observed sapling recruitment rate of 1.71±0.25 ft^2/ac/5-yr at the PEF was 96 percent above the FVS-NE_P prediction (0.87±0.15 ft^2/ac/5-yr) and 123 percent below the FVS-NE_B estimate (3.96±0.45 ft^2/ac/5-yr). The median values were less than the means in all cases, reflecting the right skewed distributions (PEF=1.12; FVS-NE_P=0.31; FVS-NE_B=3.51 ft^2/ac/5-yr). The ratio of medians taken between FVS-NE_B and PEF was more dramatic than for the means (3.1 vs. 2.3).

Mortality dynamics among the newly recruited saplings as portrayed by FVS-NE also differed substantially from observations. Specifically, whereas mortality claimed approximately 6 percent of sapling recruitment across all treatments at the PEF (0.13 ft^2/ac/5-yr), the proportions forecast by FVS-NE were markedly higher, amounting to 28 percent (FVS-NE_P=0.27 ft^2/ac/5-yr) and 23 percent (FVS-NE_B=0.98 ft^2/ac/5-yr) of total

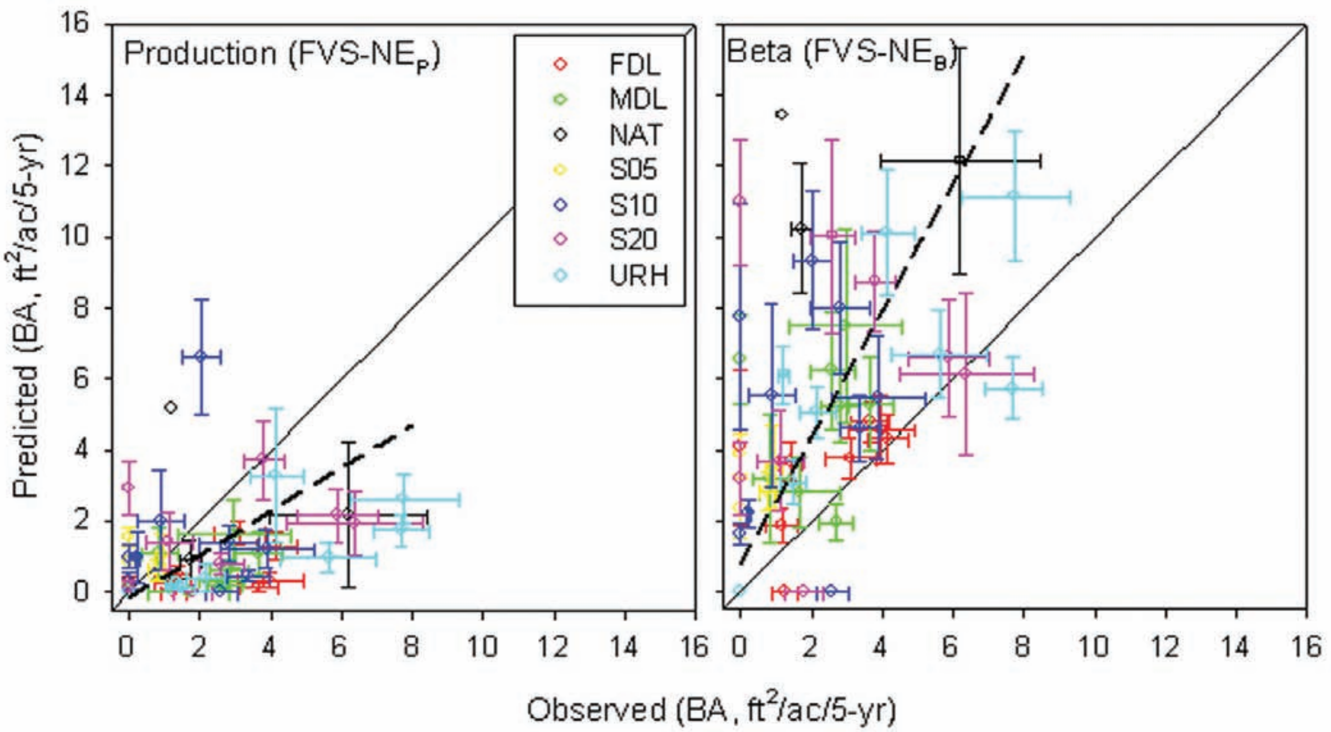


Figure 3—Comparison between observed (PEF) and predicted (FVS-NE$_P$; FVS-NE$_B$) rates of sapling recruitment (BA; ft^2/ac/5-yr). Data points means and standard errors for all compartment/interval combinations associated with the partial-cutting treatments. The dashed line corresponds to the reduced major axis regression (RMA).

Table 3—Model parameters and fit statistics from reduced major axis (RMA) regression relating observed and predicted recruitment rates for both versions of FVS-NE tested; standard errors of the estimates are in parenthesis.

Model	Intercept	Slope	R^2
Production code (FVS-NE$_P$)	-0.176 (0.184)	0.6126 (0.069)	0.180
Beta code (FVS-NE$_B$)	0.771 (0.480)	1.788 (0.180)	0.341

sapling recruitment (fig. 4). Compositionally, sapling recruitment was proportional to overstory make-up at the PEF, which averaged approximately 80 percent conifer BA (fig. 4). By contrast, mortality was considerably higher among broadleaf species at the PEF than predicted by FVS-NE (fig. 4). Thus, not only was the ratio of survival to mortality approximately four times higher according to the PEF dataset, but the ratio of conifer to broadleaf survival was considerably underestimated.

The predicted rates of sapling recruitment were seldom very accurate (table 3). For example, evaluated at the level of the individual plot/interval combination (n=729), only approximately 30 percent of predictions were within 10 percent of the observed value according to either FVS-NE$_P$ or FVS-NE$_B$. As the accuracy criteria were relaxed to ±30 percent and ±50 percent of the observed sapling recruitment rate, approximately 40 percent and 50 percent of the plot/interval combinations projected with FVS-NE$_B$, respectively, fell into those ranges; predictions from FVS-NE$_P$ were somewhat less accurate.

Diameter Distributions

A composite diameter distribution across all treatment/plot/interval combinations was derived for all three data sources (PEF, FVS-NE$_P$, FVS-NE$_B$). The FVS data came from the TREELIST output at the end of the simulation period, which allowed large

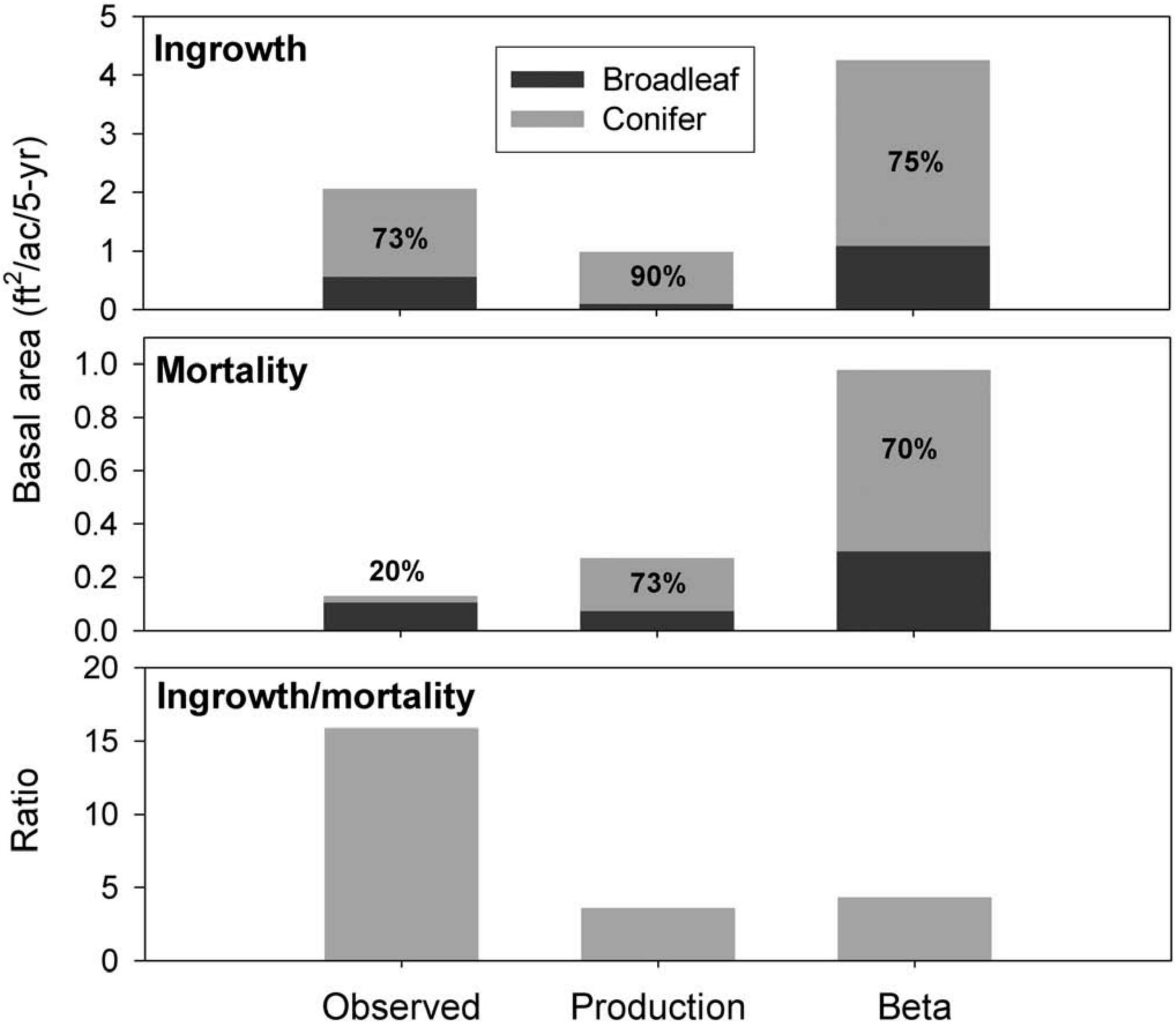


Figure 4—Average ingrowth and mortality rates, and the proportion of those totals accounted for by broadleaf and conifer (percentage shown) species at the PEF (observed) and according to the FVS-NE models (production and beta; top two panels). The bottom panel presents the ratio between ingrowth and mortality for each of the estimates.

regeneration (always <0.5-in dbh at the beginning of the interval) to persist below the recruitment threshold over the course of the 5-yr projection. Similar information was not available for the research plots at the PEF, because only counts of stems between 4.5-ft tall and 0.5-in dbh were taken.

There was a dramatic separation between the two FVS predicted diameter distributions, with peak frequencies occurring at 0.4-in dbh for FVS-NE_P and 0.9-in dbh for FVS-NE_B; the peak in the observed distribution was intermediate at 0.6-in dbh (fig. 5). Approximately half of the surviving large regeneration projected by FVS-NE_P remained below the threshold for sapling ingrowth established in this study. By contrast, all surviving stems projected with FVS-NE_B had grown up above 0.5-in dbh over the subsequent 5-yr intervals. The long tail on the diameter distribution for the PEF data likely reflects some measurement errors, where ingrowth trees were inadvertently overlooked during the inventory period when they initially crossed that size-class threshold, being added to the inventory during a subsequent remeasurement.

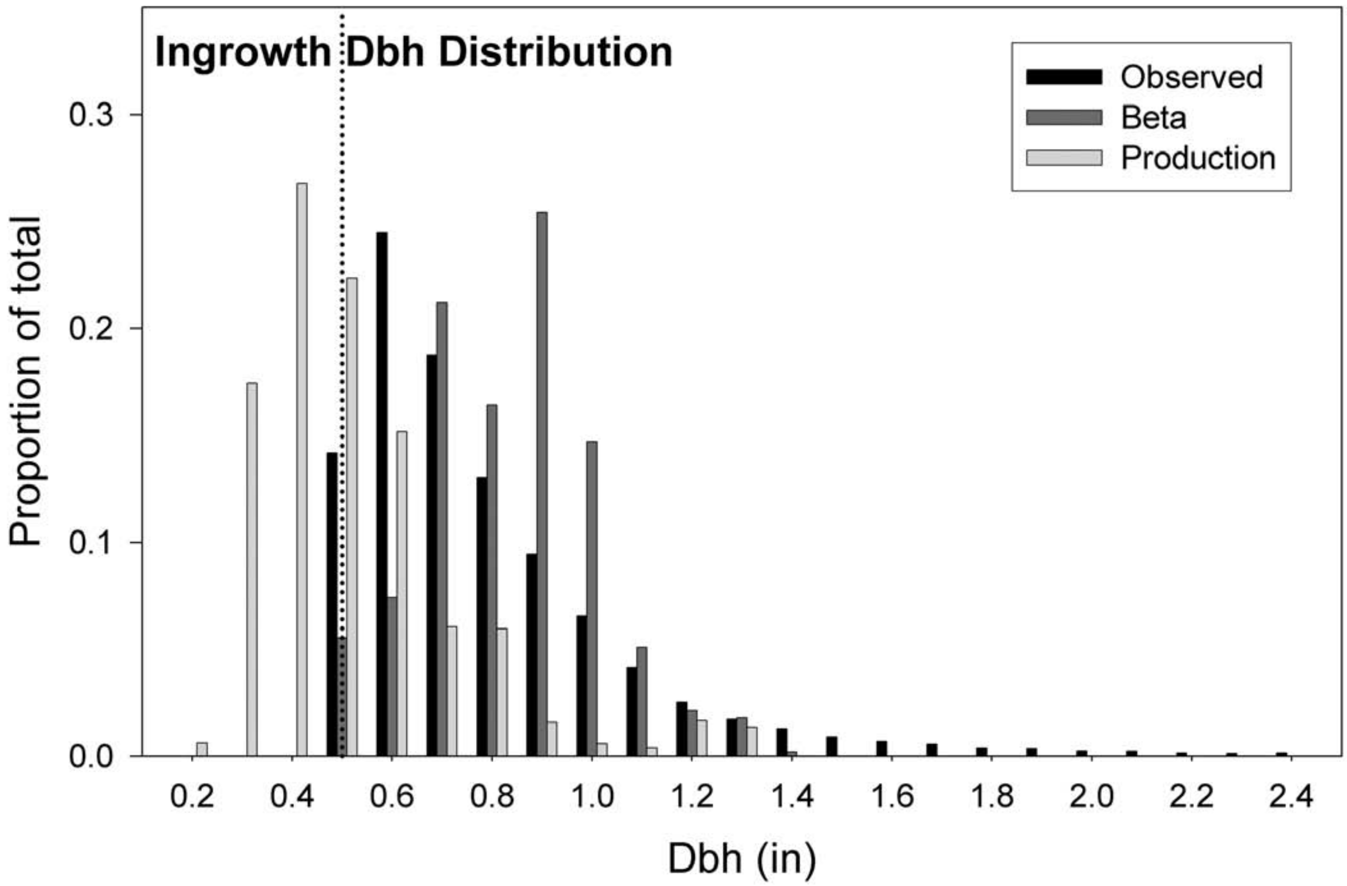


Figure 5—Composite diameter distribution comparing sapling recruitment in the partially cut treatments at the PEF with that forecast by the production (FVS-NEP) and beta (FVS-NEB) versions of the model. The vertical line at 0.5-in corresponds to the lower end of the 1-in dbh class threshold established for sapling recruitment.

Correlates of Model Bias

Prediction bias was strongly correlated with the absolute amount of recruitment to the sapling size class forecast by the models (fig. 6). The characteristic of individual plot/interval combinations most closely associated with the overall negative bias in FVS-NE_B (model overestimates) was the quantity of large regeneration present at the beginning of the simulation (R=–0.67; P<0.001); the residuals from FVS-NE_P were uncorrelated with this variable. According to the linear fit presented in the correlation matrix, plots with abundant large regeneration, perhaps in excess of 2,000 stems/ac, and certainly beyond 4,000 or 8,000 stems/ac, were associated with substantial overestimates of sapling recruitment on the order of 10 to 20 ft^2/ac/5-yr.

Attempts to uncover the factor(s) behind the positive residuals (model underestimates) associated with FVS-NE_P involved the consideration of more independent variables, none of which explained a very high proportion of the total error (fig. 6). Increasing the percentage of large regeneration accounted for by conifer species on a plot, the average plot diameter (Dq) based on trees above sapling size, and the cumulative number of harvests carried out in a compartment, were all modestly negatively related with prediction bias for FVS-NE_P; in other words, predictions were more similar to observation as the proportion of conifer regeneration increased, on plots with more large trees, and following multiple harvests.

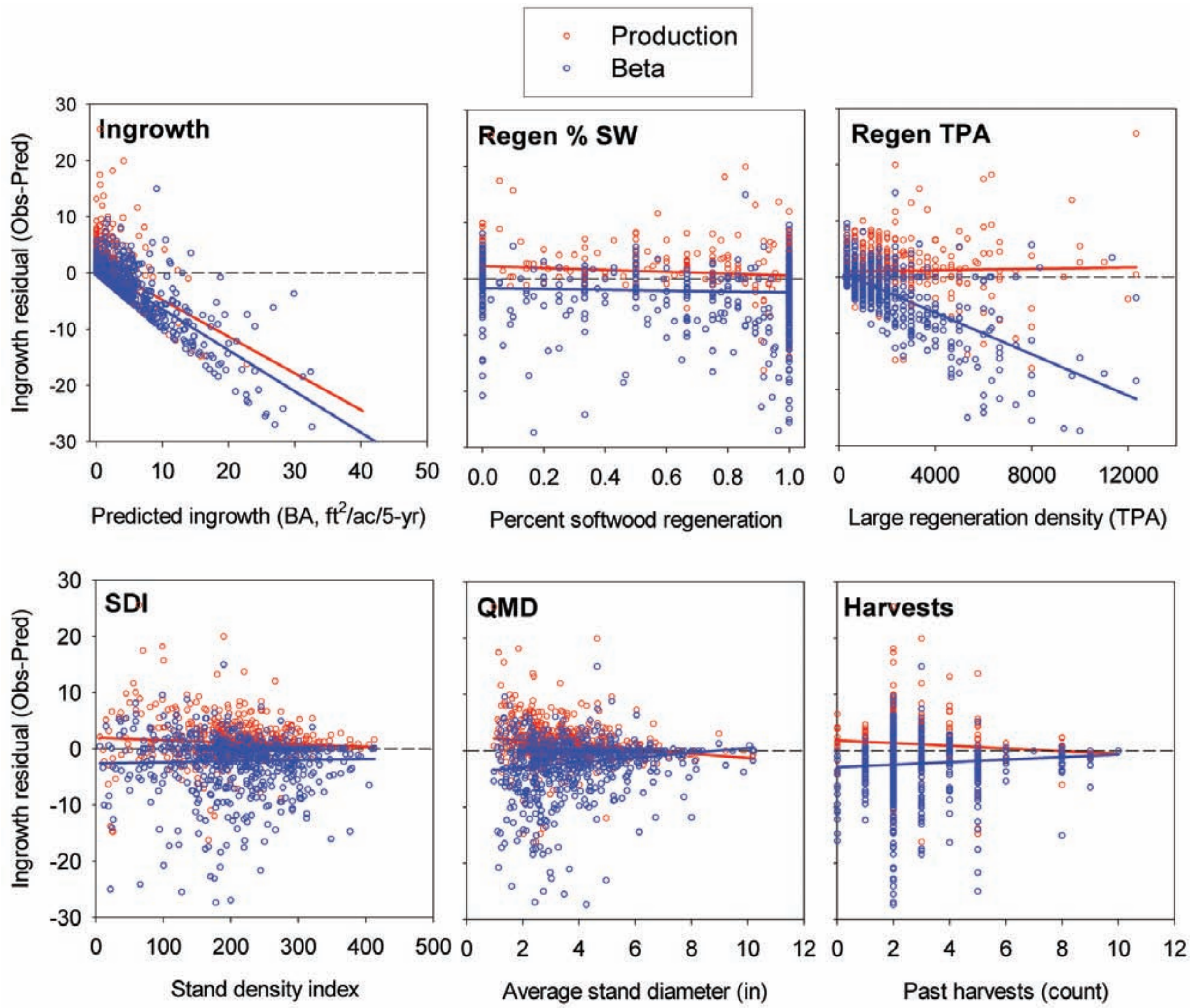


Figure 6—Scatterplot matrix relating ingrowth rate residuals (observed-predicted) with characteristics of the inventory plots at the PEF. A linear smoother was fit through the data clouds.

