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Simulating Historical Landscape Dynamics Using the Landscape Fire Succession Model LANDSUM version 4.0

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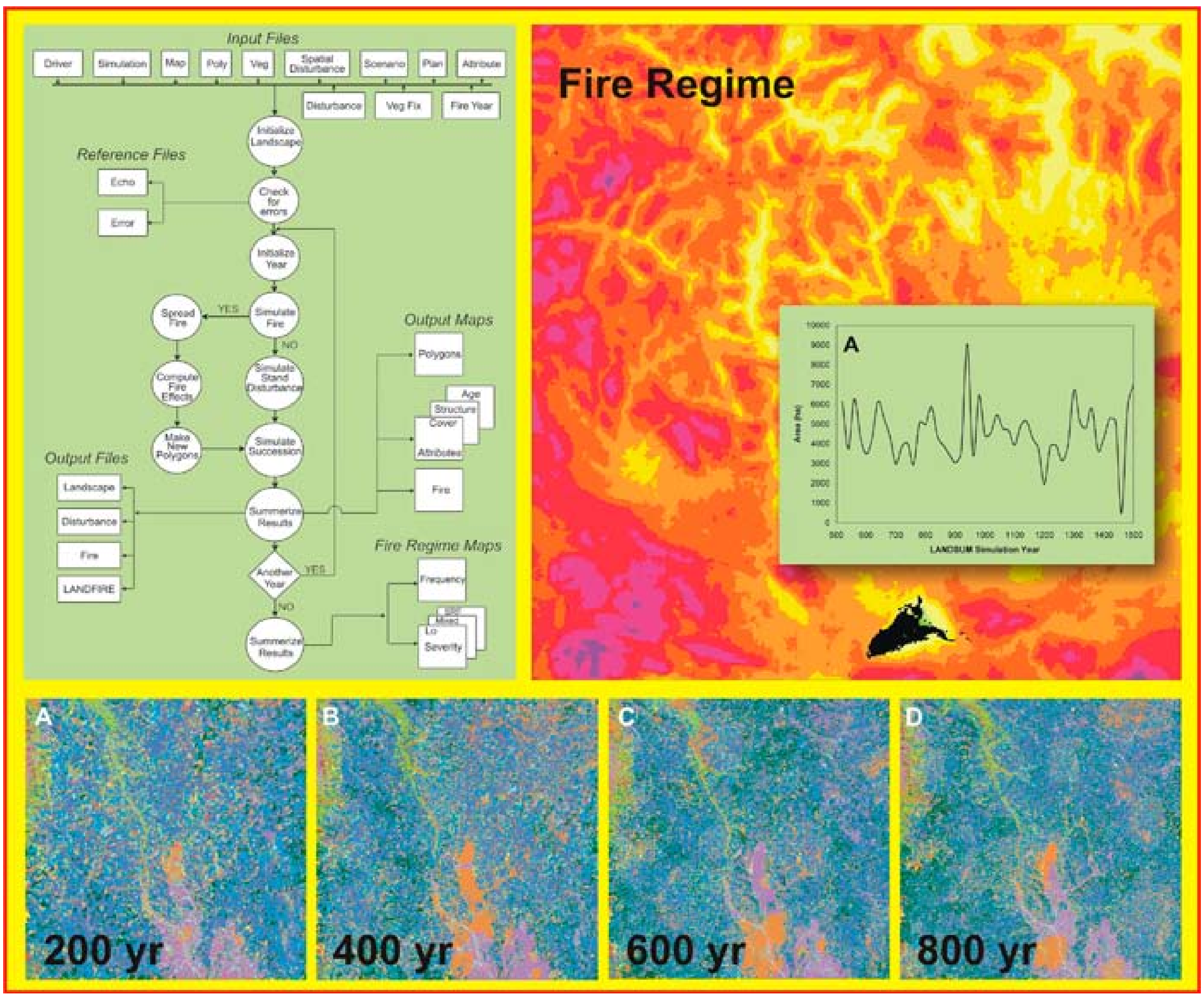
and Sarah D. Pratt**



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Abstract

The range and variation of historical landscape dynamics could provide a useful reference for designing fuel treatments on today's landscapes. Simulation modeling is a vehicle that can be used to estimate the range of conditions experienced on historical landscapes. A landscape fire succession model called LANDSUMv4 (LANDscape SUccession Model version 4.0) is presented here as a tool for estimating historical range and variation (HRV) of landscape characteristics. The model simulates fire and succession on fine scale landscapes for land management applications. It simulates vegetation development as a deterministic process by changing the species composition and stand structure assigned to a polygon. Disturbance initiation is modeled stochastically and disturbance effects are based on the current vegetation conditions of the polygon. Details of all model algorithms are discussed and the model is demonstrated for two applications. Results of an extensive sensitivity and model behavior analysis are also presented.

Key words: Historical range and variation (HRV), simulation modeling, LANDSUM, landscape modeling, landscape fire ecology, spatial modeling

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Research Summary

Current landscape management often requires an approximation of the range and variation of historical landscape characteristics and processes to use as a target or reference for designing effective ecosystem restoration or fuel reduction treatments. Temporally deep chronosequences of historical landscape conditions are rare because there are few useful spatial data layers and vegetation maps prior to the 1900s. Spatial simulation modeling provides a vehicle to understand historical landscape dynamics and to estimate the historical range of landscape conditions. This report presents a landscape fire succession model called LANDSUMv4 that is used to simulate fire and vegetation dynamics in a spatial domain and then details how this model was used to simulate the range and variation of historical landscape dynamics using examples from the LANDFIRE prototype project. LANDSUMv4 is the fourth version of the LANDSUM model and was developed specifically for the LANDFIRE prototype project, an effort to develop methods that integrate the sciences of remote sensing, biophysical modeling, and landscape simulation to produce nationally consistent and comprehensive maps of historical fire regimes, Fire Regime Condition Class (FRCC), and fuel characteristics. LANDSUMv4 contains a deterministic simulation of vegetation dynamics where successional communities are linked along multiple pathways of development that converge to a somewhat stable climax community in the absence of disturbance. Disturbances are stochastically modeled at the stand-level from probabilities specified by the user, except for fire. Fire is spread across the landscape based on simplistic slope and wind factors. Using historical disturbance probabilities and successional community pathways, LANDSUMv4 was applied to an example landscape to generate a time series of vegetation and disturbance conditions (area by vegetation or disturbance type) that is used to quantify the range and variation of historical landscape characteristics for the LANDFIRE project. An extensive sensitivity and model behavior analysis was performed on a number of important LANDSUMv4 parameters to determine their effect on simulation results and the results show that many polygon-level parameters, such as fire size, fire frequency, and succession transition times are important, but their importance varies by landscape and ecosystem.

Acknowledgments

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Introduction

The spatial arrangement, composition, and structure of vegetation communities on a landscape reflects the cumulative and interactive effects of past disturbance regimes, biophysical environments, and successional processes over long time periods (Baker 1989b, Bormann and Likens 1994, Crutzen and Goldammer 1993, Pickett and White 1985, Wright 1974). Most landscapes in the western United States are shaped primarily by wildland fire and vegetation succession, and conversely, the current landscape condition will invariably influence future fire patterns, species migration, and plant community development (Hessburg and others 1999a, Keane and others 2002d, Turner and others 1994, Veblen and others 1994).

Historical fluctuations in landscape characteristics, such as species composition and structure, can provide an important reference for evaluating the current condition of the same landscape. Moreover, a quantification of the fluctuations can be used to guide the design and implementation of management treatments. The historical range and variability (HRV) of patch sizes or percent species composition on a landscape can be used to plan the fuel treatments and prescribed fire activities (Cissel and others 1994, Mladenoff and others 1994, Swetnam and others 1999). For example, a preponderance of large patches in the historical record may indicate a fire regime dominated by large, severe fires and any prescribed fire program should attempt to mimic these types of historical burns (Baker 1989a, Baker and others 1991, Keane and others 1999, Keane and others 2002c). Current landscape conditions can also be compared with historical landscape conditions to detect ecologically significant change, such as that incurred by fire exclusion and timber harvesting (Baker 1992, Baker 1994, Hessburg and others 1999b, Landres and others 1999). This information can be used to plan and prioritize treatment areas where stands that have significantly departed from historical conditions may warrant treatment first.

This report presents the use of simulation modeling as a method of estimating historical landscape dynamics for reference to determine the departure of current landscapes from their historical fluctuations. The concepts of historical range and variation (HRV) are presented first, along with methods for their computation including a summary of landscape modeling. Then, a model called LANDSUMv4 is presented in detail. LANDSUMv4 is a modification of previous LANDSUM models (Keane and others 1996b, Keane and others 1997, Keane and others 2002c) but modified specifically as the primary vehicle to estimate landscape HRV for the LANDFIRE project (www.landfire.gov; Rollins and others, in press). The LANDFIRE project is a national mapping effort that integrates the sciences of remote sensing, biophysical modeling, and landscape simulation to produce nationally consistent and comprehensive maps of historical fire regimes, Fire Regime Condition Class (FRCC), and fuel characteristics for prioritizing, planning, and implementing fuel treatments (www.landfire.gov). The LANDSUMv4 section includes a full discussion of all algorithms, assumptions, and parameters and then instructions on how to run the model are presented. Next, LANDSUMv4 results for several nested landscapes in Utah and Montana are shown to demonstrate the simulation output needed to approximate landscape composition HRV. Then, the behavior of model was explored to document the strengths and limitations of using this simulation model to describe HRV dynamics using a hierarchical sensitivity analysis. Recommendations and limitations on running the model are finally presented, including demonstrations of using HRV calculations to compute departure indices. Results from this effort can be used to plan and implement landscape-scale ecosystem management activities.

Historical Range and Variability (HRV)

Landscape structure and composition describe patch distributions and biotic characteristics for a spatially defined area that will be referred to as a "landscape" in this report. The spatial and size distribution of patches describes landscape structure; while landscape composition is described by the relative abundance of ecosystem features across the spatial domain (percent area by cover types, for example). The term "patches" is synonymous with stands or polygons in this paper, where polygons refer to mapped stands. Ecosystem features, such as the dominant plant species (cover type) or vertical stand structure (structural stage), or disturbance processes, such as fuel models and fire regime, can be related to each polygon. Landscape composition can be summarized from spatial data layers using standard GIS techniques to estimate the area by composition category (area by cover type, for example).