Discussion

The rate at which advance regeneration was recruited to the sapling size class on partially cut plots dominated by shade-tolerant northern conifers at the PEF was not closely approximated by FVS-NE running either the production ($FVS\text{-}NE_P$) or beta coded ($FVS\text{-}NE_B$) versions of the model. The tendency was for $FVS\text{-}NE_P$ to underestimate (–0.84 ft^2/ac/5-yr) and $FVS\text{-}NE_B$ to overestimate (+2.12 ft^2/ac/5-yr) the observed rates (1.71 ft^2/ac/5-yr). Although shortcomings associated with the nested-plot sampling design used at the PEF tempered expectations about the correspondence between observed and predicted values, we believe that the magnitude of the differences revealed here suggest other factors are involved. The fact that nearly all of the plot/interval combinations (96 percent) had sufficient large regeneration present at the beginning of a simulation to yield the observed ingrowth is offered in support of this contention. Given the plan to transition to the beta coded version of the FVS model ($FVS\text{-}NE_B$), the following discussion focuses on the behavior of that new parameterization.

Changes to the Model

Alterations to the model structure implemented between FVS-NE_P and FVS-NE_B (table 2), while difficult to view in isolation, can be expected to exert substantial influence on the prediction of small tree dynamics. Most notable among these was the shift away from a generic height growth model for conifers and broadleafs (Bush 1995) to regionally appropriate species-specific h/d allometry and growth functions. Also, the consideration of species shade-tolerance characteristics and relative height in the allocation of SDI based density dependent mortality. Even so, while these changes represent clear improvements from a theoretical standpoint, there appear to be some issues with their current behavior, at least in relation to predicting sapling recruitment dynamics in the Acadian Forest Region.

For example, we believe that the growth modifier (GMOD) used to adjust the SI based potential height growth in the 'small' tree model may be set too high in the new model. Specifically, raising the minimum value of GMOD from 0.15 in FVS-NE_P to 0.5 in FVS-NE_B is inconsistent with the growth dynamics of the shade-tolerant northern conifers that dominate reproduction following partial-cutting in the Acadian Forest Region (Brissette 1996). Evidence from a recent study of sapling growth rates under the influence of partial canopy cover suggests that the signature shade-tolerant species in this system (i.e. spruce/fir/hemlock) are able to persist while growing at rates well below 10 percent of their potential (Moores et al, in press).

Assessing changes to the mortality function was complicated by the fact that relatively few of the plot/interval combinations had SDIs exceeding 55 percent of RD, the level that triggers density dependent mortality in FVS. Consistent with expectations, mortality rates predicted by FVS-NE_B were twice as high for plots with RD>55 percent than below that threshold (1.25 vs. 0.58 ft^2/ac/5-yr), also providing an indication of the level of background mortality forecast by the new model. These estimates did not correspond very well, however, with mortality dynamics measured on the PEF plots, where average rates were only 1.3 times higher on the plots with RD<55 percent. The tendency for FVS-NE_B to overestimate mortality, and to kill-off a disproportionate number of shade-tolerant conifers relative to broadleafs on these multiaged plots (fig. 4), suggests addressing this component of model behavior may require more than simply increasing the threshold for density dependent mortality.

The Issue of Regeneration Density

The fact that overestimation of sapling recruitment by FVS-NE_B was strongly related to the amount of large regeneration at the beginning of the simulation (fig. 6) points to another facet of FVS-NE_B that is worthy of consideration: the possibility of developing rules for passing only a subset of the 'best,' i.e. most likely to survive, individuals tallied in the inventory to the model. According to the field procedures used by Ferguson and Carlson (1993, p. 4), after all the established regeneration were tallied by species, the two tallest trees, regardless of species, and the tallest individual of each species, were identified on their 300^{th} ac circular plots. At a minimum, the four tallest trees taller than a species specific establishment threshold were sought. In our study, regeneration was sampled on three milacre plots per overstory plot, corresponding to 90 percent of the ground area occupied by a 300^{th} ac plot. The regeneration sampling protocol at the PEF, that of counts by size class interval, disallowed the identification of best trees based on differences in relative height, because all stems of a given species within the large regeneration class had the same estimated height.

As noted previously, regeneration density in the Acadian Forest Region is typically quite high, owing both to favorable growing season water balance and high shade-tolerance of the component species. The average density of large regeneration on the plots entered into the simulations (i.e. those that contained large regeneration at the beginning of the projection interval) was 1,747 TPA, which corresponds to between five and six trees on a 300^{th} ac plot, and is in line with levels recommended for input to the model. Approximately 70 percent of the plots included in this analysis had large regeneration densities at or below this level. A follow-up analysis suggested that model bias could be largely eliminated by restricting the comparison between sapling recruitment rates predicted by FVS-NE_B and those observed at the PEF, to plots with no more than 1,800 TPA (6 stems on a 300^{th} ac plot, or ~2/milacre) of large regeneration (fig. 7). Model accuracy was improved somewhat (R^2 up from 0.341 to 0.398), according to the restricted model.

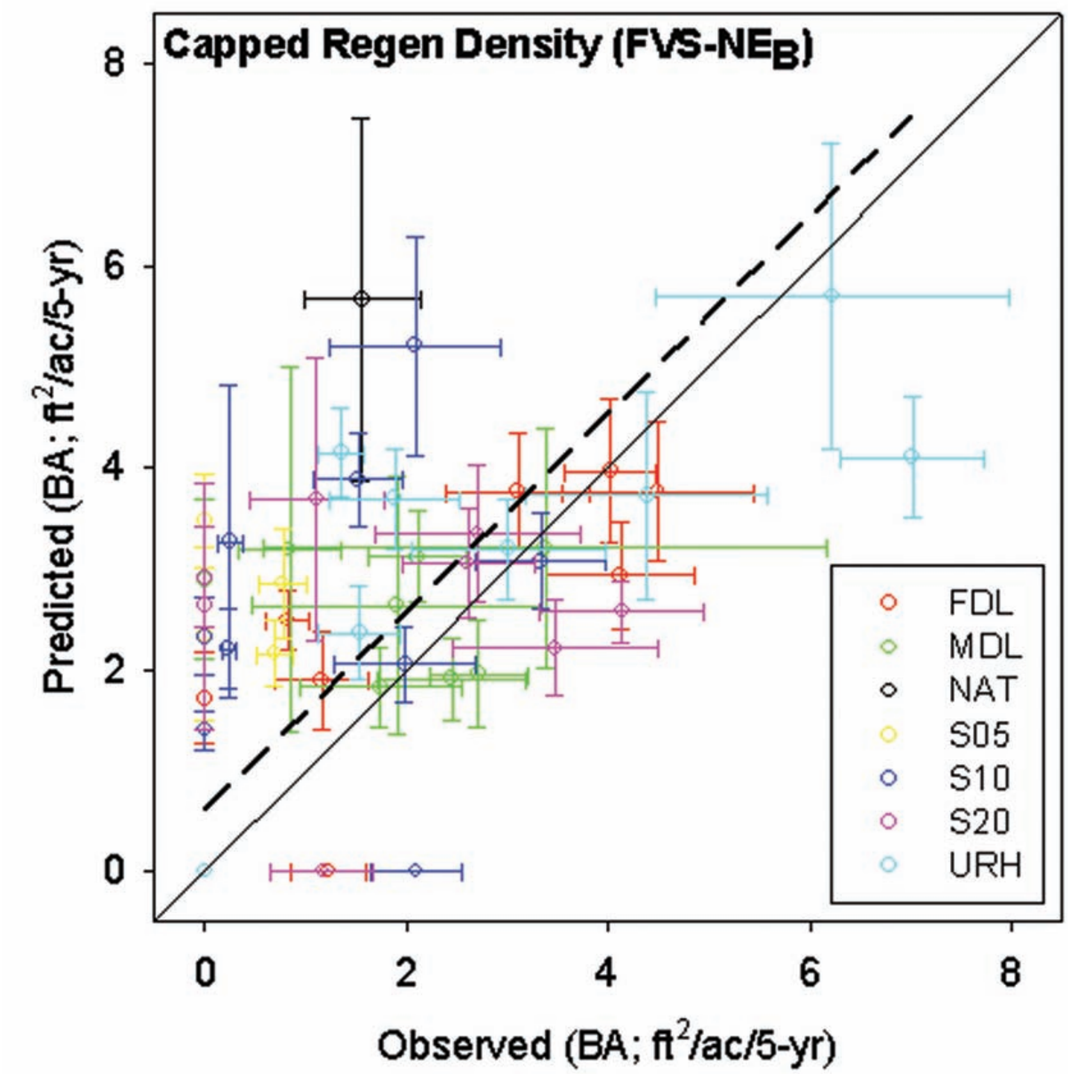


Figure 7—Relationship between observed (PEF) and predicted (FVS-NEB) sapling recruitment rates for plots with no more than 1,800 TPA of large regeneration. Data points means and standard errors from the compartment/interval combinations associated with the partial cutting treatments (codes are provided in Table 1). The dashed line corresponds to the reduced major axis regression (RMA); n=65, intercept=0.613±0.211, slope=0.998±0.098, R2 = 0.398.

A notable improvement was also achieved in terms of the overestimation of sapling mortality. Whereas mortality estimates averaged 8 times higher (0.67 vs. 0.08 ft^2/ac/5-yr) when the full range of large regeneration density was considered, this multiplier was reduced to 3 (0.18 vs. 0.06 ft^2/ac/5-yr) when the density of large regeneration was constrained.

The rationale presented for restricting the amount of regeneration projected by FVS to only the best trees, while a convenient simplifying assumption in terms of forecasting future timber yields, may be limiting in the context of other values. The linkage between early successional forest structure and viability of the threatened Canada Lynx (*Lynx canadensis*) population in Northern Maine (Hoving and others 2004) illustrates this point. Specifically, the snowshoe hair (*Lepus americanus*) populations on which the Lynx feeds appear to depend on the dense conifer cover provided by sapling sized spruce-fir stands (Fuller and others 2004). According to a recently established SDI relationship for the spruce-fir forest type in Maine (Ray and Seymour 2006), fully stocked (defined here as between 55 and 85 percent of SDImax) sapling stands with average diameters (Dq) between 1- and 4-in dbh can have from 16.9 times down to 1.2 times, respectively, the stem densities attainable if regeneration input to FVS were to be capped at 1,800 TPA. That such high stem densities are less likely to develop under partial canopy cover (30 percent of the samples in this study) suggests this issue may be more relevant in the context of even-aged stand development.

Towards a Full Establishment Model

The fact that FVS-NE lacks a full establishment model represents a limitation in terms of making long-term projections of multiaged stand dynamics. Partial-cuttings patterned on those at the PEF, carried out at 5- to 20-yr intervals could result in stands consisting of 5–20 cohorts over a 100-yr management cycle. Ignoring this dynamic will result in unrealistic projections over considerably shorter timeframes, depending on the partial-cutting scenario envisioned.

It is fortunate, from a forest renewal perspective at least, that regeneration tends to proliferate in response to a wide range of harvest initiated disturbances in the Acadian Forest Region (Seymour 1992, Brissette 1996). This allows users interested in simulating long-term partial-cutting scenarios to input regeneration into the model, based on information from inventory plots or even personal experience, with a fair degree of confidence that regeneration will fill growing space not occupied by the overstory. However, resolving the issue of species composition remains a daunting challenge. On this issue, some guidance is provided by the observation that less shade-tolerant hardwoods tend to increase in abundance with disturbance intensity in the Acadian Forest Region (Sendak and others 2003).

Alternatively, information about stand structure, species composition, and site quality (e.g. soil texture and drainage) obtainable from the FIA Database and other sources could be correlated with seedling/sapling populations on those plots and developed into an automated regeneration algorithm, following the methodology for the Prognosis based Variants of FVS that support full establishment models (Ferguson and Crookston 1991). We believe this approach represents the best way forward, and would be the most expedient means of generating objective estimates of forest renewal in the context of long-term partial-cutting scenarios within the existing FVS framework. In the meantime, the Regeneration Imputation Extractor, REPUTE (Vandendrieshe 2005)—a recently developed FVS Post-Processor that creates ‘regeneration’ addfiles based on the sapling component of an existing stand table, and available to all Regional Variants of FVS—provides an option that may be used where direct measurements or expert knowledge is lacking.

Summary and Recommendations

The accurate portrayal of regeneration and sapling recruitment dynamics presents a significant challenge to modeling stand development over the long-term, particularly where management practices give rise to multiaged stand structures. The current and soon to be released version(s) of FVS-NE exhibit some serious limitations in this regard, and users seeking reliable predictions of sapling recruitment rates in response to partial-cutting within the shade-tolerant conifer dominated portion of the Acadian Forest Region should be cognizant of them. The fact that no strong correlates of model bias were detected for the predictions obtained from FVS-NE_P, and perhaps more importantly that the parameterization of the small tree model is based on tenuous relationships (i.e. allometry and growth from western variants of FVS, table 2), questions the relevance of seeking improvements to that model. The overestimation of recruitment rates by FVS-NE_B, in contrast, was closely linked to regeneration density input to the model, and prediction bias could be eliminated by capping the amount of regeneration input to FVS-NE at ~1,800 TPA. Prediction accuracy was only modestly improved, however, and the regeneration density-constrained estimates still only explained approximately 40 percent of the total variation. Further, evidence from past work suggests that the elevation of the growth modifier function (GMOD) in FVS-NE_B from 0.15 to 0.5 is unrealistically high for the shade-tolerant conifers that dominate our study system. It follows that lowering GMOD to reflect observed sapling recruitment dynamics while maintaining the regeneration density cap is likely to introduce an underestimation bias. Given that the present regeneration density cap is too low to accommodate some important attributes of forest structure in this forest, calibration of both parameters may be required to improve model performance. It is also apparent that the overall mortality rates predicted by FVS-NE_B

are too high, and do not accurately reflect observed differences between shade-tolerant conifers and less tolerant broadleafs in this forest. Finally, we believe that the development of a full establishment model for FVS-NE, based on modifications to the existing framework for the Prognosis Model, would represent a significant step forward in our ability to forecast medium and long-term stand dynamics in response to contemporary forest management scenarios (i.e. partial-cuttings that result in multiaged stands) in the Northeast.

References

Brissette, J.C. 1996. Effects of intensity and frequency of harvesting on abundance, stocking and composition of natural regeneration in the Acadian Forest of eastern North America. Silva Fenn. 30(2-3):301-314.

Bush, R.R. 1995. Northeastern TWIGS Variant of the Forest Vegetation Simulator. http://www.fs.fed.us/fmsc/fvs/documents/variant_overviews.php

Crookston, Nicholas L.; Gammel, Dennis L; Rebain, Stephanie. 2005. Users Guide to the Database Extension of the Forest Vegetation Simulator Version 2.0. Moscow, ID. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station http://www.fs.fed.us/fmsc/fvs/documents/gtrs_db-fvs.php

Department of Conservation, Maine Forest Service. 2005. The 2005 biennial report on the State of the Forest and progress report on sustainability standards. Report to the Joint Standing Committee of the 122nd Legislature on Agriculture, Conservation and Forestry. Maine Department of Conservation: Augusta. 124 p.

Dixon, G.E. 2002. Essential FVS: A User's Guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U.S. Forest Service. Forest Management Service Center. 204 p. (Revised: January 2007).

Ferguson, Dennis E.; Carlson, Clinton E. 1993. Predicting regeneration establishment with the Prognosis Model. Res. Paper. INT-467. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 54 p.

Ferguson, Dennis E.; Crookston, Nicholas L. 1991. User's guide to version 2 of The Regeneration Establishment Model: Part of the Prognosis Model. Gen. Tech. Rep. INT-279. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 34 p.

Fuller, A.K.; Harrison, D.J.; Lachowski, H.J.. 2004. Stand-scale effects of partial harvesting and clearcutting on small mammals and forest structure. Forest Ecology and Management. 191:373-386.

Hoving, C.L.; Harrison, D.J.; Krohn, W.B.; Jakubas, W.J.; McCollough, M.A. 2004. Canada lynx habitat and forest succession in northern Maine, United States. Wildlife Biology. 10(4): 285-294.

Moores, A.R., Seymour, R.S.; Kenefic, L.S. In press. Relative height development of shade-tolerant Acadian conifer saplings in irregular multi-aged stands. Canadian Journal of Forest Research.

Ray, D.G., Seymour, R.S.; Keyser, C.E. 2006. A test of FVS-NE for simulating long-term growth dynamics following partial-cutting in the Acadian forest type. In: Larocque, C.G.; and others, comps. Proc. Eastern Canada U.S.A. Conference-Forest Science across the Borders; October 19–21, 2006; Leval University, Quebec, CA.

Reineke, L.H. 1933. Perfecting a stand density index for even-aged forests. J. Agric. Res. 46:627-638.

Seymour, R.S. 1992. The red spruce-balsam fir forest of Maine: Evolution of silvicultural practice in response to stand development patterns and disturbances. In: Kelty, M.J.; Larson, B.C.; Oliver, C.D., eds. The ecology and silviculture of mixed-species forests. Norwell, MA: Kluwer Publishers. 287 p.

Seymour, R.S.; Gadzik, C. J. 1985. A Nomogram for predicting precommercial thinning costs in overstocked spruce-fir stands. North. J. Applied For. 2 (June 1985):2-15.

Sendak, P.E.; Brissette, J.C.; Frank, R.M. 2003. Silviculture affects composition, growth, and yield in mixed northern conifers: 40-year results from the Penobscot Experimental Forest. Can. J. For. Res. 33:2116-2128.

Sokal, R.R.; Rohlf, F.J. 1981. Biometry. 2nd edition. Freeman, NY.

Stage, Albert R. 1973. Prognosis model for stand development Res. Pap. INT-137. Ogden, UT: U.S. Dept. of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Teck, Richard M.; Hilt, Donald E. 1990. Individual-tree Probability of Survival Model for the Northeastern United States. Res. Pap. NE-642. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 10 p.

Teck, Richard M.; Hilt, Donald E. 1991. Individual-Tree Diameter Growth Model for the Northeastern United States. Res. Pap. NE-649. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 11 p.

Vandendrieshe, Don. 2005. Advance FVS Topics for forest planning. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. Available at: http://www.fs.fed.us/fmsc/fvs/documents/gtrs_advance-topics.php. 152 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Model Development II

Building the ECON Extension: Functionality and Lessons Learned

Fred C. Martin[1]

Abstract—The functionality of the ECON extension to FVS is described with emphasis on the ability to dynamically interact with all elements of the FVS simulation process. Like other extensions, ECON is fully integrated within FVS. This integration allows: (1) analysis of multiple alternative tree-removal actions within a single simulation without altering "normal" stand development, (2) imposing financial effects dynamically in response to stand development and activities, (3) scheduling activities based on economic criteria with the Event Monitor, and (4) analyzing alternative rotation lengths within a single simulation. Outputs from ECON include investment decision indices (present net value, internal rate of return, benefit cost ratio, realizable rate of return, soil expectation value, value of forest, and value of trees) and harvested tree and log values. Designing, coding, and integrating the ECON extension into the FVS framework evoked new perspectives about the use and significance of FVS. The importance of FVS as a modeling environment within which multiple management issues can be simultaneously examined was recognized. The prominence of traditional model prediction precision was reassessed relative to the value of quantifying the marginal effects among stand developmental processes. Metrics from the FVS framework render a convergence of evidence for decision making that may be more valuable than prediction of absolute future conditions. The need for FVS to evolve as a framework, not just a growth model, was recognized, and a disciplined approach to extending FVS is proposed.

Introduction

The economic extension (ECON) (Martin 2008) to the Forest Vegetation Simulator (FVS) (Wykoff and others 1982) was developed to aid financial analysis of activities simulated with FVS. Two computer programs, CHEAPO (Medema and Hatch 1982) and CHEAPO II (Horn and others 1986) were developed in the 1980s to quantify economic impacts of timber harvests simulated with FVS. But, CHEAPO and CHEAPO II were "post-processors" designed to run after completion of an FVS simulation. Further, CHEAPO lacked interaction with the biological and management components available within FVS and its extensions during a simulation. For example, financial measures could not be used to "trigger" alternative actions during a simulation. This made economic analysis of silvicultural activities time-consuming and cumbersome by requiring multiple FVS simulations. Renner (2001) linked CHEAPO II with FVS demonstrating a proof-of-concept for an interactive approach (Renner and Martin 2002). But integration of the CHEAPO II code-base was problematical, prompting restructuring and re-writing, thus creating the ECON extension. Like other extensions, ECON interacts with multiple FVS components adding to the simulation framework created by FVS and its many extensions.