Many types of landscape metrics are used to quantitatively describe patch dynamics for landscape structure such as mean patch size and largest patch index. They are calculated by importing spatial thematic data layers, usually from a Geographic Information System (GIS), into any of the many landscape metrics programs available (Baker and Cai 1992, McGarigal and Marks 1995, Turner and Gardner 1991). However, this report is concerned only with landscape composition to determine HRV because it was the primary characteristic used by the LANDFIRE effort (www.landfire.gov) to describe historical reference conditions (Rollins and others, in press). However, the methods and models discussed here can also be used to determine the HRV of landscape structure (Keane and others 1999, Keane and others 2002b, Stewart and Arno 1997, for examples).

As mentioned, historical range and variability (HRV) of landscape compositional characteristics provides a useful concept for prioritizing, planning and designing landscape treatments at multiple scales (Keane and others 2002b, Landres and others 1999, Swetnam and others 1999). In this report, we define HRV as the quantification of temporal fluctuations in ecological processes and characteristics prior to European settlement (before 1900). Naturally, HRV is highly scale-dependent and inherently unstable due to climate change, human land use, and geologic processes. The variability of ponderosa pine cover across a landscape, for example, depends on the range of years used to compute the HRV statistics; fluctuations over a 1,000 year period taken 10,000 years ago at the end of the last ice age would be dramatically different from a recent 1,000-year time slice.

To use HRV in an operational context, it must be assumed that the record of historical conditions more or less reflects the range of possible conditions for future landscapes; an assumption that we now know is overly simplistic because of documented climate change, exotic introductions, and human land use. But, despite its drawbacks, the HRV concept has the potential to be indispensable to ecosystem management because it can be used to define limits of acceptable change and compare historical and current stand or landscape condition to prioritize for restoration treatments (Hessburg and others 1999a, Swetnam and others 1999). Since HRV estimates do not integrate past and future trends resulting from climate change and human activities, we feel that HRV is NOT the final answer to land management planning, but it does provide a good reference point or target for planning future management projects (Keane and others 2002c).

The range and variation of historical landscape dynamics can be quantified from three main sources. The best sources are spatial chronosequences defined as sequences of maps from one landscape over many time periods. These maps can be digitized with GIS software so that landscape analysis programs can be used to compute HRV in landscape composition and pattern. Unfortunately, temporally deep spatially explicit chronosequences of historical landscape conditions are absent for many western landscapes because aerial photography and satellite imagery were rare or non-existent before 1930 and comprehensive maps of forest vegetation are scarce and inconsistent prior to 1900. Other sources are vegetation maps from many similar, unmanaged landscapes, taken from one or more time periods, that are gathered across a geographic region and used to quantify the HRV of landscape characteristics (Hessburg and others 1999a, Hessburg and others 1999b). This spatial series essentially substitutes space for time and assumes all landscapes in the series contain highly similar environmental, disturbance, topographical, and biological conditions (Pickett and others 1987). The primary limitation of this assumption is that subtle differences in landform, relief, soils, and climate make each landscape unique (Keane and others 2002c). Landscapes may be similar in terms of the processes that govern vegetation, such as climate, disturbance, and species succession (Hessburg and others 2000), but this does not ensure that fire growth, pattern, and occurrence dynamics will be similar across the similar landscapes because of subtle differences in topography, orientation, and wind direction (Keane and others 2002b).

The third method of quantifying HRV involves simulating historical dynamics to produce a chronosequence of simulated maps to compute landscape statistics and metrics. This approach assumes that succession and disturbance processes are simulated accurately in space and time, and that the spatial properties of the disturbance and succession simulation are reflected in the patch dynamics (Keane and others 1999). Many spatially explicit ecosystem simulation models are available for quantifying HRV patch dynamics (Gardner and others 1999, Keane and Finney 2003, Keane and others 2004b, Mladenoff and Baker 1999), but most are computationally intensive, difficult to parameterize and initialize, and complex in design, thereby making them difficult to use across large regions over long time periods. On the other hand, those landscape models designed specifically for management planning tend to oversimplify successional development and disturbance initiation, spread and effects (Keane and others 2004b). Even the most complex landscape models rarely simulate direct spatial interactions between biophysical environments, fire dynamics, and vegetation development because of the lack of research in those areas and the great computer resources required for such an effort. However, simulation models can include explicit simulations of climate and human activities to generate more relevant estimates of the range and variation of landscape dynamics.

The problem then is how to obtain an historical time series (a record of landscape composition and structure over time) that could be used as reference to calculate HRV landscape statistics consistently and comprehensively for any landscape in the United States. Spatial chronosequences derived from historical maps are impossible because of the limited historical depth and inadequate and inconsistent coverage across the nation. Space-for-time substitutions are difficult because landscape similarity is difficult to assess and it is highly dependent on scale, recent disturbance history, and topography. It appears that simulated chronosequences may be the only alternative for large scale mapping efforts, but they also have limitations. This report is concerned only with the simulation approach for generating HRV landscape statistics because we feel that it is the most viable alternative at this time.

A simulation approach was taken in the LANDFIRE prototype project for estimating HRV because it was determined to be the only approach that could guarantee a consistent estimation of HRV statistics for all ecosystems, landscapes, and geographic regions of the United States (Pratt and others, in press, Rollins and others, in press). The LANDFIRE prototype project was dedicated to developing methods to map vegetation, fuels, and fire regime condition classes across the entire contiguous United States (National LANDFIRE Project; www.landfire.gov). A fire regime condition class (FRCC) is a three category index that reflects the degree of departure of current landscape conditions from historical landscape conditions. The LANDFIRE effort uses output from the spatial simulation model presented in this paper to describe historical landscape conditions that, in turn, are used as a reference for computing FRCC. This simulation approach also allows the generation of multiple time series reflecting alternate landscape histories so that a full complement of range and variation statistics can be computed to more extensively manage landscapes. For example, a climate change scenario could be simulated to generate a temporal stream of landscape composition data reflecting landscape behavior under future climate, or the invasion of exotics can be integrated into the succession parameters to include their influence on historical departures. The simulation approach is easily replicated so new HRV landscape statistics can be generated as new and improved spatial models are developed, and as more accurate input parameters are measured on the landscape.