Extensions that are integrated into FVS allow simultaneous evaluation of multiple effects from alternative futures. For example (based on Renner 2001), assume two alternative prescriptions for a young mixed species stand: a "No Fuels Treatment" prescription consisting of thinning at 10, 30, 50, and 80 years and a "Fuel Treatment" prescription implementing the same thinning actions but with additional slash disposal. A wildfire is simulated in the stand at age 60 under both prescriptions. Outputs for each prescription over the simulated period include standing inventory (fig. 1) from the base FVS model (Wykoff and others 1982), surface fuels (fig. 2) from the Fire and Fuels Extension (FFE) (Reinhardt and Crookston 2003), and net present value (fig. 3) from the ECON Extension (Martin, in review). Examination of the figures reveals the following: standing timber volume is nearly identical between the prescriptions even after wildfire; surface fuels are reduced only temporarily following thinning; and present net value is substantially reduced for the Fuel Treatment prescription. Despite the added expenditure for slash disposal, the Fuel Treatment appeared to have little effect on reducing long-term surface fuel loading or protecting timber from wildfire. Based on metrics provided by FVS, ECON, and FFE managers might conclude that the added costs for slash disposal was both economically and biologically inefficient as a means of wildfire protection.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Forest Biometrician, Washington Department of Natural Resources, Olympia, WA; e-mail: FRED.MARTIN@dnr.wa.gov.

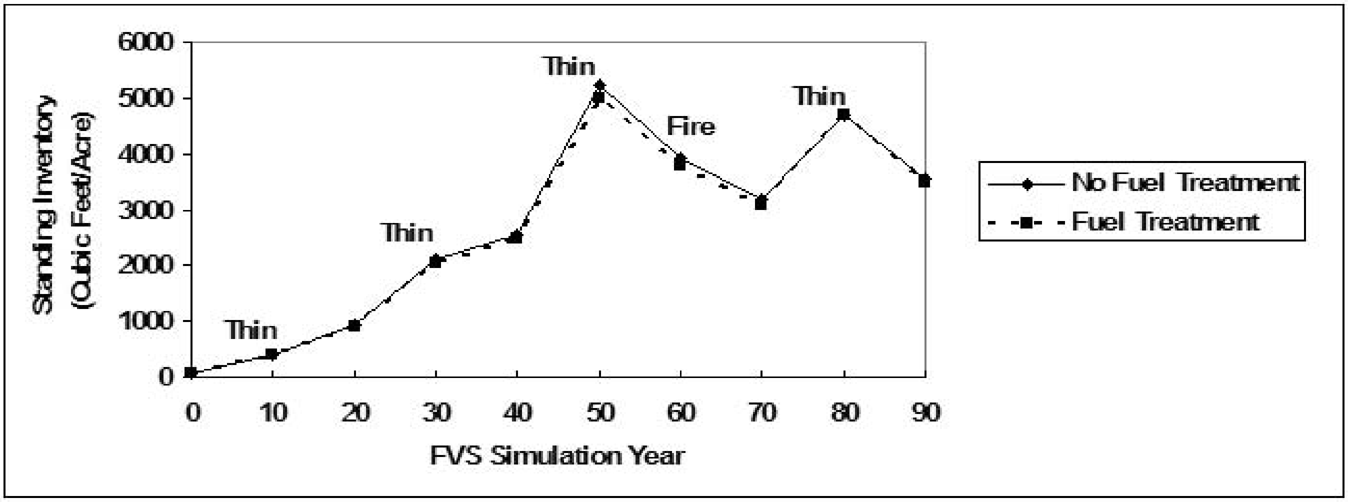


Figure 1—Standing inventory for Fuel Treatment and No Fuel Treatment alternative prescriptions.

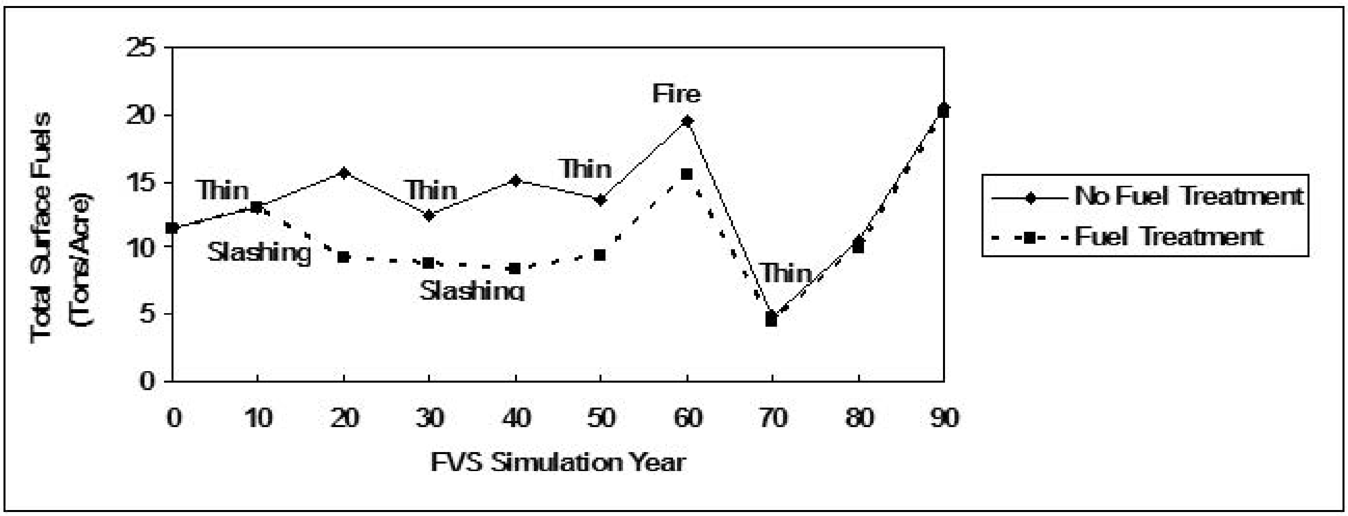


Figure 2—Total surface fuels for Fuel Treatment and No Fuel Treatment alternative prescriptions.

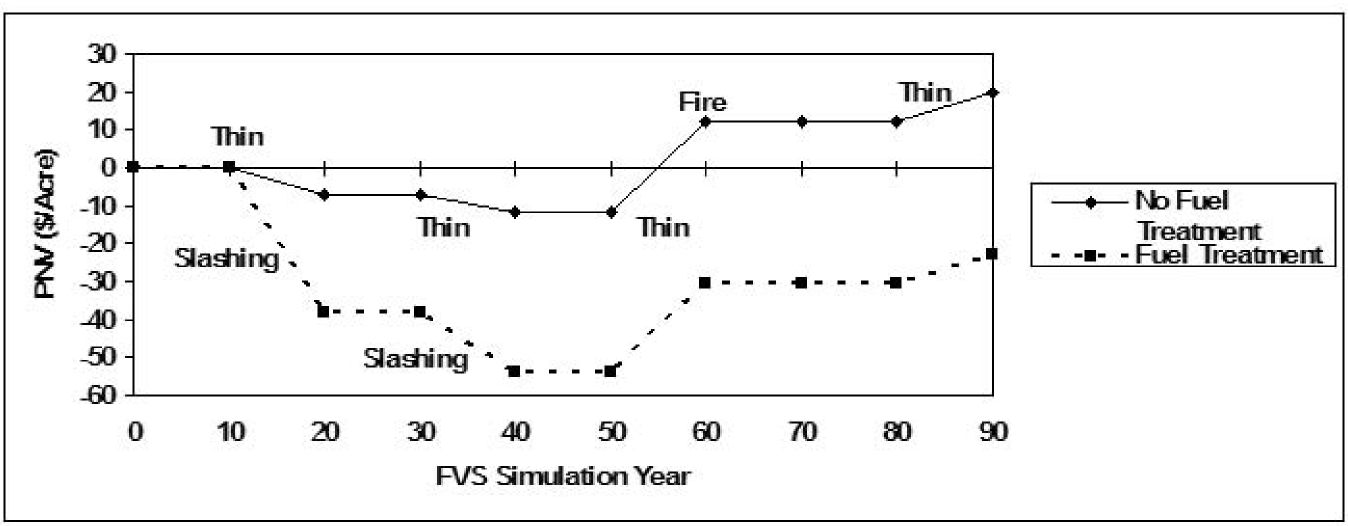


Figure 3—PNV for Fuel Treatment and No Fuel Treatment alternative prescriptions.

This paper describes: (1) the functionality of the ECON extension, (2) the economic questions that motivated the design of ECON, and (3) lessons learned during the development and integration of ECON into FVS. Familiarity with both FVS and economic analysis is assumed. Operational details about ECON can be found in the ECON User's Manual (Martin 2008).

Functionality

Operation of FVS is managed using keywords that users prepare to communicate input parameters and to control model actions. In the case of ECON, users enter keywords that specify the costs and revenues that govern the financial valuation of activities simulated by FVS. Keywords permit specifying the following costs: (1) costs that occur annually regardless of stand actions, such as land rents, road maintenance, taxes, etc.; (2) costs resulting from regeneration and site preparation events simulated by FVS regeneration sub-models; and (3) pre-commercial and commercial thinning and harvest costs resulting from FVS thinning keywords. Additionally, a special cost keyword can expense any activity that can be accessed using the Event Monitor (Crookston 1990), such as burning, fertilizing, or pruning events. Similarly, keywords permit specifying: (1) revenues that occur annually regardless of stand actions, such as recreation leases, non-timber vegetation revenues (e.g., mushrooms), etc., and (2) revenues from commercial timber harvests. Multiple revenue keywords can be used to specify different dollar values for individual species, different tree and log diameter classes, and different units of measure (number of harvested trees, harvested board feet, or harvested cubic feet). Another keyword allows specifying criteria for determining pre-commercial from commercial harvests based on harvested tree size and harvested volume. Finally, a special revenue keyword can accrue revenue from any activity assessed using the Event Monitor, such as valuing carbon sequestration or bough production.

Inflation and other financial conditions can alter costs and prices over time. To accommodate such events, costs and prices can be appreciated or depreciated. These changes, known as value rate changes, can be specified individually on all cost and revenue keywords. Multiple value rate changes can be entered for each keyword allowing rate changes to be altered over time and applied for specific periods. Value rate changes can also be used to depreciate a cost or price to zero, thus terminating a cost or revenue. For example, an annual weed control charge required for the first ten years of stand establishment could be terminated at the end of ten-years using value rate keyword records.

ECON can be started at any time, even within an FVS cycle, which permits ECON to start after growing an inventory to the current year or after some initial stand treatment. The investment period over which costs and revenues are evaluated can also be re-initialized during a simulation, permitting analysis of multiple management regimes within a single simulation. Costs and revenues are accumulated and discounted annually within each investment period, and the following economic measures can be computed and reported at the end of each FVS cycle:

- Present net value (PNV)
- Internal rate of return (IRR)
- Benefit cost (BC) ratio
- Realizable rate of return (RRR)
- Soil expectation value (SEV)
- Value of forest
- Value of trees

PNV, IRR, BC ratio, RRR, and SEV are defined and computed as per standard economic and management practices (Davis and Johnson 1987). "Value of forest" is the term used to describe the PNV of cash flows from managing the existing stand (trees) plus the SEV, where SEV represents the inherent value of the land to produce perpetual timber crops under a specified management regime. SEV is discounted for the delay period until the existing stand is harvested and the future regime represented by SEV can be initiated. "Value of trees," also known as "reprod value," is the PNV of cash flows from harvested trees separate from the inherent value of the land. Relevance of "value of forest" and "value of trees" metrics is discussed below. These computed decision indices along with undiscounted and discounted costs and revenues are passed from ECON to the Event Monitor and are available for use in scheduling activities or defining new variables.

The integration of ECON with FVS permits additional functionality beyond that possible with the CHEAPO post-processers, including: (1) the ability to evaluate multiple harvest scenarios within a single simulation, (2) the ability to schedule management activities based on economic measures with the Event Monitor (Crookston 1990), and (3) the ability to dynamically initiate and value future management prescriptions. Central to ECON design is that only simulated activities are valued, i.e., standing inventory is not valued, as was the case with the CHEAPO post-processors. Harvest costs and revenues are applied only to harvests resulting from execution of FVS thinning keywords.

To allow modeling of multiple alternative harvest scenarios in a single FVS simulation, the "PRETEND" keyword was developed. This ECON keyword is used in conjunction with FVS thinning keywords. When active, the PRETEND keyword allows harvests to be simulated but prevents removal of the harvested trees from the FVS internal tree list upon execution of a thinning keyword. Normal (i.e., without harvest) stand development in the current or future cycles is not affected because the internal tree list is not changed. This allows the modeler to analyze any number of different hypothetical, or pretend, harvests completely independent of and unaffected by previous "pretend" harvests. Each "pretend" harvest is restricted to the FVS cycle in which it occurs and hence has no effect on either past or future actual (harvests that remove trees from the FVS internal tree list) or "pretend" harvests. Any number of PRETEND keywords can be submitted by the user, permitting activation and inactivation of the PRETEND functionality at will during a simulation. In this way, both actual and "pretend" harvests can each occur in different cycles. When the PRETEND keyword is active ECON metrics (PNV, etc.) computed from the harvest costs and revenues are confined to that cycle, allowing the user to examine mutually exclusive harvest alternatives at different time periods. Hence, multiple hypothetical harvest scenarios can be analyzed in a single simulation without changing the normal stand development.

ECON produces two types of output at each FVS cycle - summary measures and harvest values. The Economic Analysis Summary Table (fig. 4) displays the undiscounted and discounted costs and revenues, and computed decision indices (PNV, etc.) over the investment period. When the PRETEND keyword is active, costs and revenues from a "pretend" harvest are reported only in the respective cycle, they are not accumulated across cycles. Costs and revenues not associated with "pretend" harvests accrue across all cycles of the investment period. The decision indices computed depend on the type of analysis being conducted, i.e., is SEV being computed or is SEV input by the user. A Harvest Volume and Gross Value Table can be generated (fig. 5) whenever a harvest occurs during a cycle. This figure summarizes harvest volumes and revenues by species and by tree diameter at breast height (dbh) and log small-end diameter inside bark (dib). Reported harvest characteristics include trees per acre, tons per acre, cubic, and board foot volumes, along with the dollar value for each characteristic. Reported characteristics and values are controlled by harvest revenue keywords that permit pricing by species, size classes, and units of measure. Harvest characteristics and values are produced for both actual and "pretend" harvests.

Motivating Questions

Five economic questions motivated the development of ECON. Addressing these questions required functionality not in the CHEAPO systems, such as the ability to analyze multiple harvest possibilities within the same simulation or to dynamically initiate silvicultural actions using the Event Monitor. Although ECON can be used to address many potential economic issues, these five financial questions guided its development:

1. When is the economically efficient time to harvest an existing stand?
2. What is the value of forestland for timber production?
3. Given an existing stand and its forestland value, when is the economically efficient harvest time?
4. Given harvest deferral of an existing stand until a target condition is achieved, what is the forestland value for timber production that maintains the target condition?
5. Given an existing immature stand having a known land value, what is the value of the immature trees ("reprod" value)?

These questions are elaborated below with the intent of emphasizing the dynamic nature of the procedures used in their analysis. Worked examples of the questions, including

A)

FVS/ECON EXTENSION VERSION 1.0

STAND ID: Compute_SEV MANAGEMENT CODE: NONE - Dynamically initiate and value a proposed prescription

ECONOMIC ANALYSIS SUMMARY TABLE (DISCOUNT RATE: 4.0%)

YEAR	INVEST-MENT PERIOD	PRETEND MODE IS ACTIVE	UNDISCNTED VALUES COSTS	UNDISCNTED VALUES REVENUES	PRESENT VALUES COSTS	PRESENT VALUES REVENUES	PNV	INTERNAL RATE OF RETURN %	B/C RATIO	REALIZABLE RATE OF RETURN %	SEV	VALUE OF FOREST	VALUE OF TREES
2004	10	NO	0	0	0	0	0						
2014	20	NO	0	0	0	0	0						
2024	30	NO	0	0	0	0	0						
2034	31	NO	1062	6361	315	1886	1571	> 50.0	5.99	10.2			
2035	9	NO	50	0	48	0	-48		0.00		-162		
2044	19	YES	60	0	48	0	-48		0.00		-92		
2054	29	YES	50	0	48	0	-48		0.00		-71		
2064	39	YES	50	0	48	0	-48		0.00		-61		
2074	49	YES	50	0	48	0	-48		0.00		-56		
2084	59	YES	684	1622	137	228	91	6.3	1.66	4.9	101		
2094	69	YES	1110	3337	149	317	168	6.7	2.13	5.1	180		

B)

FVS/ECON EXTENSION VERSION 1.0

STAND ID: Evaluate_SEV MANAGEMENT CODE: NONE - Economically efficient time to implement a future prescription

ECONOMIC ANALYSIS SUMMARY TABLE (DISCOUNT RATE: 4.0%, FOREST/TREE VALUES BASED ON USER-SUPPLLIED SEV: $154)

YEAR	INVEST-MENT PERIOD	PRETEND MODE IS ACTIVE	UNDISCNTED VALUES COSTS	UNDISCNTED VALUES REVENUES	PRESENT VALUES COSTS	PRESENT VALUES REVENUES	PNV	INTERNAL RATE OF RETURN %	B/C RATIO	REALIZABLE RATE OF RETURN %	SEV	VALUE OF FOREST	VALUE OF TREES
2004	10	YES	1181	1407	1131	1352	221	> 50.0	1.20	5.9		391	237
2014	20	YES	1454	1828	946	1187	241	46.6	1.25	5.2		356	202
2024	30	YES	1620	2328	723	1022	298	21.2	1.41	5.2		375	221
2034	40	YES	1753	3082	543	914	370	14.8	1.68	5.4		422	268
2044	50	YES	1801	3868	395	775	380	11.4	1.96	5.4		415	261

Figure 4—Economic Analysis Summary Tables from two different simulations. A) In this simulation SEV was computed over time for a future stand after the existing stand was harvested in year 2034. The most economical efficient future prescription is achieved with a 69 year rotation period when SEV equals $180. B) In this simulation the preferred harvest time for an existing stand was assessed assuming a known land value (shown by "USER-SUPPLIED SEV: $154"). The most economically efficient harvest time is year 2034 when the "value of forest" is greatest ($422), ten years earlier than maximum PNV.

HARVEST VOLUME AND GROSS VALUE TABLE

YEAR = 2034 - PRETEND HARVEST: NO

SPECIES	SMALL-END DIB MIN	SMALL-END DIB MAX	TREE DBH MIN	TREE DBH MAX	TPA REMOVED	TPA VALUE $	TONS/ ACRE	CU FT REMOVED	CU FT VALUE $	BD FT REMOVED	BD FT VALUE $	TOTAL VALUE $
DF			6.0	10.0	14	0						0
DF			10.0	20.0	65	0						0
DF			20.0	999.9	10	0						0
DF	4.0	10.0								5203	780	780
DF	10.0	16.0								14497	4349	4349
DF	16.0	18.0								1055	369	369
DF	18.0	20.0								115	46	46
DF	0.0	999.9						3783	0			0
WH			0.0	999.9	10	0						0
WH	6.0	10.0								407	20	20
WH	10.0	20.0								5889	589	589
WH	20.0	999.9								795	199	199
WH	6.0	10.0						111	0			0
WH	10.0	20.0						925	0			0
WH	20.0	999.9						104	0			0
Totals					99	0		4923	0	27960	6353	6353

Figure 5—Example of the Harvest Volume and Gross Value Table for a single FVS cycle. Note that the harvested Douglas-fir (DF) was grouped by both tree dbh and log dib, and that harvested western hemlock (WH) was grouped by different log dibs for cubic foot than for board foot volume. The grouping is controlled via keywords.

keyword files and economic output tables, can be found in the ECON User's Manual (Martin, in review).

Economically Efficient Harvest Time

The first motivating question, determining the economically efficient time for harvest, requires examination of alternative harvest schedules. Harvests can be scheduled in each FVS cycle with the PRETEND keyword. Using PRETEND, each FVS cycle represents an independent and mutually exclusive alternative unaffected by harvests from previous cycles. Examination of the economic decision indices (PNV, IRR, etc.) computed for each cycle can then be used to choose among the alternative harvests. Further, the prescribed harvests need not be simply a traditional final harvest each cycle. For example, if the silvicultural objective is to maintain some level of continuous tree cover in the stand, then the harvest prescription might be changed each cycle to retain a different residual density or tree size. In this way non-economic stand objectives can also be evaluated for their financial impacts.

Value of Forestland for Timber Production

The second question, identifying the value of forestland for timber production, requires that we examine the SEV for alternative perpetually repeating stand treatments. Typically bare ground is the starting point for this analysis, and the stand is regenerated, grown forward in time, and thinned or otherwise treated until it becomes merchantable for final harvest. Upon reaching merchantability, a series of "pretend" harvests are examined for their SEV at different points in time. Each simulated "pretend" cycle represents a different mutually exclusive management regime, e.g., the stand can be managed as a repeating series of 80-year cutting-cycle stands or a repeating series of 90-year cutting-cycles, but not both. The SEV at each cycle is based on the costs and revenues from activities to establish the merchantable stand plus the costs and revenues from "pretend" harvests at each cycle. When the PRETEND keyword is active, costs and revenues from harvests are not accumulated between cycles; they are valued only in their respective cycles. Hence, the SEV at each cycle shows the present value of the land parcel to produce like-managed stands in perpetuity, unaffected by the harvests from previous cycles.

Economically Efficient Stand Management

The third question is a combination of questions one and two, i.e., assess the harvest date of an existing stand while considering the "opportunity cost" of delaying initiation of a future management regime. "Value of forest" is the metric used to identify the economically efficient time to convert the existing stand to the desired future repeating management regime. It provides a "normalized" measure for evaluating mutually exclusive alternatives of different length and size (Davis and Johnson 1987, pp. 317-320). The process for addressing this question is similar to the process described for question one, but the SEV of the land parcel is included in the analysis. Alternative "pretend" harvest prescriptions for the existing stand are conducted each cycle and the "value of forest" is examined to determine the economically efficient harvest period. The "value of forest" takes into account the delay until the future regime represented by SEV can be implemented, i.e., the opportunity cost. Calculation of "value of forest" is "normalized" over time by discounting the SEV until the time that the future regime is implemented and adding it to the PNV from the existing stand at each "pretend" cycle. The above process can also be applied to issues that arise with uneven-aged management. Bullard and Straka (1998) discuss the question of evaluating the forest value of a perpetual uneven-aged management prescription that is "off cycle." That is, the SEV of the perpetual cutting cycle is known, but the current scheduled entry time is in the middle of a cutting cycle. Hence SEV needs to be "normalized" as provided by the "value of forest" metric.

Forestland Value for Timber Production that Maintains the Target Condition

The fourth question is to determine when a target condition is achieved in an existing stand and then to select the most economically efficient future management regime that will perpetually re-create the desired target condition. This question requires dynamic evaluation of both the existing stand and the future management treatments. For example, assume an existing "wild" stand is grown until a specified number of large trees have developed, whereupon it is harvested but large legacy trees are reserved. Upon harvest a new "managed" stand is regenerated and examined over time to identify the most economically efficient rotation age that will again produce the desired legacy trees. The process to address this question starts with use of the Event Monitor to track development of the existing stand until the target number of large trees develops and to trigger a harvest and regeneration initiating the new "managed" stand. The Event Monitor also triggers activation of ECON, initiating a new investment period for computing and discounting economic indices. The managed stand is monitored by the Event Monitor until it has developed sufficiently to re-create the desired legacy features. From that point in time "pretend" harvests, each retaining the desired legacy trees, are simulated forward over multiple cycles. Each "pretend" cycle represents a different mutually exclusive alternative which achieves the desired condition but with a different harvest or rotation age. The most economically efficient regime can then be identified based on the highest SEV. The Event Monitor permits analysis of multiple stand decisions within a single FVS simulation by dynamically scheduling management activities and re-initializing the ECON investment period. Evaluation of other future management prescriptions based on some unknown, but computable target condition, would be similar to that used in this instance.

Value of the Immature Trees

The last question is the value of existing trees, separate from the land's potential for timber production, i.e., the "reprod" value of the trees. Stands that are stocked but have yet to attain merchantable size may have value beyond that of their land value, or SEV, because they are closer to harvest age. The value of the immature trees is dependent on the stand's planned harvest date and the delay in implementing the future management prescription, denoted by the SEV. This question is addressed in a similar manner to question three, in that a SEV value for the stand is input and "pretend" harvests are simulated each cycle. Each "pretend" cycle then represents a different alternative harvest age for the stand. "Value of trees" at each cycle is the present value of the trees separate from the land assuming the stand is harvested in the given cycle. The result of such an analysis can be used to estimate the market value of existing trees when assessing land purchase or tree damage (e.g., by trespass, wind, or fire).

Lessons Learned

Building the ECON extension made evident that FVS had evolved significantly from its beginnings as an individual tree growth model (Stage 1973). A paradigm shift has occurred among both users and developers; FVS is not just for projecting tree growth but provides a framework for simulating multiple elements of the forest environment. This framework permits users to simulate diverse forest community processes, not just tree growth, and provides descriptive interpretations of the resulting alternative futures. Three insights about FVS emerged from the construction, integration, and testing of ECON:

1. The modeling framework is as important as individual tree growth prediction.
2. Relative comparisons may be more germane than absolute predictions.
3. The FVS code-base needs to be modernized to facilitate continued evolution.

The FVS framework includes extensions for modeling regeneration processes (Ferguson and Crookston 1991), insect and disease incidence (Crookston and others1990; Frankel 1998; Monserud and Crookston 1982), understory vegetation dynamics (Moeur 1985), fuel dynamics and potential fire behavior (Reinhardt and Crookston 2003), and landscape interactions (Crookston and Stage 1991). These extensions impart unique value to the FVS system by allowing examination of a wide range of biological processes in relation to silvicultural activities and providing multiple descriptive measures for evaluating their implications. The ECON extension is the newest addition to this suite of tools and adds descriptive measures for assessing economic effects. The example in the Introduction (figs. 1–3) illustrated this multi-descriptive capability, wherein ECON and the FFE extensions combine to provide metrics for evaluating environmental and economic effects of stand development that may be peripheral to timber production.

In the past, growth models were principally viewed as predictors of future harvest volume; volume prediction is still emphasized when the overriding objective is the commercial production of short-rotation timber crops. Under these circumstances growth models are judged solely on the perceived accuracy of their yield predictions. It is becoming more common, however, to have multiple, and even competing, objectives for the same forest stand, resulting in silvicultural prescriptions that have both timber and non-timber goals. Evaluation of such actions requires the consideration of numerous potential environmental impacts. The collection of multiple decision criteria available through FVS and its numerous extensions allows such evaluation and provides a basis for relative comparisons among alternatives. But, appraising the fidelity of these multiple metrics in the same sense as judging the accuracy of volume predictions is problematical. The interdependency of environmental processes, the often long projection periods, and the stochastic nature of many processes all contribute to uncertainty in the resulting predictions. But the array of metrics provides a convergence of evidence that can be used by the decision-maker to weigh alternatives. In this sense, simulation outputs are deemed less a prediction of future conditions than a quantification of marginal effects. And it is these marginal differences that may be more valuable for planning activities than the expectation of absolute future conditions.

The FVS framework needs to modernize to meet future needs. Detailed procedures to facilitate this modernization are beyond the scope of this paper, but the subject is introduced to motivate additional emphasis on code modernization as FVS is maintained and extended. Although the code-base has undergone numerous changes since its creation, major new concepts in application design and development have developed. FVS was originally designed with an algorithmic architecture and it retains this architecture today. A more modern approach to application design uses an object-oriented architecture. Where algorithmic design highlights the ordering of procedures, object-oriented design emphasizes agents that incorporate both state (data) and operations. These new techniques aid the handling of application complexity by focusing on computer code elements (objects) that resemble real-world objects better than algorithmic processes. This focus permits re-use of existing code thus eliminating its duplication in multiple procedures, and provides a mechanism (inheritance) for formalizing similarities between objects of similar behavior (Booch and others 2007). Some of these new techniques have already been used in parts of FVS, as exemplified by the Event Monitor functionality. These new techniques permit crafting program code that not only controls machine computations, but also better communicates the intent and logic of the developer (Eckel 2000). New techniques also exist for improving the design of existing applications. Refactoring is a set of disciplined practices and design patterns for revising systems structure and organization without changing behavior or introducing computer bugs. It has been used to improve the design and enhance the extension of many existing systems (Fowler and others 1999). Refactoring techniques could be used to ease the burden of both code maintenance and the addition of new functionality to FVS. Object-oriented design would also aid “plug and play” code additions. Plug and play techniques appear especially applicable for substituting alternative growth engines, such as engines that focus on plantation tree growth and address commercial management questions in contrast to more physiologically-based process engines to aid modeling of potential climatic changes. Improvements to code architecture could not only aid application deployment but also advance the latest science through more rapid delivery of ecological knowledge. Enhancing the code-base to accommodate increasingly complex simulations will foster the continued extension of FVS to new environmental and ecological findings.

References

Booch, Grady; Maksimchuk, Bob; Engle, Michael; Young, Bobbi, Connallen, Jim; Houston, Kelli. 2007. Object-oriented analysis and design with applications. 3rd ed. Boston: Addison-Wesley. 578 p.

Bullard, Steven H.; Straka, Thomas J. 1998. Basics concepts in forest valuation and investment analysis. 2nd ed. Mississippi State, MS: Mississippi State University. 276 p.

Crookston, Nicholas L. 1990. User's guide to the Event Monitor: Part of Prognosis Model 6. Gen. Tech. Rep. INT-275. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 21 p.

Crookston, N.L.; Colbert, J.J.; Thomas, P.W.; Sheehan, K.A.; Kemp, W.P. 1990. User's guide to the western spruce budworm modeling system. Gen. Tech. Rep. INT-274. Ogden UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 75 p.

Crookston, N.L.; Stage, A.R. 1991. User's guide to the parallel processing extension of the Prognosis Model. Gen. Tech. Rep. INT-281. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 87 p.

Davis, Lawrence S.; Johnson, K. Norman. 1987. Forest management, 3rd ed. New York: McGraw-Hill Publishing.

Eckel, Bruce. 2000. Thinking in Java. 2nd ed. New Jersey: Prentice Hall. 1117 p.

Ferguson, D.E.; Crookston, N.L. 1991. User's guide to version 2 of the regeneration establishment model: part of the Prognosis Model. Gen. Tech. Rep. INT-279. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 34 p.

Fowler, Martin; Beck, Kent; Brant, John; Opdyke, William; Roberts, Don. 1999. Refactoring: Improving the design of existing code. Boston: Addison-Wesley. 431 p.

Frankel, S.J., tech. coord. 1998. User's guide to the western root disease model, version 3.0. Gen. Tech. Rep. PSW-165. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 164 p.

Horn, Joseph E.; Medema, E. Lee; Schuster, Ervin G. 1986. User's guide to CHEAPO II—Economic analysis of Stand Prognosis model outputs. Gen. Tech. Rep. INT-211. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 39 p.

Martin, Fred C. 2008. User's guide to the FVS Economic Extension (ECON). Internal Rep. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 43 p. Online: http://www.fs.fed.us/fmsc/ftp/fvs/docs/gtr/EconUserGuide.pdf [August 5, 2008]

Medema, E. Lee; Hatch, Charles R. 1982. Computerized help for the economic analysis of prognosis-model outputs: a user's manual. Contribution No. 227. Moscow, ID: University of Idaho, Forest, Wildlife and Range Experiment Station. 72 p.

Moeur, M. 1985. COVER: A user's guide to the CANOPY and SHURBS extension of the Stand Prognosis Model. Gen. Tech. Rep. INT-190. Ogden, UT: U. S. Department of Agriculture, Forest Service, Intermountain Research Station. 49 p.

Monserud, R.A.; Crookston, N.L. 1982. A user's guide to the combined Stand Prognosis and Douglas-fir tussock moth outbreak model. Gen. Tech. Rep. INT-127. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 49 p.

Reinhardt, Elizabeth; Crookston, Nicholas L. tech. eds. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Ogden, UT: Gen. Tech. Rep. RMRS-GTR-116. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Renner, D. 2001. Economic extension (ECON) to FVS, Release 1.0 user's manual. [unpublished draft]. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 48 p.

Renner, David L.; Martin, Fred C. 2002. Using the Fuels and Fire Effects (FFE) and Economic (ECON) Extensions to the Forest Vegetation Simulator (FVS) to evaluate the impacts of silvicultural regimes. In: Crookston, Nicholas L.; Havis, Robert N., comps. Second Forest Vegetation Simulator Conference; 2002 February 12–14; Fort Collins, CO. Proc. RMRS-P-25. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 97–103.

Stage, A.R. 1973. Prognosis Model for stand development. Res. Pap. INT-137. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Development of FVS^{Ontario}: A Forest Vegetation Simulator Variant and Application Software for Ontario

Murray E. Woods[1]
Donald C.E. Robinson[2]

Abstract—The Ontario Ministry of Natural Resources is leading a government-industry partnership to develop an Ontario variant of the Forest Vegetation Simulator (FVS). Based on the Lake States variant and the Prognosis^{BC} user-interface, the FVS^{Ontario} project is motivated by a need to model the impacts of intensive forest management strategies and the multiple ecological and social objectives faced by today's resource managers. Currently, the large tree diameter model and the small tree height model of the Lake States variant have been replaced with localized equations from data sets from the Great Lakes and Boreal forest zones of the province. A companion application, "Tree List Manager" has also been created to develop FVS tree-lists from the data collected through various field-cruising methods. Current efforts with the model involve the identification of equation weaknesses, improvement of user control on silvicultural treatments, and development of methods for populating stand species- and diameter-distributions for inventory polygons through enhanced forest inventory attribution using high resolution digital imagery combined with LiDAR and Individual Tree Crown classification approaches.

Ontario's Landbase

The province of Ontario, Canada, is made up of four main climactic forest types, ranging from sparsely-treed spruce in the northerly Hudson's Bay Lowland zone; wide expanses of jack pine and black spruce in the Boreal forest zone; white and red pine and tolerant hardwood species typical of the Great Lakes-St. Lawrence zone; and tolerant and mid-tolerant hardwood stands of the Deciduous zone (fig. 1). Productive forests supporting forest management activities represent 53 percent (56.8 million hectares) of Ontario's total landbase of 107.6 million ha.

Table 1 summarizes the leading species within the productive landbase and clearly shows that boreal black spruce (see table 1 for scientific names) and jack pine forests represent by far the largest area, with shade-intolerant groups like poplar and white birch representing an additional 18 and 9 percent respectively. Other important species in the transition between the Boreal and Great Lakes-St. Lawrence zones include balsam fir, white spruce, and cedar which, when combined, account for about 6 percent. The areal percentage of leading deciduous species in the Great Lakes-St. Lawrence and Deciduous zones is much smaller than the species leading in the Boreal zone: white and red pine, hard maple, oaks, yellow birch, other hardwoods and eastern hemlock comprise only about 12 percent of the productive landbase. Although these species represent much smaller portions of Ontario's total productive forest area, they account for the most species-diverse forest conditions within the province and are managed with a wide range of silvicultural practices and systems.

Shade-intolerant species in the Boreal zone are most commonly managed with the clear cut silvicultural system (table 2), the management system that most closely represents natural wildfire disturbance; nature's regeneration method for these predominantly even-aged species which require full light conditions to regenerate and grow to maturity. Species like white and red pine, poor-quality tolerant hardwood forests and mid-tolerant species like oak and yellow birch are managed through the application of the uniform shelterwood system. The shelterwood system, with its series of partial cuts, best emulates low-intensity ground fire disturbances, which along with wind, is the dominant natural regeneration method for these species. Uneven aged tolerant hardwood stands of good stem quality and site quality are managed with the single-tree selection silvicultural system. The single-tree selection system, with its series of partial cuts, best emulates the gap-phase replacement dynamics that normally occur in these ecosystems.

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Senior Analyst, Forested Landscapes, Ontario Ministry of Natural Resources, Bay, Ontario; e-mail: murray.woods@mnr.gov.on.ca.

[2] Senior Systems Ecologist, ESSA Technologies Ltd., Vancouver, B.C.; E-mail: drobinson@essa.com.

Figure 1—FVS^Ontario has been parameterized for the province's Boreal and Great Lakes-St. Lawrence forest zones. From north to south, the four forest zones of Ontario shown here are: Hudson's Bay Lowland, Boreal, Great Lakes-St. Lawrence and Deciduous.

Table 1—Summary of leading species within Ontario's productive forest landbase.

Species	Common name	% Productive landbase area	
Picea mariana	black spruce	39.5	
Pinus banksiana	Jack pine	14.2	North
Populus tremuloides	poplars	18.1	
Populus balsamifera			
Betula papyrifera	white birch	9.5	
Abies balsamea	balsam fir	2.8	
Picea glauca	white spruce	1.0	
Thuja occidentalis	cedar	2.4	»
Pinus strobes	white pine	2.4	
Pinus resinosa	red pine	0.5	
Acer saccharum	hard maple	5.7	
Quercus sp.	oaks	0.9	
Betula alleghaniensis	yellow birch	0.5	South
Fagus sp.	basswood, beech	1.5	
Tilia sp.	("other hardwoods")		
Tsuga canadensis	eastern hemlock	0.5	

Table 2—Summary of prevalent stand management systems within Ontario.

Management system	Average annual harvest		Forest zone
	Hectares	Percent	
Clearcut	57,723	75	Boreal
Single tree selection	8,663	11	Great Lakes—St. Lawrence
Uniform shelterwood	6,769	9	
Seed tree	3,787	5	

Regeneration methods in Ontario include planting, aerial seeding and natural stem recruitment. This range of strategies may also rely on some level of mid-rotation thinning to accelerate tree diameter growth and to reduce the potential of stand stagnation.

Ontario's requirements from a growth and yield model are large. The model must be able to simulate stand development across a wide range of climatic and geological conditions, permit single and multi-species stand projections and provide for wide range silvicultural treatments to be simulated and evaluated.

Role of FVS^Ontario in Assisting Forest Management

Ontario's Growth and Yield program began evaluating suitable growth and yield models for the province's varied range of species and silvicultural methods in the 1990s. The Prognosis-FVS (Stage 1973) family of models rose to the top of the list as the most appropriate in meeting the majority of the required elements. These desirable elements include a modeling system that:

- Represents our current understanding of the dynamic forest ecosystem and how it responds over time to management interventions;
- Reduces uncertainty in strategic forest estate model inputs by providing empirical yield trajectories;
- Provides a monitoring target to test our assumptions with (for example, stand yield following different silvicultural treatments and successional pathways when no treatments are applied);
- Provides a modeling framework to integrate our existing modeling components such as taper equations, site index curves and ecological land classification;
- Provides a "gaming" or "what-if" tool to develop and compare various silvicultural treatments;
- Identifies gaps in our Growth and Yield "toolbox" and data;
- Visually animates a stand through time to inform and instruct professionals and the general public; and
- Provides Ontario with an appropriate tool to transform a static inventory into a dynamic one.

FVS^Ontario Development

A few years before similar efforts began in Ontario, work was begun by the British Columbia Ministry of Forests and Range (BCMoFR) to develop Prognosis^BC, a metric variant of FVS for interior British Columbia (Snowdon 1997). Prognosis^BC was initially based on the North Idaho variant of the model and was tailored to the province's southern interior forests. BCMoFR subsequently developed its own metric user interface (UI) driven by the needs of BC practitioners, along with a refit of all the FVS submodels. The Ontario Ministry of Natural Resources subsequently approached the BCMoFR, the USDA Forest Service and ESSA Technologies Ltd. to explore opportunities to leverage the benefits of work already developed, namely the source code for the Prognosis^BC interface and the source code for the Lake States (LS) variant of the FVS model. The LS-FVS variant was originally developed from the growth model—TWIGS (Miner and others 1988); a model that had some history of testing and application in Ontario (Payandeh and Papadopol 1994).

The LS variant of the model was linked into a cosmetically modified version of Prognosis^BC and renamed FVS^Ontario. Figure 2 illustrates the linkage of two Prognosis^BC UI components (SimProg and ViewProg) with the base LS variant model (Bush and Brand 1995). SimProg allows users to easily enter (and subsequently store and modify) stand conditions and perform silvicultural treatments. ViewProg allows simulation results to be viewed in tabular and graphic output forms.

A detailed exercise was undertaken by research modelers to use Ontario growth and yield plot data to determine how well the LS variant growth equations represented growing conditions north of the model's Great Lakes origins. Results of the validation exercise (Lacerte and others 2004) indicated that the LS variant did not adequately represent growing conditions throughout Ontario for the species tested, and that model calibration would be required. Comparisons of model and data predictions were particularly poor for the LS mortality model applied in Ontario.