Landscape Simulation Models

A class of simulation models, called landscape fire succession models (LFSMs), can be used to generate time series of landscape characteristics to quantify HRV (Keane and others 2004a). These models simulate the linked processes of fire and succession in a spatial domain. Although the complexity of spatial relationships of vegetation, fire ignition, and fire spread may vary from model to model, all LFSMs, by definition, produce time-dependent, georeferenced results in the form of digital maps or GIS layers. Several references provide excellent reviews of existing LFSMs. Keane and others (2004b) reviewed 44 LFSMs and then classified them into similar groups based on scale of application, simulation detail, and fire modeling approaches. Baker (1989b) examined several models of landscape change and grouped them into whole, distributional, and spatial landscape models depending on the level of data aggregation. Details of some landscape models are also presented in Mladenoff and Baker (1999). A review of spatial fire spread and effects models is provided by Gardner and others (1999), while and Keane and Finney (2003) present a summary of fire and succession modeling efforts.

Several existing landscape models provide examples of the diverse approaches used to simulate landscape, climate, and fire dynamics. At the complex end, Fire-BGC integrates the FOREST-BGC biogeochemical model (Running and Coughlan 1988, Running and Gower 1991) with the FIRESUM gap model (Keane and others 1989) to simulate climate-fire-vegetation dynamics (Keane and others 1996c). The LANDIS model was used to evaluate fire, windthrow, and harvest disturbance regimes on landscape pattern and structure (He and Mladenoff 1999, Mladenoff and others 1996, Mladenoff and He 1999). Fire is indirectly simulated at the stand-level by quantifying fire effects based on age class structure, and succession is simulated as a competitive process driven by species life history parameters. Roberts and Betz (1999) used life history parameters or vital attributes (Noble and Slatyer 1977) to drive succession in their polygon-based model LANDSIM that also simulates fire effects at the polygon level without a fire spread model. The DISPATCH model of Baker (1992, 1993, 1999) stochastically simulates fire occurrence and spread based on dynamically simulated weather, fuel loadings and topographic setting, and then simulates subsequent forest succession as a change in cover type and stand age. Miller and Urban (1999) implemented a spatial application of fire in the Zelig gap model to assess the interaction of fire, climate, and pattern in Sierra Nevada forests. More simplistic approaches include the SIMPPLLE model (Chew 1997, Chew and others 2003) that uses a multiple pathway approach to simulate succession on landscape polygons and a stochastic approach to simulate fire. This same theme can be found in the FETM, VDDT, and LANDSUM models by Schaaf and Carlton (1998), Kurz and others (2000), Keane and others (2002c), respectively. Any one of the models mentioned here could be used to estimate landscape composition HRV for evaluation of potential departure to use in planning and implementation. This paper concerns one particular model – the LANDSUM model (Keane and others 1997, Keane and others 2002c) – selected for application in the LANDFIRE project.

The Model

General Description

The LANDscape SUccession Model version 4.0 (LANDSUMv4) is a spatially explicit vegetation dynamics simulation C program wherein succession is mostly simulated as a deterministic process and disturbances (for example, fire, insects, and disease) are modeled as stochastic processes. LANDSUMv4 is the fourth major revision of the original LANDSUM developed to simulate alternative management scenarios on small landscapes delineated by polygons (Keane and others 1997). The current model is a spatial state-and-transition stand-level succession model with a spatially explicit fire model that simulates fire growth using a cell percolation method. LANDSUM is a descendent of the CRBSUM model used to simulate coarse scale vegetation dynamics in the interior Columbia River Basin at a 1 km pixel resolution (Keane and others 1996b). CRBSUM was altered to create LANDSUM by changing spatial resolution from the 1 km pixel to a polygon level to simulate fine scale disturbance and succession processes (Keane and others 1997). A spatially explicit fire spread algorithm was included later to realistically simulate landscape patch dynamics over time and the new model revision (LANDSUM version 2.0) was used to explore the limitations and implications of using a simulation approach to describe landscape dynamics

(Keane and others 2002b, 2002c). A simplistic climate driver was then included to create LANDSUM version 3.0 to simulate fire regimes (Keane and others 2004b) and contrast results to other LFSMs (Cary and others 2005). This current version (version 4.0) contains extensive refinements to the fire spread and successional development algorithms, and it allows options for easily importing and exporting LANDFIRE data layers.

LANDSUMv4 simulates succession within a patch (adjacent similar pixels) or polygon using the multiple pathway succession modeling approach presented by Kessell and Fischer (1981) that was based on the seminal work of Noble and Slatyer (1977), Cattelino and others (1979), and Davis and others (1980). This approach assumes all pathways of successional development will eventually converge to a stable or climax plant community called a Potential Vegetation Type (PVT) (fig. 1). A PVT identifies a distinct biophysical setting that supports a unique and stable climax plant community under a constant climate regime (Daubenmire 1966, Pfister and Arno 1980). In LANDSUMv4, a PVT can have multiple climax plant species indicators to identify broad trends in successional dynamics. There is a single set of successional pathways for each PVT on the

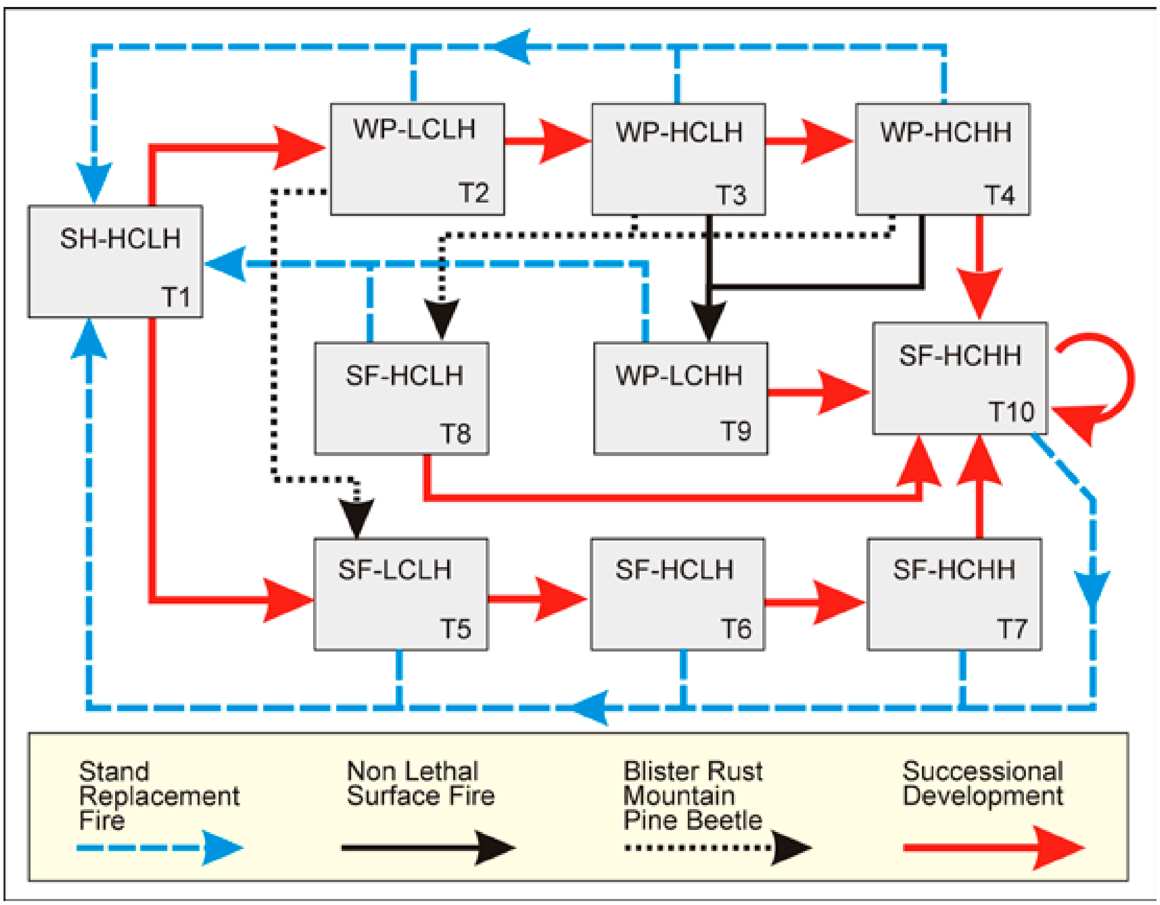


Figure 1—An example of a subalpine fir succession PVT (Potential Vegetation Type) pathway model used in LANDSUMv4. Succession pathways are defined by sequences of succession classes named for cover type and structural stage. Cover type names are as follows: SH-mountain shrub, WP-whitebark pine, SF-subalpine fir. Structural stage names are defined as: LCLH-low cover low height early succession stage, HCLH-high cover low height mid-seral stage, HCHH-high cover high height late succession stage, LCHH-low cover high height disturbance maintained late succession stage. Labels T1-11 identifies unique succession classes. Fire, beetle, and blister rust disturbance pathways are also shown.

simulation landscape (Arno and others 1985, Steele 1984) (fig. 1). Each pathway is composed of a sequence of plant communities called succession classes that are linked along gradients of vegetation development. Each succession class is represented by a cover type (dominant species) and a structural stage (vertical and horizontal stand structure). Successional development within a polygon is simulated at an annual time step where the polygon's succession class would change if the length of time spent in the current succession class (transition time) exceeds a user-defined input parameter (called maximum residence time in a succession class) that is held constant throughout the simulation. The PVT of a polygon never changes throughout the simulation, but the succession class is dynamic depending on disturbance regime and successional development rate.

Static PVTs are a major limitation of LANDSUMv4. Since PVTs are determined over time by biophysical processes, such as climate, that are constantly changing (global climate change, for example), ideally the PVTs should also change throughout simulation time. Unfortunately, the simplistic structure and limited input parameters in LANDSUMv4 do not allow a dynamic simulation of the biophysical processes that affect PVTs. An effort is underway to develop empirical models that migrate PVTs across the landscape as the climate changes and human land use affects long-term successional trajectories.