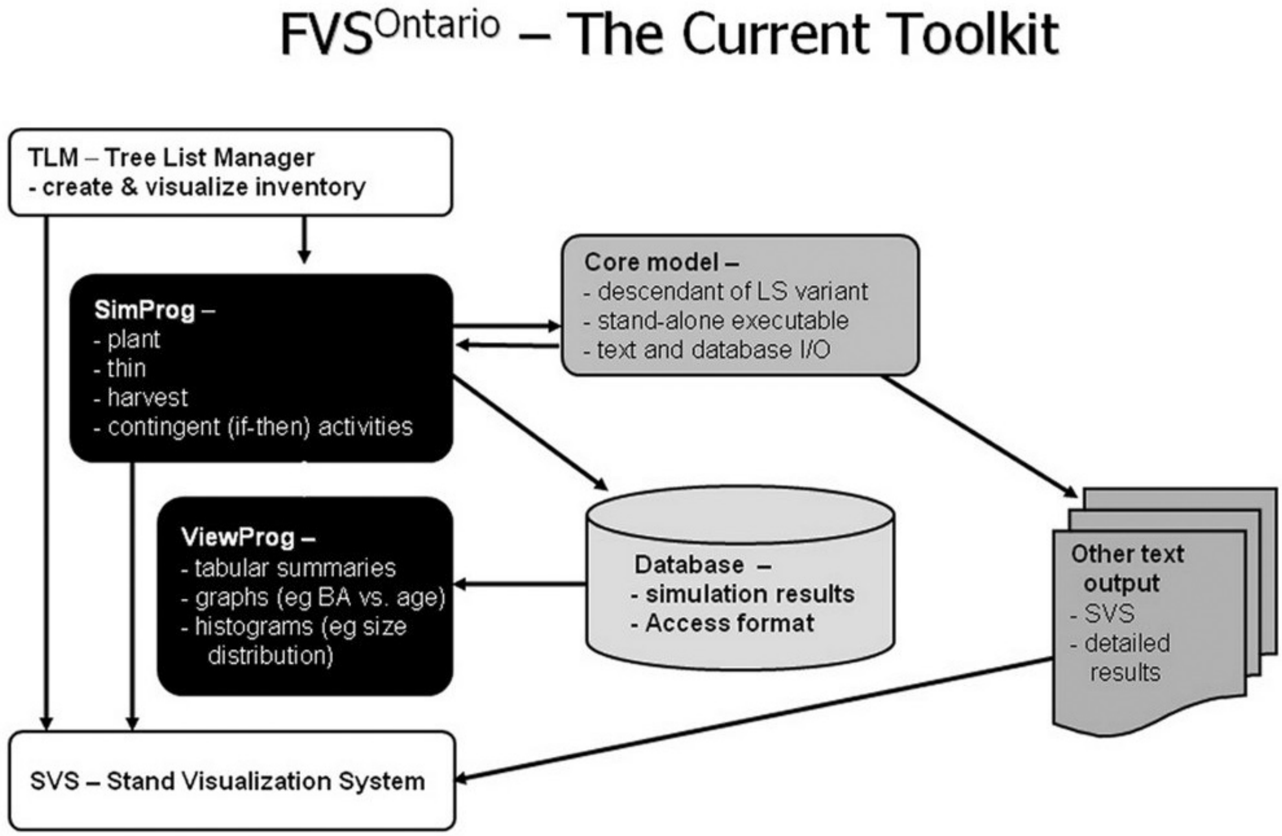


Figure 2—FVS^Ontario modeling system combines the core FVS model with SimProg and ViewProg interface programs, an Access database and SVS for visualization. TLM is used to create inventory treelists or SVS diagrams.

The next round of calibration of the large- and small-tree models was undertaken with a moderate number of Ontario growth and yield plots (Lacerte and others 2006a) and showed improved performance of the new model forms. These findings were later demonstrated in a validation report (Lacerte and others 2006b). However, with additional testing it became apparent that the revised model forms, while an improvement over the original LS equations, did not provide credible predictions across the full range of site conditions found in Ontario. These model shortcomings were the result of a reduced calibration data set available for the first round of 2006 calibration efforts.

Late in 2006, Ontario's maturing government-industry cooperative growth and yield efforts provided the FVS^Ontario team with a data set of over 172,000 remeasurement observations (Woods and Penner 2007) , about 66 percent more observations than were available to Lacerte in 2004. Accordingly, the submodels were recalibrated and model forms evaluated once more. As a result of the additional data, many model forms were modified from those of Miner and others (1988) and Lacerte and others (2006a).

Large Tree Diameter Model

A number of potential independent variables were evaluated for their ability to predict dbh growth. Most dbh-prediction equations appear to avoid height terms (for example, Lessard and others 2000), probably due in part to heights being measured on a sub-sample only, coupled with the significant measurement errors often found with height estimation. The final large tree diameter growth equation follows an exponential model that predicts annual diameter growth, subsequently scaled as required to the FVS cycle length:

$$ln(DG) = \beta_0 + \beta_1 ln(Dbh) + \beta_2 Dbh + \beta_3 BAL + \beta_4 HT + \beta_5 SI + \beta_6 BA + \beta_7 Dbh_q + \beta_8 AGS \quad [1]$$

The model terms include site index (SI), dbh, *ln*(dbh), quadratic mean diameter (QMD), stand basal area (BA), basal area in larger trees (BAL), height, and for some species a binary variable, "acceptable growing stock" (AGS). For some species that are extensively planted, separate equations were fit for natural and plantation stems (fig. 3).

Within the shade-tolerant hardwood group (hemlock, hard and soft maple, yellow birch, red oak, beech, white and black ash, basswood, ironwood, and black cherry), tree quality is identified in the stand exam as either acceptable (AGS) or unacceptable (UGS) growing stock. AGS is a partially subjective assignment that identifies individual trees that exhibit characteristics of high vigor and good stem quality. For the shade-tolerant hardwoods the AGS term is assigned a value of 1 if a tree is recorded as AGS, and a value of 0 otherwise. Including this term in the model assumes that these trees will maintain this quality over a cutting cycle, and empirical evidence supports this assumption. Since quality observations may not always be available during the stand exam, model equations without an AGS term (fig. 4) are also provided.

Predictions of diameter growth are constrained so that they do not exceed the 90th percentile of observations taken from the fitting data, preventing unrealistic extrapolation of growth estimates outside the range of data.

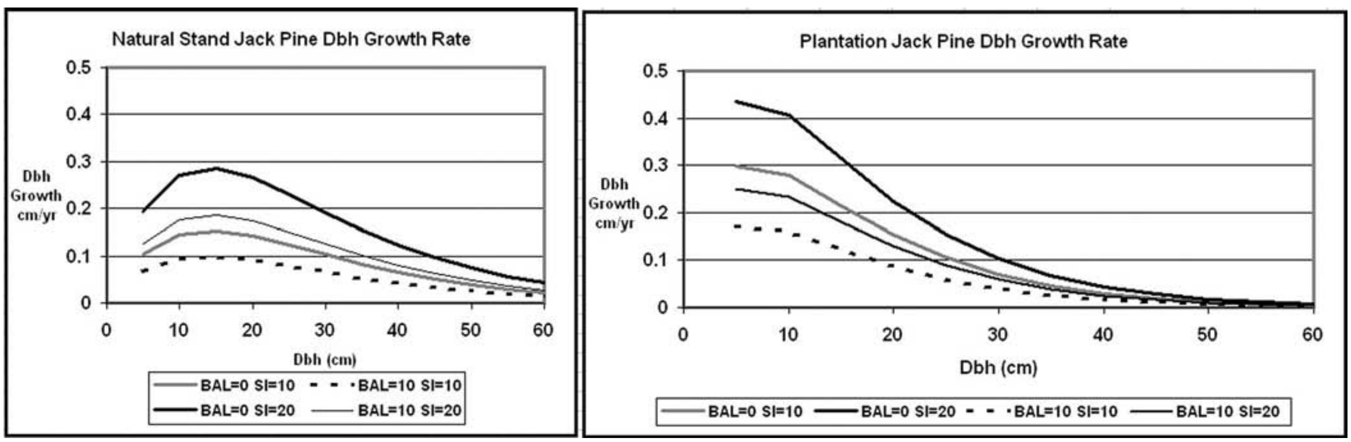


Figure 3—Models of annual diameter growth (cm yr¬–1) are fitted separately for naturally regenerated and plantation Jack pine. Model behavior is shown here for a variety of combinations of SI and stand BAL

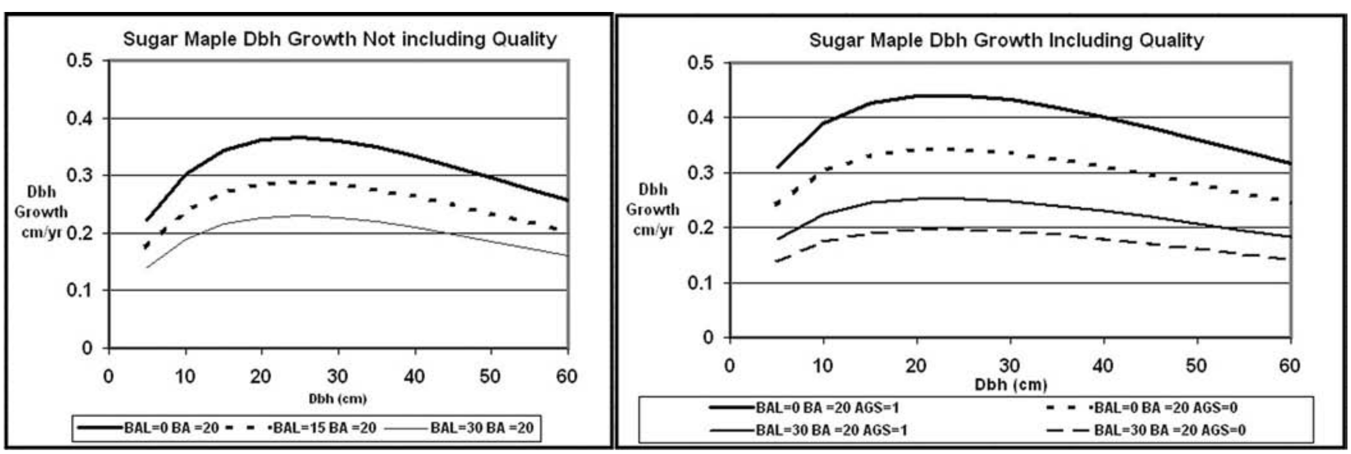


Figure 4—Models of annual diameter growth (cm yr¬–1) are fitted separately for sugar maple, with and without AGS criteria.

Large Tree Height Model

The LS-FVS large tree height model was modified to:

$$HT = 1.3 + \left(\beta_0 + \beta_1 SI + \beta_2 Dbh_q + \beta_3 BA\right)\left(1 - e^{\beta_4 Dbh^{\beta_5}}\right) \quad [2]$$

Height model linear terms include Site Index, QMD and stand BA; dbh is present as the exponential allometric variable in equation 2.

Over the course of model development, the height equations have been revised to reflect the expanded dataset available. For species within the shade-tolerant hardwood group (hemlock, hard and soft maple, yellow birch, red oak, beech, white and black ash, basswood, ironwood, and black cherry), site index is often difficult to assess due to the mix of ages and species and the difficulty of finding trees that have not been suppressed at some point. Therefore, height equations with and without an SI term are fit to these species. For all other species, an SI term is included in the model. In addition, QMD and BA are admitted on a case by case basis only if they are statistically significant ($\alpha = 0.05$) for the species.

Small Tree Diameter Model

The small tree diameter growth model is implemented for trees smaller than 7.6 cm dbh as a rearrangement of the large tree height dubbing model (equation 2), simulating height growth (described below) and then solving for change in diameter. Although this expression loses the least squares solution property of the original formulation, it maintains compatibility between diameter and height. Predicted change in dbh is also constrained by the 90th percentile of height growth from the original height equation.

Small Tree Height Model

Annual growth of small trees (<7.6 cm dbh) is modeled with an exponential formulation:

$$ln(HG) = \beta_0 + \beta_1 ln(HT) + \beta_2 HT + \beta_3 SI + \beta_4 BAL \quad [3]$$

and includes terms for SI, BAL, HT and *ln*(HT). The small tree height growth model is similar to the conifer small tree height growth model of Lacerte and others (2006a): height growth increases as a function of height up to a maximum and then declines. Increasing SI has a positive effect on height growth and increased BAL a negative effect. The SI and BAL terms are included only if they are statistically significant ($\alpha = 0.05$). As with the large tree diameter growth model, predictions of height growth are constrained so that they do not exceed the 90th percentile of observations taken from the fitting data, preventing extrapolation outside the range of data and unrealistic growth estimates.

$FVS^{Ontario}$ User Interface

Modifications and additions to the original $Prognosis^{BC}$ UI have been underway over the past few years for $FVS^{Ontario}$. While $FVS^{Ontario}$ shares many of the same functional screens as $Prognosis^{BC}$, a great deal of effort has been invested in modifying and adding additional functionality required for Ontario species and silvicultural systems.

The $FVS^{Ontario}$ screens include the following interface screens: site quality information for the species being modeled (fig. 5), input data source (existing stand or bare ground regeneration) (fig. 6), juvenile spacing treatments (fig. 7), thinning from above or below and by diameter class (figs. 8 and 9), single-tree selection (fig. 10), uniform shelterwood treatments (fig. 11) and seed tree harvest (fig. 12). In addition, a set of two forms were created to permit manual keyword entry (fig. 13) to allow users access to the full flexibility of the FVS modeling system.

$FVS^{Ontario}$ provides a variety of output styles: tabular and graphical stand summaries (fig. 14), stand visualization through linkage to the Stand Visualization System (McGaughey 2002) and stand and stock tables (fig. 15).

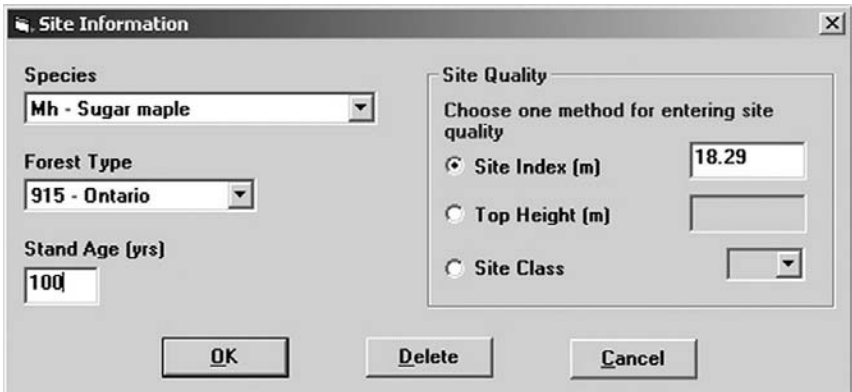


Figure 5—The FVS^Ontario site quality user interface form.

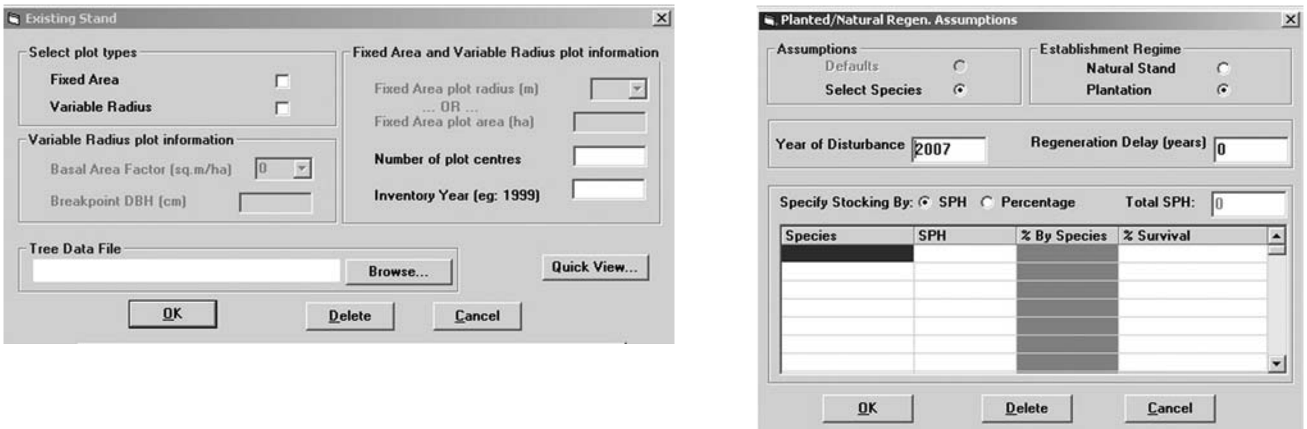


Figure 6—FVS^Ontario tree input format forms allow a model run to be initialized with an existing inventory (left) or through bare ground planting (right).

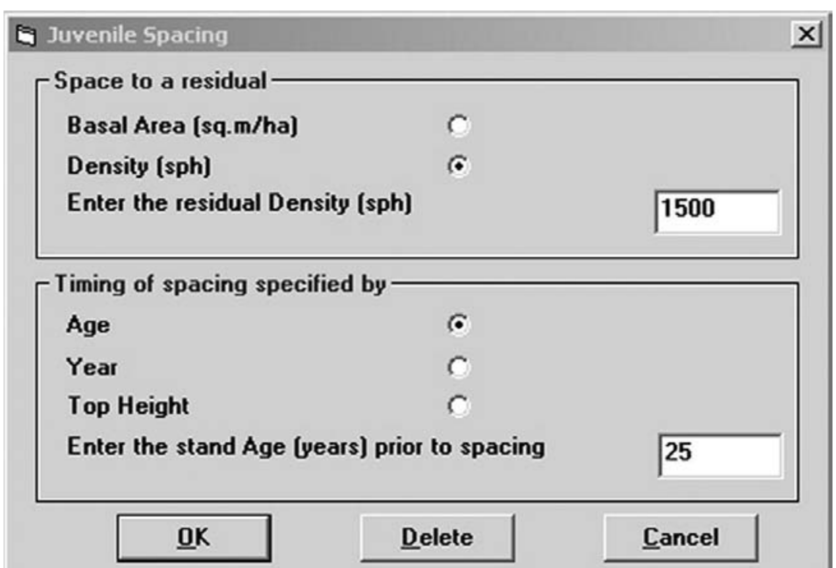


Figure 7—The FVS^Ontario juvenile spacing treatment interface allows spacing thinning using a variety of criteria.

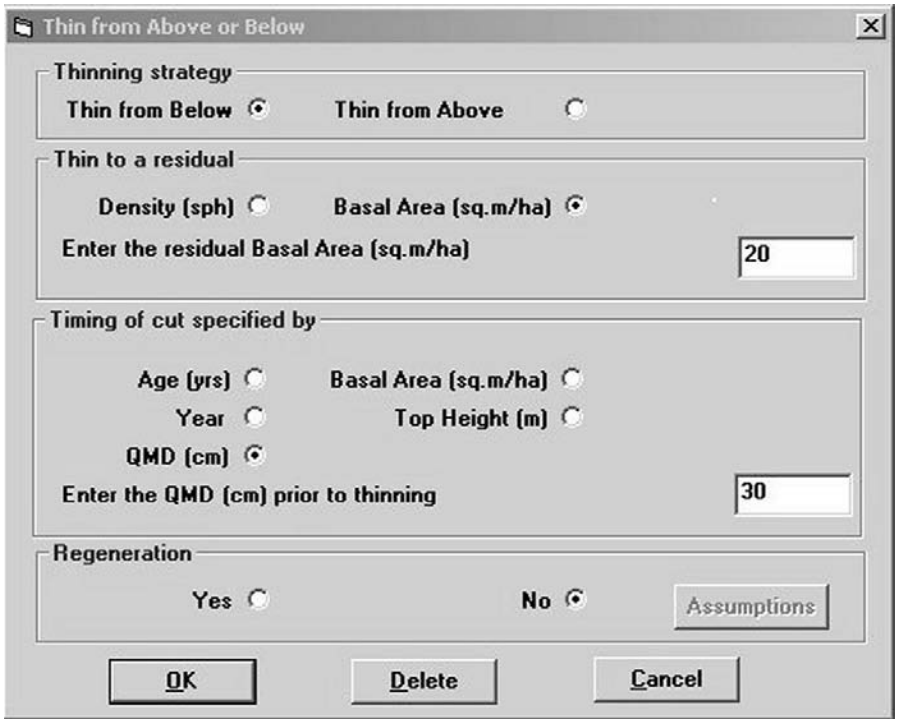


Figure 8—The FVS^Ontario thinning form allows thinning from above or below according to different criteria.