Disturbances can disrupt succession by delaying or advancing the time spent in a succession class, or they can cause an abrupt change to another succession class (see disturbance pathways in fig. 1). Occurrences of human-caused and natural disturbances are stochastically modeled from probabilities based on historical frequencies. All disturbances are simulated at a polygon-level, except for wildland fire, which is simulated as a spatial cell spread process across the landscape, as discussed in the next section. Only one disturbance can be simulated in a polygon during a simulation year.

We selected LANDSUMv4 as the landscape model to use in LANDFIRE because its minimal number of inputs and generalized structure allows it to be portable, flexible, and robust with respect to geographic area, ecosystem, disturbance regime, and available expertise (Keane and others 1996b). More complex models, such as LANDIS (Mladenoff and others 1996), might have generated more realistic landscape simulations, but the extensive parameterization required to run the model for every ecosystem and landscape in the United States probably would have been difficult. The more complex models probably would also have had prohibitively long execution times to generate sufficient time series to adequately capture historical fluctuations, especially on landscapes with infrequent fires. Less complex models, such as TELSA (Kurz and others 1999) or SIMPPLLE (Chew and others 2003), would have been easy to parameterize but these models did not adequately simulate the spatial dynamics of fire spread and effects to allow variation in landscape composition and structure to be fully assessed. LANDSUMv4 seemed a good balance between feasibility and realism, especially for the LANDFIRE project. The LANDSUM design allowed the addition of any stand-level disturbance, succession pathway, and succession development sequence as long as the event occurred within the one-year internal time step. Moreover, the aspatial succession model VDDT (Beukema and Kurz 1998) was modified for the LANDFIRE prototype project so that pathways in LANDSUM could be easily created and tested outside of the spatial environment to facilitate efficient pathway development and implementation (see later sections).

Some terminology must be defined to fully understand the following sections. First, polygons are stands or patches that have been mapped in a digital environment such as a GIS (Geographical Information System). Polygons in LANDSUMv4 are delineated by pixels of identical PVT, cover type, and structural stage combinations. All spatial data in LANDSUMv4 are stored in raster format, which is a grid of square pixels often measuring 30 meters on a side. A succession class is defined by a cover type and structural stage and the developmental sequence of succession classes is called a pathway (fig. 1).

The succession simulation in LANDSUMv4 is similar to that presented in Keane and others (1996b) for CRBSUM, while the spatial fire spread and effects