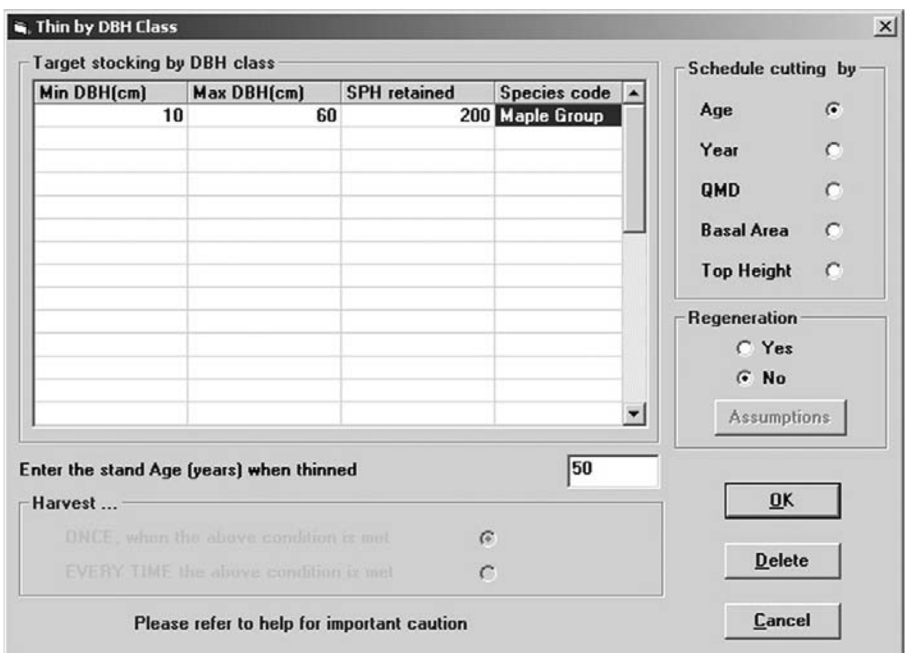


Figure 9—FVS^Ontario allows thinning by diameter class and species and can be scheduled by different criteria.

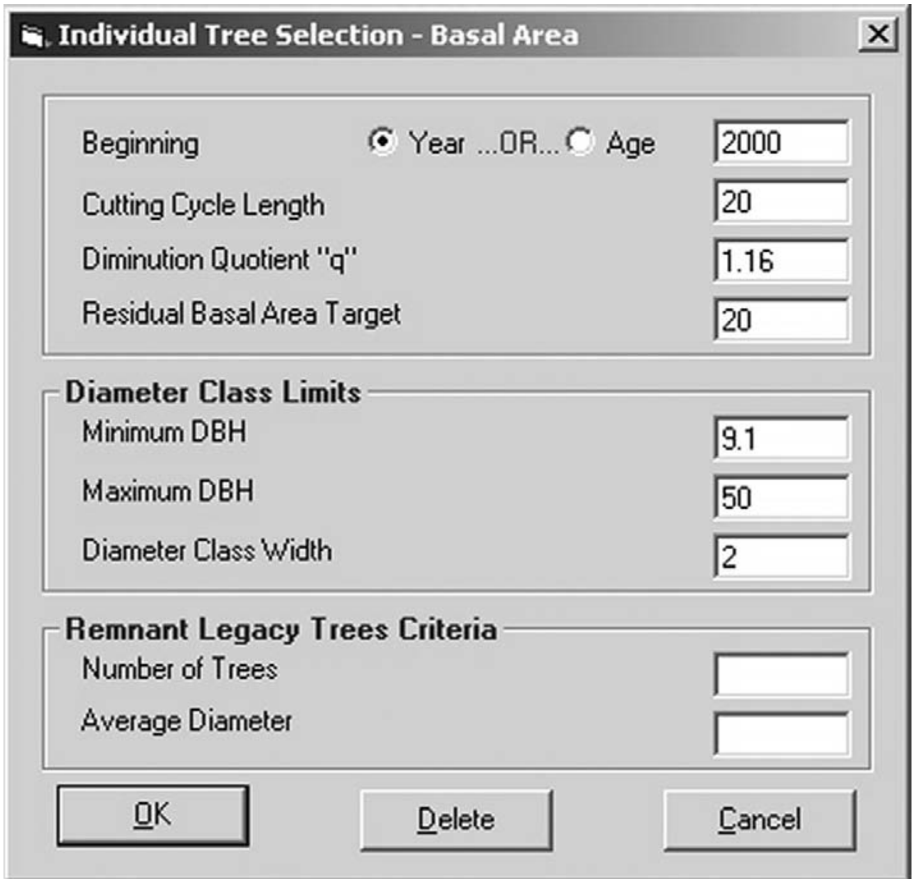


Figure 10—FVS[Ontario] allow single-tree-selection treatments, modeled after the same treatment form offered by the Suppose interface.

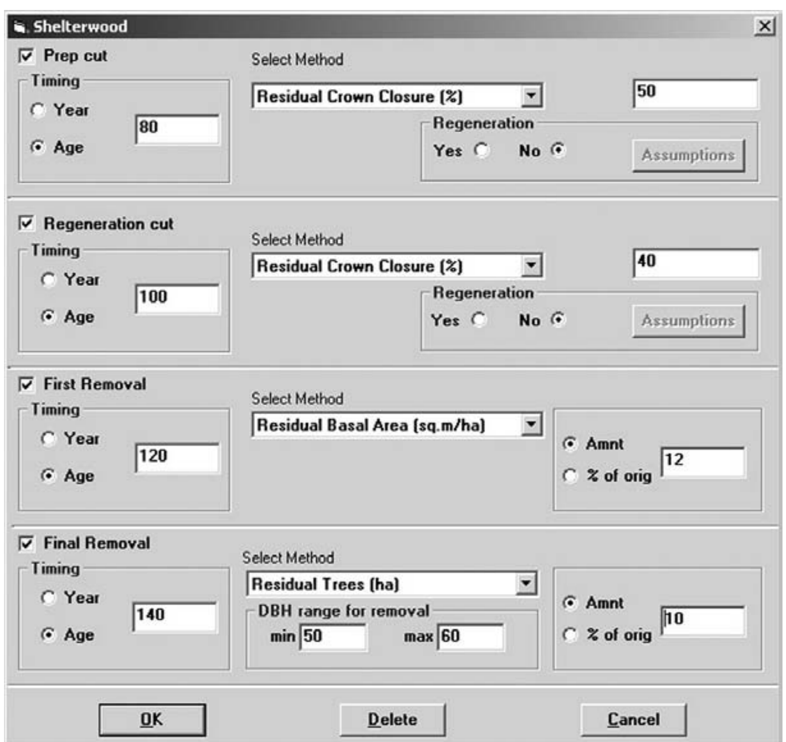
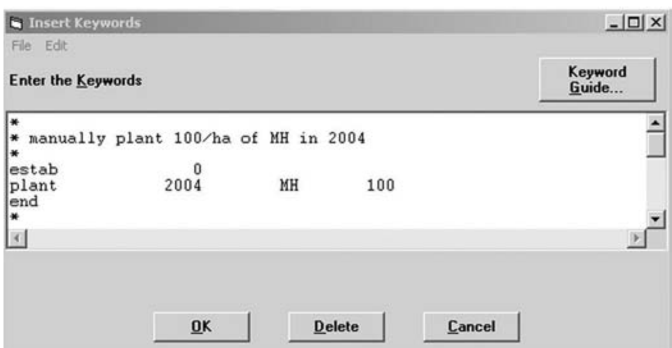


Figure 11—FVS[Ontario] allows users to carry out up to four stand entries in a uniform shelterwood treatment system.

Figure 12—FVS^Ontario allows a simple two entry seed tree harvest treatment.



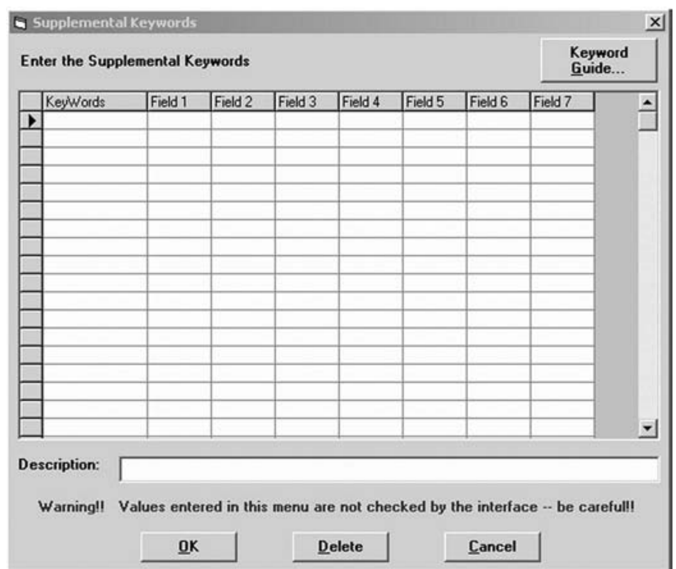
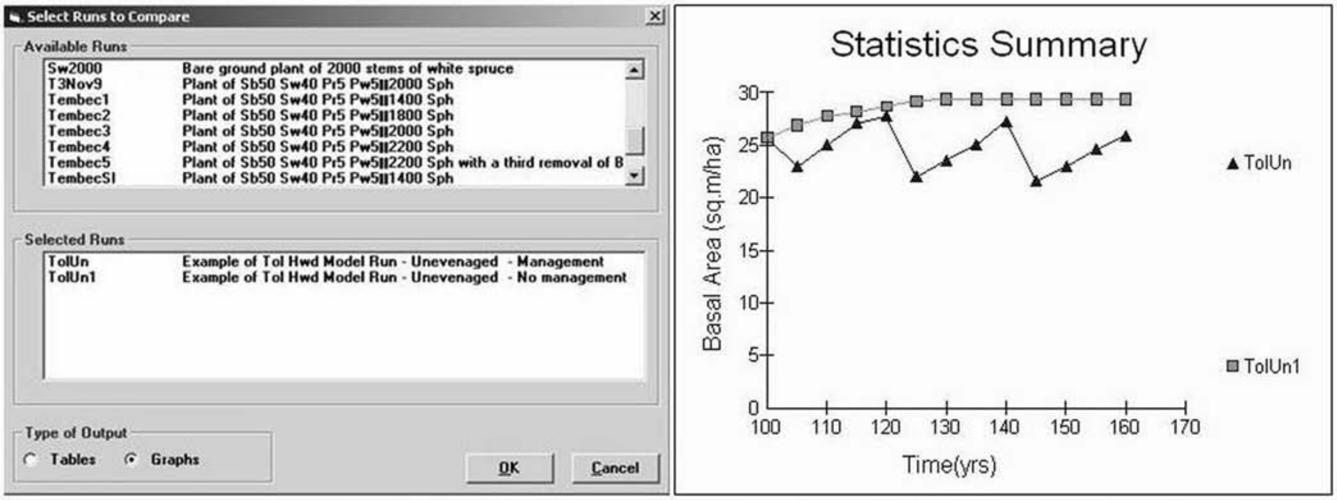
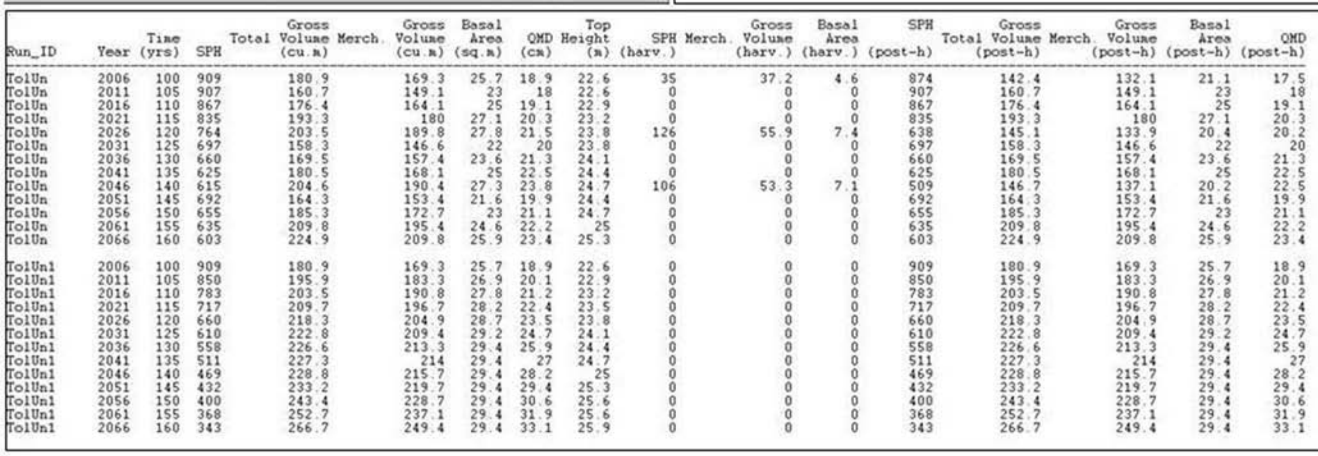


Figure 13—FVS^Ontario allows users to enter keywords in either free-form, as files (above), or in a structured grid (right).





Run_ID	Year	Time (yrs)	SPH	Total Gross Volume (cu.m)	Merch. Gross Volume (cu.m)	Basal Area (sq.m)	QMD (cm)	Top Height (m)	SPH (harv.)	Merch. Gross Volume (harv.)	Basal Area (harv.)	SPH (post-h)	Total Gross Volume (post-h)	Merch. Gross Volume (post-h)	Basal Area (post-h)	QMD (post-h)
TolUn	2006	100	909	180.9	169.3	25.7	18.9	22.6	35	37.2	4.6	874	142.4	132.1	21.1	17.5
TolUn	2011	105	907	160.7	149.1	23	18	22.6	0	0	0	907	160.7	149.1	23	18
TolUn	2016	110	867	176.4	164.1	25	19.1	22.9	0	0	0	867	176.4	164.1	25	19.1
TolUn	2021	115	835	193.3	180	27.1	20.3	23.2	0	0	0	835	193.3	180	27.1	20.3
TolUn	2026	120	764	203.5	189.8	27.8	21.5	23.8	126	55.9	7.4	638	145.1	133.9	20.4	20.2
TolUn	2031	125	697	158.3	146.6	22	20	23.8	0	0	0	697	158.3	146.6	22	20
TolUn	2036	130	660	169.5	157.4	23.6	21.3	24.1	0	0	0	660	169.5	157.4	23.6	21.3
TolUn	2041	135	625	180.5	168.1	25	22.5	24.4	0	0	0	625	180.5	168.1	25	22.5
TolUn	2046	140	615	204.6	190.4	27.3	23.8	24.7	106	53.3	7.1	509	146.7	137.1	20.2	22.5
TolUn	2051	145	692	164.3	153.4	21.6	19.9	24.4	0	0	0	692	164.3	153.4	21.6	19.9
TolUn	2056	150	655	185.3	172.7	23	21.1	24.7	0	0	0	655	185.3	172.7	23	21.1
TolUn	2061	155	635	209.8	195.4	24.6	22.2	25	0	0	0	635	209.8	195.4	24.6	22.2
TolUn	2066	160	603	224.9	209.8	25.9	23.4	25.3	0	0	0	603	224.9	209.8	25.9	23.4
TolUn1	2006	100	909	180.9	169.3	25.7	18.9	22.6	0	0	0	909	180.9	169.3	25.7	18.9
TolUn1	2011	105	850	195.9	183.3	26.9	20.1	22.9	0	0	0	850	195.9	183.3	26.9	20.1
TolUn1	2016	110	783	203.5	190.8	27.8	21.2	23.2	0	0	0	783	203.5	190.8	27.8	21.2
TolUn1	2021	115	717	209.7	196.7	28.2	22.4	23.5	0	0	0	717	209.7	196.7	28.2	22.4
TolUn1	2026	120	660	218.3	204.9	28.7	23.5	23.8	0	0	0	660	218.3	204.9	28.7	23.5
TolUn1	2031	125	610	222.8	209.4	29.2	24.7	24.1	0	0	0	610	222.8	209.4	29.2	24.7
TolUn1	2036	130	558	226.6	213.3	29.4	25.9	24.4	0	0	0	558	226.6	213.3	29.4	25.9
TolUn1	2041	135	511	227.3	214	29.4	27	24.7	0	0	0	511	227.3	214	29.4	27
TolUn1	2046	140	469	228.8	215.7	29.4	28.2	25	0	0	0	469	228.8	215.7	29.4	28.2
TolUn1	2051	145	432	233.2	219.7	29.4	29.4	25.3	0	0	0	432	233.2	219.7	29.4	29.4
TolUn1	2056	150	400	243.4	228.7	29.4	30.6	25.6	0	0	0	400	243.4	228.7	29.4	30.6
TolUn1	2061	155	368	252.7	237.1	29.4	31.9	25.6	0	0	0	368	252.7	237.1	29.4	31.9
TolUn1	2066	160	343	266.7	249.4	29.4	33.1	25.9	0	0	0	343	266.7	249.4	29.4	33.1

Figure 14—Some examples of simple FVS[Ontario] graphic and tabular outputs.

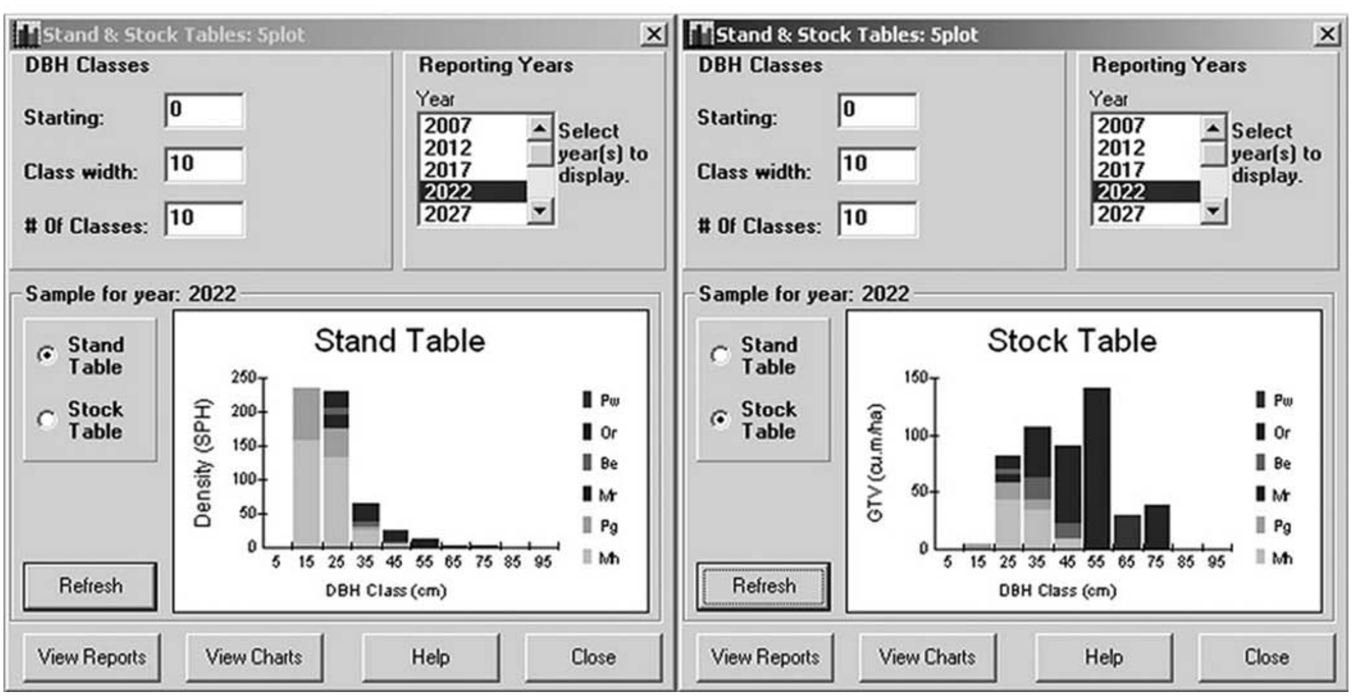


Figure 15—FVS[Ontario] can produce stand and stock table figures and tables with user-defined size classes.

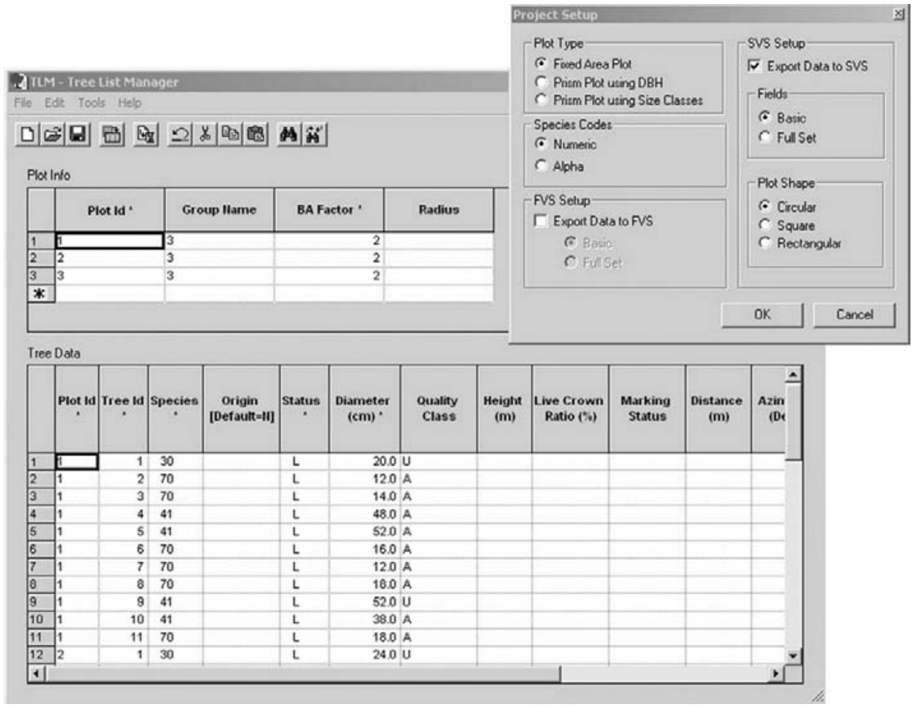


Figure 16—The companion Tree List Manager (TLM) software allows users to create or import inventories, producing FVS-ready treelists

Tree List Management Software

To support the necessary linkage between field-collected data and the stand projection, a software utility called the Tree List Manager Software (TLM) has been developed. TLM supports the entry of both fixed-area plot data and variable radius samples collected by a variety of methods (fig. 16). FVS-ready tree lists can be created directly through an Excel-like grid interface, or indirectly by importing from Excel, Access or DBF files. Users have the option of either exporting the compiled inventory as an FVS^{Ontario} treelist or as an SVS file.

Future Directions

FVS^{Ontario} has matured to the point where increased user testing and refinement is required. An expanded user group of resource managers is being provided the model along with training packages and online technical support to help determine the model's strengths and areas for refinement.

An increased technology transfer effort is also planned to support this new version of the model, and SVS continues to play a key role in visually explaining forest management practices to the lay population. The value of "cartoon" representations of time zero silvicultural treatments and fifty-year projections of the treatment have proven beneficial to increasing public participation in the forest management process.

Ongoing refinements to the model forms are provided by provincial program staff and through an extremely productive partnership with Michigan Technological University (MTU). With the help of MTU partners, new modeling approaches for growth and mortality are being explored using Ontario permanent sample plot data. As is the case with most variants, natural regeneration and mortality functions are a weakness in FVS^{Ontario}, and efforts will be focused on improving these areas.

Populating a stand level inventory with tree list information continues to be a challenge in Ontario and elsewhere. Recent advancement in Light Detection and Ranging Radar (LiDAR) technology may help to bridge this critical gap. In the past, LiDAR point density levels necessary to predict stand and tree attributes were prohibitively expensive and technologically limited. With the new 100 kHz sensors currently on the market, it is widely believed that these advances will soon provide a means to impute tree list information across forest inventory polygons. Optical tree crown classification methods based on the current suite of multi-band digital imagery products also holds great promise to bridge the gap between stand level inventories and individual tree model requirements. (Gougeon and Leckie 2003). Perhaps this goal may ultimately be achieved through the merging of these two technologies

Conclusions

FVS^{Ontario} has been developed through the cooperative partnerships of the Ontario Ministry of Natural Resources, BC Ministry of Forests and Range, USDA Forest Service, ESSA Technologies Ltd., Canadian Forest Service and Forest Analysis Ltd. All of these groups have openly provided software, advice or expertise to develop FVS^{Ontario} to its current state. This admirable arrangement has permitted Ontario to quickly develop a modeling system that will permit empirically-based growth estimates to provide support to sustainable management decisions now and into the future.

Acknowledgments

We express our appreciation to Don Vandendriesche at the Forest Management Service Center, who developed the Event Monitor keywords necessary to implement Individual Tree Selection.

References

Bush, R.R.; Brand, G. 1995. Lake States TWIGS geographic variant of the Forest Vegetation Simulator. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Management Service Center. Online: [http://www.fs.fed.us/fmsc/ftp/fvs/docs/overviews/lsvar.txt.

Gougeon, F.A.; Leckie, D.G. 2003. Forest Information extraction from high spatial resolution images using an individual tree crown approach. CFS-PFC Info Report BC-X-396. Natural Resources Canada.

Lacerte, V.; Larocque, G.R.; Woods, M.; Parton, W.J.; Penner, M. 2004. Testing the Lake States variant of FVS (Forest Vegetation Simulator) for the main forest types of northern Ontario. Forestry Chronical. 80:495–506.

Lacerte, V.; Larocque, G.R.; Woods, M.; Parton, W.J.; Penner, M. 2006a. Calibration of the Forest Vegetation Simulator (FVS) for the major forest species of Ontario, Canada. Ecological Modeling. 199:336–349.

Lacerte, V.; Larocque, G.R.; Woods, M.; Parton, W.J.; Penner, M. 2006b. Forest Vegetation Simulator model validation for Ontario (FVS^{Ontario}). Southern Science and Information Section Technical Report 120. North Bay, Ontario: Ontario Ministry of Natural Resources. 398 p.

Lessard, V.C.; McRoberts, R.E.; Holdaway, M.R. 2000. Diameter growth models using FIA data from the Northeastern, Southern and North Central Research Stations. In: McRoberts, R.E.; Reams, G.A.; Van Deusen, P.C., eds. Proceedings of the first annual forest inventory and analysis Symposium; 1999 November 2–3; San Antonio, TX. Gen. Tech. Rep. NC-213. St. Paul, MN; U.S. Department of Agriculture, Forest Service, North Central Research Station: 37–42.

McGaughey, R.J. 2002. Stand Visualization System. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. Version 3.36.

Miner, C.L., Walters, N.R.; Belli, M.L.1988. A guide to the TWIGS program for the North Central United States. Gen. Tech. Rep. NC-125. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 105 p.

Payandeh, B.; Papadopol, P. 1994. Calibrating ONTWIGS for drained and fertilized peatland and black spruce stands in northern Ontario. Information Report O-X-441. Sault Ste. Marie, Ontario: Natural Resources Canada, Canadian Forest Service, Ontario Region. 7 p.

Snowdon, B. 1997. British Columbia's Forest Vegetation Simulator application software. In: Teck, R.; Moeur, M.; Adams, J., comps. 1997. Proceedings: Forest Vegetation Simulator conference; 1997 February 3–7; Fort Collins, CO. Gen. Tech. Rep. INT-GTR-373. Ogden, UT; U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 15–20.

Stage, A.R. 1973. Prognosis model for stand development. Res. Pap. INT-137. Ogden, UT; U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, 32 p.

Woods, M.; Penner, M. 2007. Revised FVS^{Ontario} model forms based on an expanded Ontario data set. (Draft internal document).

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Development of External Regeneration Models for FVS: Another Wrench in the Toolkit

Donald C.E. Robinson[1]

Abstract—Despite more than three decades of development, only one full-featured regeneration model has been developed for the Forest Vegetation Simulator (FVS). Regeneration remains a challenging problem because of its all-or-none nature: the need for field inventories that span the vast range of stand structure conditions; the need to accommodate environmental and climatic influences, and the need to integrate these within the FVS core model source code. We introduce and provide two examples of a recent FVS capability that removes one hurdle from this difficult problem: allowing the development of external models that can be executed from within the FVS system with minimal modification to the FVS source code. External models developed from any computer programming language can be incorporated into FVS by obeying a few simple rules.

Introduction

Since its first publication more than three decades ago (Stage 1973), the Forest Vegetation Simulator (FVS) has grown to include twenty geographic variants in the United States. Additionally, model extensions that simulate the impacts of various insects, diseases, and fires have been developed. Despite this singular achievement—what other software with a 1973 vintage is still in use and constantly being enhanced?—FVS has only one full featured regeneration submodel (Ferguson and others1986; Ferguson and Crookston 1984, 1991; Ferguson and Carlson 1993)[2].

There are numerous reasons that few regeneration models exist. Biologically, regeneration is a hard science problem because it is an "all-or-none" event, making it harder to observe than more continuous processes like diameter and height growth. Inventorying seedlings, therefore, requires a multitude of intensive ground samples, and advances in remote sensing may never be able to contribute much at this small spatial scale. In the development of Ferguson's model, for example, over 12,000 regeneration plots were established in 500 stands. Regeneration can be triggered by sudden disturbances like wildfire, but also by slower on-going disturbances like root disease or stand senescence and decline, both of which create openings gradually. In the case of slow disturbances, it can be difficult to define the time or threshold cues that lead to regeneration. Finally, regeneration is not solely dependent on available overstory seed stock but also upon micro-site conditions for success. When triggered, it can appear as a flush of new seedlings or may sputter unevenly over time. Together, these three factors conspire to make it a hard science problem.

Regeneration can also be a hard management problem. Forestry practices geared toward commodity production have historically implemented even-aged rotations that inherently employ manual planting if necessary. Under this management regime, natural regeneration is usually ignored and is of little relevance for funding or research. However, over the past two decades this situation has changed, and it is now common practice for planners to develop forest management plans that incorporate ecosystem components that include natural disturbances such as insects, diseases, and fire. Under an environmental paradigm, natural regeneration takes on a more important role. In the century before us, forest planners must contemplate forest ecosystems in which complex, largely unknown relationships between global climate, species composition, disturbance agents, and invasive species all combine to make forecasting even more precarious. In

In: Havis, Robert N.; Crookston, Nicholas L., comps. 2008. Third Forest Vegetation Simulator Conference; 2007 February 13–15; Fort Collins, CO. Proceedings RMRS-P-54. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

[1] Senior Systems Ecologist, ESSA Technologies Ltd., Vancouver, B.C.; e-mail: drobinson@essa.com.

[2] Some might say there are five such models. I consider the Northern Idaho/Inland Empire Regeneration Establishment model and the neighboring geographic variants (Central Idaho, Kootenai/Kaniksu/Tally Lake, Eastern Montana) that have adopted it, as well as the closely related Southeast Alaska regeneration extension, as one model.

this uncertain future, regeneration predictions will be an important component of forest planning, and the juxtaposition of a hard science problem with a hard management problem could signal either a perfect storm or a perfect opportunity.

Current FVS Regeneration Options

FVS geographic variants without the full establishment model extension have a range of options—some simple, some complex—for introducing regeneration. Figure 1 shows a hypothetical simple example in which the local silviculturist knows what will regenerate after a given disturbance. The Event Monitor (Crookston 1990) is invoked to thin the stand and immediately thereafter add new stems. Figure 2 shows a more complex hypothetical example that follows a simple rule: a 20 percent decline in stand basal area triggers regeneration of two species, Douglas-fir and lodgepole pine. The composition and amount of regeneration is equal to these two species' densities observed when the 20 percent threshold is detected by the Event Monitor. Compared to figure 1, rules like the one shown in figure 2 imply a deeper understanding of the processes driving stand regeneration.

At an even more abstract level, a fragment of a third and more complex example is shown in figure 3. The full example contains nearly 1,000 lines of Event Monitor statements and represents a regeneration model developed by Wilson, Maguire, and Ager (2003), hereafter referred to as the Blue Mountains model. This model mimics the key components of the Ferguson regeneration model by recognizing habitat types, site effects,

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+ Keyword	fld1	fld2	fld3	fld4	fld5
1	If					
2	Year EQ 2005					
3	Then					
4	ThinBBA		30			
5	Estab					
6	Plant		3	350	90	2
7	Plant		7	120	90	2
8	End					
9	EndIf					

Figure 1—An example of simple regeneration following a stand entry using elementary Event Monitor capabilities. Not all possible keyword fields are shown.

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+ Keyword	fld1	fld2	fld3	fld4	fld5
1	Compute	0				
2	TPH_DF = SpMcDbh(1,3,0)					
3	TPH_LP = SpMcDbh(1,7,0)					
4	End					
5	If					
6	EVphase EQ 2 AND DBA% LT -20					
7	Then					
8	Estab					
9	Plant		3	Parms(TPH_DF,100,2,0.5,0)		
10	Plant		7	Parms(TPH_LP,100,2,0.5,0)		
11	End					
12	EndIf					

Figure 2—A more complex hypothetical example of regeneration in which simple rules for regeneration are written using the Event Monitor and the stem density of species 3 and 7 (Douglas-fir and lodgepole pine) when a 20 percent decline occurs in stand basal area. In this example the lost stems are simply replaced by the current density of each species.

```
                          Column ruler
----+----1----+----2----+----3----+----4----+----5----+----6----+
   Keyword      fld1      fld2      fld3      fld4      fld5
Compute            1
SQRT_SL = Sqrt(Slope/100)
SL_Cos = Cos(Aspect*((2*3.1415)/360))*SQRT_SL)
SL_Sin = Sin(Aspect*((2*3.1415)/360))*SQRT_SL
GS_Harv = 10
GS_Harv2 = 100
E = Elev
EL = Elev/100
EL2 = EL*EL
GS_Cos = 10*SL_Cos
GS_Sin = 10*SL_Sin
LN_EL = ALog(EL)
HCycle = 100
Minus1 = 100
End
Compute            0
Add = 3
H = Yes
Heavy = No
! 963 lines deleted.
Natural            1  Parms(WP,SPA_PIMO,80,10,3,0)
Natural            1  Parms(PP,SPA_PIPO,80,10,3,0)
Natural            1  Parms(DF,SPA_PSME,80,10,3,0)
MinPlots          20
End
EndIf
```

Figure 3—A fragment of a complex Event Monitor regeneration model. Because of the way Event Monitor instructions are stored and processed, this example is extremely difficult to debug.

levels of disturbance, presence or absence of stocking, probability of regeneration for six species, and if present, existing seedlings per acre of each species. Its complexity provides some realism. However, this comes at the expense of being very difficult to debug within the Event Monitor. Also, there is a performance penalty when run in conjunction with the fire and fuels (FFE; Reinhardt and Crookston 2003) and parallel processing (PPE; Crookston and Stage 1991) extensions of FVS. Landscape simulations of this magnitude require immense use of the computer's hard drive to store stand-state information during the projection.

External Regeneration Model Examples

1: The Blue Mountains Model

Based on advanced FFE-PPE research studies led by Alan Ager, a new keyword—AddTrees—was incorporated into the Regeneration Establishment model source code. Figure 4 shows an example of this new keyword coupled with an external version of the Blue Mountains model. The external model codes the same relationships presented in the Event Monitor version shown in figure 3 as a stand-alone executable ("BMEstab.exe") written in Fortran (Ager and others 2007; Robinson 2004). The model name is entered as a supplemental record following the AddTrees keyword and may be invoked directly or conditionally through the Event Monitor. Although the example in figure 4 runs an executable program, the external model could be a batch file, shell script, R-script, or web service (depending on the operating system and connectivity to the internet or other databases). As long as the external process given on the AddTrees supplemental record results in the creation of a file in a standard format (described below), FVS will process the contents of the returned file and schedule natural regeneration.

The relationship between FVS and the Blue Mountains model is shown schematically in figure 5. The left part of the figure shows the cyclical sequence of events for a single stand within the BM-FFE-PPE. During each projection cycle, any Establishment

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+ Keyword	fld1	fld2	fld3	fld4	fld5
1	If					
2	*Condition*					
3	Then					
4	Estab					
5	AddTrees	0	5	1		
6	BMEstab.exe					
7	End					
8	EndIf					

AddTrees Keyword

Field	Value	Notes
1	0	Years after *Condition* is true that the AddTrees keyword is scheduled
2	5	Years after AddTrees is run to schedule a Natural planting; age to assign new trees
3	1	Method 1 signals FVS to (1) read a single supplemental record containing an executable filename; (2) submit and run the named executable using a System call, appending a command line argument containing the ES1 filename after any other command line arguments; (3) read the ES2 output file created by BMEstab; and (4) use the content of that file to schedule Natural keywords in FVS.

Figure 4—An example showing how the AddTrees keyword is used as part of a sequence of establishment model keywords with the Blue Mountains regeneration model. Assuming a 10 model year time step, this keyword set simulates natural regeneration 14 years after the *Condition* becomes true. Additional details are found in the text.

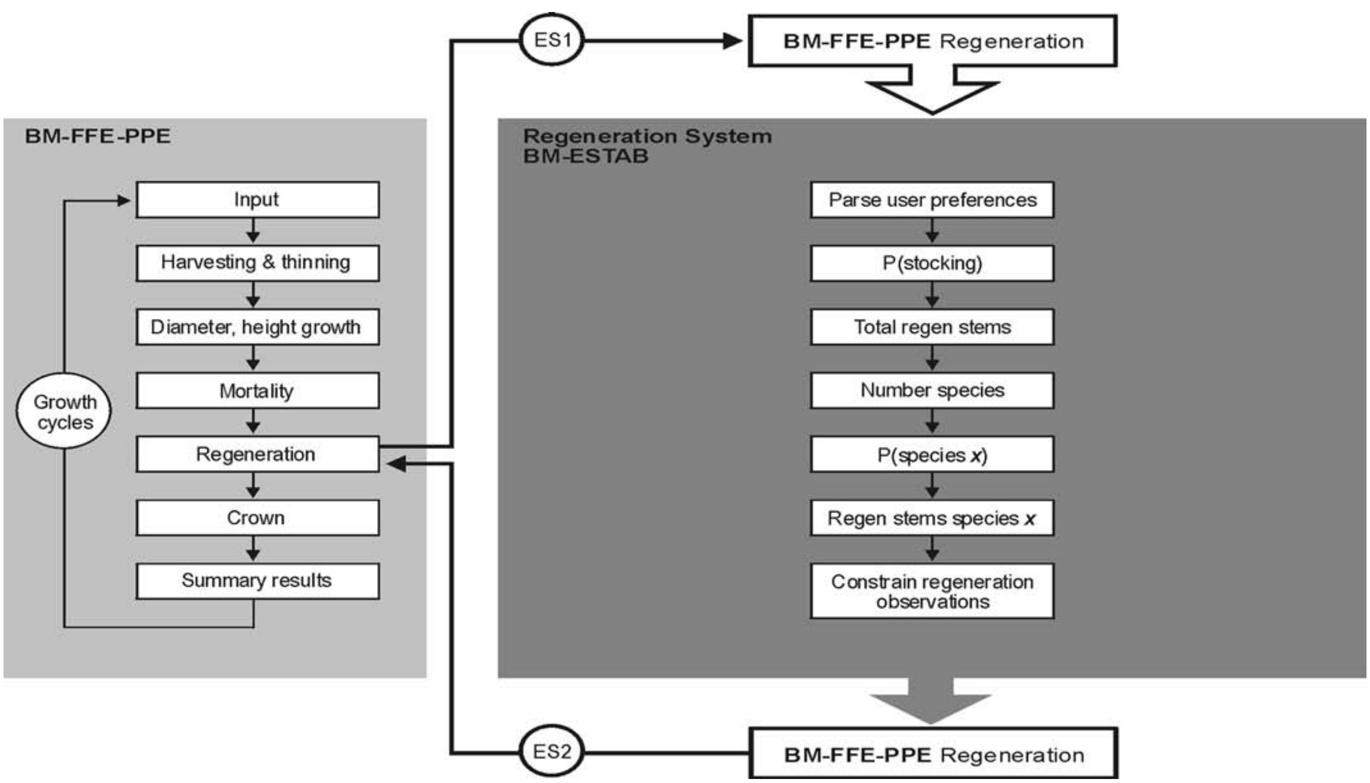


Figure 5—A simplified sequence of events is shown for predicting regeneration in a single stand within the BM-FFE-PPE. Additional details are found in the text.

model keywords are invoked at the end of the cycle, just prior to the creation of summary reports. When the AddTrees keyword is processed, a formatted text file (labeled ES1) is created by FVS. Then a call is sent by FVS to the operating system to run the Blue Mountains model (right side of fig. 5). The Blue Mountains model reads the ES1 file containing stand-state information for the projection cycle and predicts regeneration for the stand. Predicted regeneration is written to a second formatted text file (labeled ES2 in fig. 5). The Blue Mountains model exits and FVS resumes operation, reading the ES2 file and possibly scheduling natural regeneration keywords in a subsequent cycle.