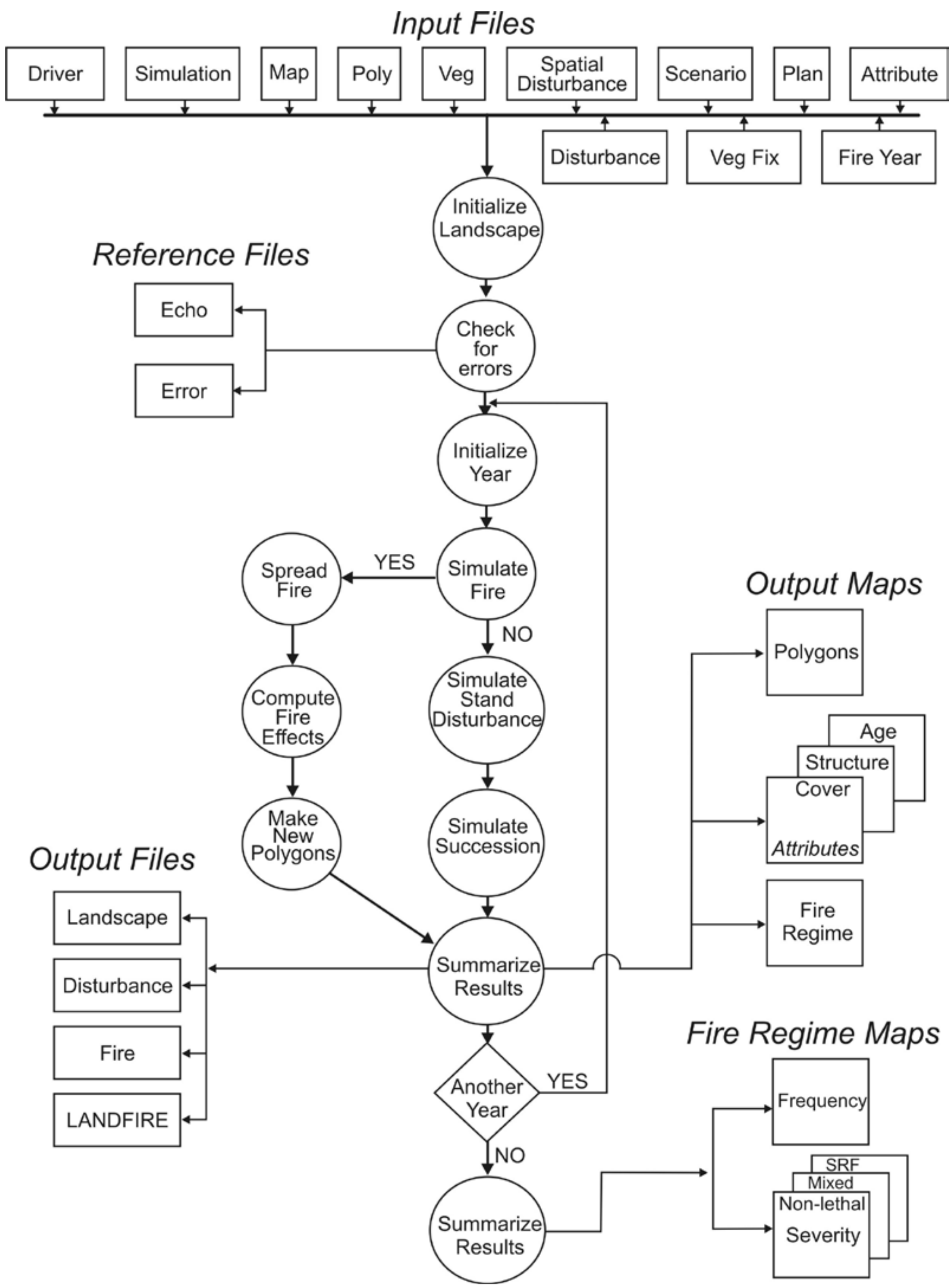


Figure 2—The flowchart for LANDSUMv4 execution. Square and retangular boxes indicate input and output data while the circles represent algorithms.

simulation is detailed in Keane and others (2002c). The following sections were taken mostly from these two references and modified to reflect the extensive refinements in LANDSUMv4. The following sections also contain references to input and output files utilized by LANDSUMv4 and these files are documented in Appendices A.1 thru A.13 (input files) and Appendix B.1 (output files). The uses of these files are detailed in the Model Execution section. A flow diagram showing the simulation logic within the model is shown in figure 2 for reference while reading the following sections.

Model Algorithms

Simulating succession**—**LANDSUMv4 simulates succession within a polygon using the multiple pathway modeling approach at an annual time step. This approach assumes all pathways of successional development will eventually converge to a stable or climax plant community called the potential vegetation type (PVT) (fig. 1). There is a single set of successional pathways for each PVT present on a given landscape (Arno and others 1985). The length of time a polygon remains in a succession class is called the residence time (years). It is defined by a range of succession ages (beginning and ending succession age, for example, 50-100 years) and this range is held constant throughout the simulation. The beginning and ending succession ages and transition succession classes are specified for every PVT-succession class combination in the Vegetation Input File (see later sections, Appendix A.7). Transition times for the last succession class in a pathway should be longer than the simulation time span. The number of successional pathways in a PVT is dictated by the input map legend, diversity of succession communities in the PVT, and the number of disturbances possible on the landscape.

Succession is simulated in LANDSUMv4 by increasing the succession age of a polygon by a single year after one year of simulation if no disturbances are simulated (see next section). When the succession age of a polygon exceeds the user-defined ending succession age for its succession class, a succession event is modeled where the polygon transitions to a new succession class. The polygon is assigned a new succession class as specified in the Vegetation Input File (Appendix A.7) and a new set of parameters are used for disturbance simulation (see next section).

Simulation time (number of years in simulation) and succession age are not always related in a LANDSUMv4 simulation because disturbances can retard or advance the succession clock. Succession age is simulated in years but it is more a measure of successional development rather than the actual age of the polygon. For example, a polygon in a grass-herb succession class, which normally has a succession class lifespan (transition time) of 30 years, might spend over 200 years in this succession class because disturbances such as grazing and fire keep decrementing the succession age and thereby preventing the transition to the next succession class. So, the succession age of the polygon might be 25 years but it might have been 200 years since it transitioned to that class because of repeated disturbance. Since the model outputs succession age in maps and tables, it is important that the user understand that this output age is not the same as the time since the last disturbance event.

Simulating disturbances**—**Except for fire, all disturbances in LANDSUMv4 are simulated at the polygon or stand level as a simple stochastic process using occurrence probabilities. The program generates a random number, and if the random number is less than the user-specified probability, a disturbance is simulated. The probabilities are assigned by the user to PVT and succession class combinations in the Scenario Input File (Appendix A.11). It is assumed that the occurrence and effects of all non-fire disturbances simulated for a polygon do not depend on the spatial relationships of adjacent polygons or the position the polygon occupies on the landscape. The spread of simulated non-fire disturbances is confined to the boundaries of the polygon. This assumption may be valid for many biotic and abiotic disturbances, such as grazing and browsing, but it is certainly not realistic for multi-host, wide-spread disturbances, such as mountain pine beetle. However, the lack of research and modeling in landscape level disturbance dynamics coupled with the complexity of interactions of disturbance processes with vegetation dynamics preclude a landscape level simulation approach for all disturbances at this time. LANDSUMv4 has the ability to spread non-fire disturbances across the landscape once the process has been fully studied and estimation of spatial parameters is possible (Keane and others 2002c).

Disturbances and succession processes that act at temporal scales finer than the one-year LANDSUMv4 time step, such as drought and frost kill, should not be included in the Disturbance Input File (Appendix A.8) unless their effects are manifest at the end of a single year. Mechanistic disturbance processes, such as insect population dynamics, spread, and migration, are not explicitly modeled in LANDSUMv4. Rather, the incidence or initiation of a disturbance is simulated from probabilities in the Scenario Input File (Appendix A.11) and the effect of that disturbance is simulated as a change in succession age and/or succession class as specified in the Disturbance Input File (Appendix A.8). Those disturbances that don't significantly affect the successional development of a polygon should not be included in a simulation. For example, dwarf mistletoe infections in some lodgepole pine landscapes may not significantly alter the amount of time spent in a succession class so it probably should not be included in the Disturbance or Scenario Input Files (Appendix A8, A.11).