The ES1 file is automatically created using instructions written in the FVS Fortran subroutine "esaddt.f." The prefix given to the ES1 file is a concatenation of the name of the FVS keyword file, the Stand Identifier, the FVS model year in which the file is created, and the 2-letter variant code. For example, given a keyword file "bmtest.key" containing a StdIdent keyword followed by "0404064" with the Blue Mountains model scheduled for 2010, the full name of the ES1 file would be:

bmtest_0404064_2010_BM.ES1

The actual content of the file is tailored to the needs of the Blue Mountains model as shown in figure 6.

When the Blue Mountains model starts, it searches for an initialization (INI) file of user preferences called "BMEstab.ini." In this model, the file contains three user-defined model parameters (fig. 7) that provide the model user with the flexibility to tune the model behavior if desired. As described more fully in Wilson and others (2003), the first of these parameters scales predicted regeneration up or down by a multiplier; and the second sets a probability threshold that can change the presence or absence of regeneration. The final parameter of the INI file allows the user to specify whether all intermediate files (ES1 and ES2) are to be kept after the run or whether they are to be automatically deleted.

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+	
1	bmtest	Stand ID
2	2011	calendar year to schedule
3	5	fld 2 of AddTrees keyword
4	49	FVS habitat code
5	40	slope (%)
6	90	aspect (degrees)
7	5000.0	elevation (ft)
8	259.1	before-thin Stand Density Index
9	259.1	after-thin Stand Density Index
10	121.0	basal Area (ft^2/ac)
11	121.0	after-thin basal area (ft^2/ac)
12	358.1	stem/ac (all species >1" dbh)
13	0.0	ABGR stem/ac (<1" dbh)*
14	0.0	ABLA stem/ac (<1" dbh)
15	0.0	LAOC stem/ac (<1" dbh)
16	0.0	PICO stem/ac (<1" dbh)
17	0.0	PIMO stem/ac (<1" dbh)
18	0.0	PIEN stem/ac (<1" dbh)
19	79.8	PIPO stem/ac (<1" dbh)
20	0.0	PSME stem/ac (<1" dbh)

* ABGR = *Abies grandis*; ABLA = *Abies lasiocarpa*; LAOC = *Larix occidentalis*; PICO = *Pinus contorta*; PIMO = *Pinus monticola*; PIEN = *Picea engelmannii*; PIPO = *Pinus ponderosa*; PSME = *Pseudotsuga menziesii*

Figure 6—The Blue Mountains model requires 20 lines of information written by FVS to an ES1 file. These include stand ID, calendar scheduling, site information, before- and after-thin stand information and information about small trees already present in the stand. This example has been annotated by adding comments after column 30; a working version is right-justified at column 30 without any comments.

Line Nmbr	Column ruler ----+----1----+----2----+----3----+----4----+----5----+----6----+
1	1.1 Multiply (default 1.0)
2	0.1 P_Add (default 0.5)
3	0 Keep: (default 1 = .TRUE.)

Figure 7—The Blue Mountains model searches for an INI file (described in the text) which can be used to adjust some aspects of the model's behavior. Users also have the choice of keeping or automatically deleting intermediate files for later inspection.

Line Nmbr	Column ruler 1 Keyword	2 fld1	3 fld2	4 fld3	5 fld4	6 fld5	7 fld6	8 fld7	9 fld8
1	1								
2	Bmtest								
3	431	2011	6	10	82	80	0	3	0
4	431	2011	6	3	243	80	0	3	0
5	431	2011	6	7	567	80	0	3	0
6	431	2011	6	4	367	80	0	3	0
7	End								

Line	Field	Value	Notes
1		1	This file has one set of stand instructions,
2		Bmtest	The stand name given by the StdIdent keyword
3 – 6	1	431	The internal FVS code for the Natural keyword
	2	2011	The year in which to schedule natural regeneration
	3	6	The number or fields of data for the keyword
	4	10,…	Fld 1 of the Natural keyword: species code number
	5	82,…	Fld 2 of the Natural keyword: stems acre^{-1} to plant
	6	80,…	Fld 3 of the Natural keyword: % survival
	7 – 9		*All other fields required by the Natural keyword*
7		End	End of the 'Bmtest' stand

Figure 8—The Blue Mountains model creates an output ES2 file that is subsequently processed by FVS to carry out natural planting. This example schedules planting of 4 species in 2011. To accommodate space restrictions in this printout, some blank spaces have been removed from the lines.

As the Blue Mountains model finishes, it creates an ES2 output file using the same naming rules used to create the ES1 input file. Since the purpose of the file is to send establishment information from the Blue Mountains model back to FVS, the content of the ES2 file is tailored to the production of the Natural regeneration keywords that are part of the existing FVS establishment model. The total number of records in the ES2 file depends on the number of species to be regenerated but every run produces at least three records (see fig. 8). The first record is right-justified to column 10. Apart from the first line, subsequent records are not strictly column formatted. FVS source code recognizes the ES2 file and natural regeneration is scheduled.

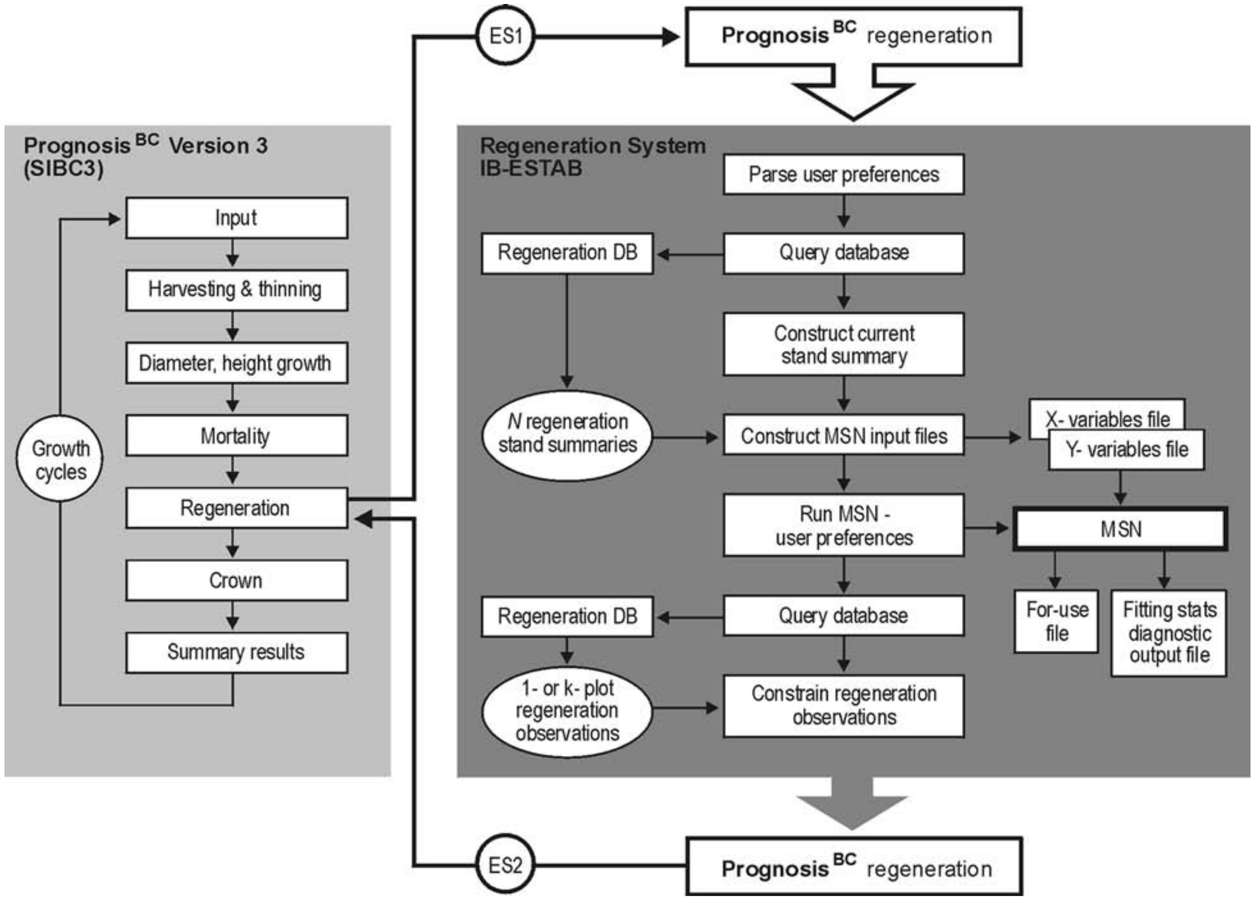


Figure 9—A simplified sequence of events is shown for predicting regeneration with Prognosis^BC^. Additional details are found in the text.

2: The Prognosis^BC^ Model

For the past 5 years, the FVS community in British Columbia has been developing regeneration models based upon linking a growing database of regeneration observations[3] to FVS (Prognosis^BC^) stand simulations using Moeur and Stage's (1995) Most Similar Neighbor (MSN) canonical procedure (Hassani and others 2004; LeMay and Temesgen 2005; Zumrawi and others 2005). The canonical procedure is implemented using MSN software (Crookston and others 2002), and as its prediction, selects the regeneration observed in the database stand that most closely matches the stand being simulated by Prognosis^BC^ (Robinson 2005). Like the Blue Mountains model, predictor variables include site and overstory variables. The Prognosis^BC^ model also includes variables for site disturbance, time since disturbance, and measures of overstory stand structure. A research application of the model has recently been developed for stands disturbed by mountain pine beetle. The site disturbance variables in this research application are replaced with stand snag variables. The framework that links Prognosis^BC^ with the MSN software and an Access database is shown in figure 9 with an example keyword set shown in figure 10.

A comparison of the Blue Mountains (fig. 5) and Prognosis^BC^ models (fig. 9) shows the ability of a common framework to handle a range of model complexity. The Blue Mountains model is a single executable while the Prognosis^BC^ system involves an intermediate program interacting with a database to dynamically set up the necessary MSN files. The MSN software is then called automatically, a match is found, and the database is again queried for the detailed regeneration information. From the user's perspective, the two

[3] As of April 2007, the database held 1,234 unique stands (most with multiple plots, some with remeasurement), with records for over 24,000 large trees, 16,000 small trees, and almost 45,000 regenerating stems.

```
Line                          Column ruler
Nmbr   ----+----1----+----2----+----3----+----4----+----5----+----6----+
          Keyword      fld1      fld2      fld3      fld4      fld5
   1   Estab
   2   PlotInfo
   3            1         5
   4   -999
   5   BurnPrep          1997       100
   6   MechPrep          1999       100
   7   AddTrees          1999         0         2
   8   ..\Regen\IBestab.exe ..\Regen\regen.mdb ..\Regen\MSN.exe 1
   9   End
```

Line	Field	Value	Notes
1			Begin an Establishment model keyword block
2			Begin entering plot information
3			Plot 1 is a ridge top (fld2 =5)
4		–999	End of plot information
5			Burning site preparation: 100% of site burned in 1997
6			Mechanical site preparation: 100% of site treated in 1997
7			AddTrees keyword
	1	1999	Year to simulate regeneration
	2	0	Years after AddTrees is run to schedule a Natural planting; age to assign new trees
	3	2	Method 2 signals FVS to: (1) read a supplemental record containing an executable filename and all its command-line arguments; (2) submit and run the record using a System call, appending an additional command line argument containing the ES1 filename; (3) read the ES2 output file created by IBEstab; and (4) use the content of that file to schedule Natural keywords in FVS.
8			Supplemental record: relative path and name of executable; relative path and name of database file; relative path and name of MSN program; canonical distance method for MSN
9			End the Establishment model keyword block

Figure 10—An example showing how the AddTrees keyword is used as part of a sequence of establishment model keywords with the Prognosis^{BC} regeneration model. Additional details are found in the text.

example models differ only in the number of command line arguments provided with the supplemental record: zero in the case of the Blue Mountains model and four arguments in the case of the Prognosis^{BC} model[4].

Linking Models to FVS: The Caveats

Even after developing a credible model, it is necessary to carefully consider the relationship between an existing simulated FVS stand and the regeneration predicted at a particular projection time step. For example, the simulated stand may already have some regeneration or small trees present, and adding predicted regeneration might incorrectly add too many small trees. The Blue Mountains model addresses this possibility by explicitly providing information about small stems to the model (see fig. 6), and then subtracts these existing small stems from the predicted regeneration. In the case of an MSN-based procedure there may be changes in stand structure between the time of the

[4] As figure 4 notes, the AddTrees keyword automatically adds the ES1 filename following any command line arguments provided in the keyword file.

disturbance (and in some cases, difficulty even assigning a single date to the disturbance) and the time at which regeneration is measured. In this case, further analyses of the sensitivity of model parameters, combined with good judgment and heuristics, may be required to create a useful database.

Conclusions

The system enhancement described here is based on a simple interface with the FVS model and is suitable for external models that interact with FVS through the automatic creation of keywords[5]. Fortunately, the Regeneration Establishment system of FVS is well-suited to this kind of linkage and the current interface code is both localized (in one subroutine) and simple to modify using FVS Fortran code that is in the public domain. The requirements of the external regeneration system are also modest, and consist of any process that creates a formatted text file (see fig. 8) with regeneration instructions for FVS to process. Development of the external regeneration model process is independent of FVS. As long as measures of stand structure (see fig. 6) are provided to the external model, the external process can predict the regeneration outcome, which can also be examined and tested outside of the FVS architecture. In short, iterative model development and testing can all take place before FVS is even considered as the engine to drive overall stand development.

Every model building exercise involves tradeoffs between simplicity and complexity. A simpler model may be easier to conceive, understand, and debug, but may gloss over details that are important in some circumstances. Moreover, conceptual model development is never a linear process. Models frequently—some might say always—go through cycles of conceptual development followed by experimental testing, refinement, further field work, and validation; only to be abandoned and re-emerge as newer models. Forest modelers and experimenters are equal and mutually dependent partners in this cycle, continually evaluating what to measure, when to measure, and how to measure the variables that drive regeneration.

Providing a means to invoke novel regeneration models is not a panacea for the shortage of existing models in FVS. Although one hurdle has been removed, the scientific work of creating such models still needs to be done, along with the substantial field work and validation required of every empirical or theoretical model.

Acknowledgments

We express our appreciation to Alan Ager for initially supporting the development of the software concept for the Blue Mountains regeneration model and to Nick Crookston and Dennis Ferguson for ideas, code, and helpful discussions. Programming of the Blue Mountains model was funded by the Pacific Northwest Research Station Focused Science Delivery Program. We also thank Valerie LeMay, Peter Marshall, Badre Hassani, Hailemariam Temesgen, and Abdel-Azim Zumrawi and their many graduate students for their collaboration in the development of the software linkages for the Prognosis^{BC} regeneration model. Programming of the Prognosis^{BC} model was funded by the BC Forest Science Program, Project Y051355. Kelly Robson provided help in preparing the figures, and our reviewers provided helpful suggestions and corrections.

References

Ager, A.A.; McMahan, A.J.; Barrett, J.J.; McHugh, C.W. 2007. A simulation study of thinning and fuel treatments on a wildland-urban interface in eastern Oregon, USA. Landscape Urban Planning. 80:292-300. doi:10.1016/j.landurbplan.2006.10.009.

Crookston, N.L. 1990. User's guide to the event monitor: part of Prognosis Model version 6. Gen. Tech. Rep. INT-275. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 21p.

Crookston, N.L.; Stage, A.R. 1991. User's guide to the Parallel Processing Extension of the Prognosis Model. Gen. Tech. Rep. INT-281. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 88 p.

[5] Components of FVS, such as the growth and mortality sabmodels, are based on equations that act upon individual tree records and present a performance challenge for linkage with external models.

Crookston, N.L.; Moeur, M.; Renner, D. 2002. Users guide to the Most Similar Neighbor imputation program Version 2. Gen. Tech. Rep. RMRS-GTR-96. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 35 p.

Ferguson, D.E.; Carlson, C.E. 1993. Predicting regeneration establishment with the Prognosis Model. Res. Paper INT-467. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 54 p.

Ferguson, D.E.; Crookston, N.L. 1984. User's guide to the regeneration establishment model—a Prognosis Model extension. Gen. Tech. Rep. INT-161. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 23p.

Ferguson, D.E.; Crookston, N.L. 1991. User's guide to version 2 of the Regeneration Establishment Model: part of the Prognosis Model. Gen. Tech. Rep. INT-279. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 34p.

Ferguson, D.E.; Stage, A.R.; Boyd, R.J., Jr. 1986. Predicting regeneration in the grand fir-cedar-hemlock ecosystem of the northern Rocky Mountains. Forest Science Monograph 26. 41p.

Hassani, B.; LeMay, V.; Marshall, P.L.; Temesgen, H; Zumrawi, A.A. 2004. Regeneration imputation models for complex stands of southeastern British Columbia. Forestry Chronicle 80:271-278.

LeMay, V.; Temesgen, H. 2005. Comparison of nearest neighbor methods for estimating basal area and stems per ha using aerial auxiliary variables. Forest Science 51:109-119.

Moeur, M.; Stage, A.R. 1995. Most similar neighbor: an improved sampling inference procedure for natural resource planning. Forest Science 41:337-359.

Reinhardt, E.D.; Crookston, N.L. (technical editors) 2003. The fire and fuels extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Robinson, D.C.E. 2004. The Blue Mountains Establishment Model: An externally executed program linked to the Forest Vegetation Simulator Establishment System. Prepared by ESSA Technologies Ltd., Vancouver, BC, for USDA Forest Service. 9 p.

Robinson, D.C.E. 2005. A regeneration model for Prognosis^{BC}. Prepared by ESSA Technologies Ltd., Vancouver, BC, for BC Ministry of Forests, Victoria, BC. 18 p.

Stage, A.R. 1973. Prognosis Model for stand development. Res. Paper INT-137. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 32 p.

Wilson, D.S.; Maguire, D.A.; Ager, A. 2003. Conifer regeneration modeling on the LaGrande Ranger District, Wallowa-Whitman National Forest, Oregon. Unpublished draft manuscript. 54 p.

Zumrawi, A.; LeMay, V.; Marshall, P.; Hassani, B.T.; Robinson, D. 2005. Implementing a Prognosis^{BC} regeneration sub-model for complex stands of southeastern and central British Columbia. Report to the Forest Science Program, Project No: Y051355. March 29, 2007, Available: http://www.forestry.ubc.ca/prognosis/documents/final_Overview_UBC_ESSA.pdf

The content of this paper reflects the views of the authors, who are responsible for the facts and accuracy of the information presented herein.

Publishing Services Staff

Managing Editor · Lane Eskew

Page Composition & Printing · Nancy Chadwick

Editorial Assistant · Loa Collins

Contract Editor · Kristi Coughlon

Page Composition & Printing · Connie Lemos

Distribution · Richard Schneider

Online Publications & Graphics · Suzy Stephens

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

The Rocky Mountain Research Station develops scientific information and technology to improve management, protection, and use of the forests and rangelands. Research is designed to meet the needs of the National Forest managers, Federal and State agencies, public and private organizations, academic institutions, industry, and individuals. Studies accelerate solutions to problems involving ecosystems, range, forests, water, recreation, fire, resource inventory, land reclamation, community sustainability, forest engineering technology, multiple use economics, wildlife and fish habitat, and forest insects and diseases. Studies are conducted cooperatively, and applications may be found worldwide.

Station Headquarters
240 West Prospect
Fort Collins, CO 80526
(970) 498-1100

Research Locations

Flagstaff, Arizona
Fort Collins, Colorado
Boise, Idaho
Moscow, Idaho
Bozeman, Montana
Missoula, Montana
Reno, Nevada
Albuquerque, New Mexico
Rapid City, South Dakota
Logan, Utah
Ogden, Utah
Provo, Utah

The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, age, disability, and where applicable, sex, marital status, familial status, parental status, religion, sexual orientation, genetic information, political beliefs, reprisal, or because all or part of an individual's income is derived from any public assistance program. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD). To file a complaint of discrimination, write to USDA, Director, Office of Civil Rights, 1400 Independence Avenue, S.W., Washington, DC 20250-9410, or call (800) 795-3272 (voice) or (202) 720-6382 (TDD). USDA is an equal opportunity provider and employer.

Federal Recycling Program Printed on Recycled Paper