In LANDSUMv4, there are two phases of disturbance simulation: the initiation phase and the effect phase. As mentioned, all fire and non-fire disturbances in LANDSUMv4 are initiated for a polygon using a stochastic approach based on probabilities specified for PVT and succession class combinations in the Scenario Input File (see Appendix A.11). Each year, the model cycles through the list of polygons in the exact order specified in the Polygon Input File (fig. 2, Appendix A.5). For each polygon, the model then evaluates each disturbance listed for the polygon's PVT-succession class combination in the order entered in the Scenario Input File (Appendix A.11) for the scenario specified for that management zone and simulation time span in the Management Plan Input File (Appendix A.10). The model generates a random number from a uniform distribution for the first disturbance evaluated, and if the random number is less than the probability of the disturbance, that disturbance is simulated and no other disturbance is evaluated. If the random number is greater than the disturbance probability, then the probability of the next disturbance in the list is added to the first to obtain a cumulative probability. If the random number is less than this cumulative probability, the second disturbance is then simulated and no other disturbances are evaluated. This stochastic process is repeated for every disturbance in the list. Succession (incrementing succession age by one year) is only simulated (see above section) if no disturbances occur. If the new succession age is greater than the ending age for the polygon's current succession class, the polygon would be assigned a new succession class according to the sequence specified in the Vegetation Input File (Appendix A.7). It is assumed that all disturbance occurrences are independent of each other and that the PVT-succession class combination and succession age are sufficient to represent changes in stand composition and structure caused by disturbance. The same probabilities are used for each year of simulation unless otherwise specified in the Management Plan Input File (Appendix A.10).

The modification of the disturbances and their associated probabilities in the Scenario Input File (Appendix A.11) represents the only way to develop simulation scenarios in LANDSUMv4. A simulation scenario is actually a set of disturbances for each PVT-succession class combination coupled with their relevant occurrence probabilities. For example, an historical scenario would consist of a unique set of native disturbances with occurrence probabilities that represent their frequency on the historical landscape for each PVT-succession class combination (for example, stand-replacement fire with a probability of 0.01 or 100 year fire return interval). However, a scenario describing current fire management would probably have the same native fire disturbances (stand-replacement fire) but at significantly lower probabilities (0.005 or 200-year fire return interval) to reflect fire suppression activities, and, the disturbance list would also include a set of human-induced disturbances such as weed invasion, prescribed burning, thinning, or timber harvest with associated probabilities.

Each set of disturbance probabilities for the PVT-succession class combinations on the simulation landscape represent a “scenario” in LANDSUMv4. The user can assign scenarios across time and space during the simulation using the Management Plan Input File (Appendix A.10). Scenarios can be assigned in space by assigning each polygon a management zone as requested in the Polygon Input File (Appendix A.5) and a unique scenario can be specified for each management zone in the Management Plan Input File (Appendix A.10). The user can also specify the application of a scenario across a specific span of years during the simulation for each management zone. For example, all polygons within a wilderness area might be assigned a unique management zone and a set of three scenarios would be built to reflect disturbance occurrence for the wilderness area during three time phases: a pre-settlement era, a post-settlement era, and during the enactment of the Wilderness Act. These three phases could be given starting and ending years that are again specified, along with scenarios for all other zones and time periods, in the Management Plan Input File (Appendix A.10).

As mentioned, the effects of an initiated disturbance are simulated as a change in succession age, succession class, or both. The simulation of some disturbances can leave the polygon in the same succession class but the succession age can be decremented (set back; after grazing, for example) or incremented (accelerated; after a beetle attack kills seral trees, for example). Effects of severe disturbances are simulated by changing the succession class and assigning a new succession age. For example, a stand-replacement fire in an old growth Douglas-fir stand may change the succession class of the polygon to a ponderosa pine seedling succession class with a resultant succession age of one year. Or, a non-lethal surface fire may change an old growth multiple strata ponderosa pine polygon to an old growth single strata ponderosa pine polygon with a resultant succession age of 250 years. All disturbance effects parameters are entered in the Disturbance Input File by PVT-succession class combination (Appendix A.8). Usually, the effect of a disturbance within a PVT-succession class does not change across scenarios. Disturbance histories for all polygons are stored by LANDSUMv4 and summarized in program output.

In review, all non-fire disturbances are independently simulated at the polygon level. This means that the position of the polygon on the landscape and the conditions and disturbance histories of other adjacent polygons do not affect the simulation of disturbance on a target polygon. This assumption was made because the spatial simulation of spread for all disturbances is impracticable due to the complexity of interacting factors, the lack of fundamental research in landscape disturbance dynamics, and insufficient computing resources. However, wildland fire is one disturbance where there have been significant advances in simulating spatial interactions and spread (Finney 2001, Gardner and others 1999, Keane and others 2004a). Since fire is one of the most dominant disturbances in the many ecosystems of the United States, it has a major effect on the composition and structure of many landscapes (Agee 1993, DeBano and others 1998, Heinselman 1981). Therefore, it was decided that fire deserved an independent and more comprehensive treatment in LANDSUMv4. A separate fire module was created that simulated the spread of fire across a landscape as a pixel-to-pixel growth process. This means that fires can cleave or divide polygons to create new burned polygons that will be assigned different succession classes or succession ages. These new polygons are added to the bottom of the polygon list in LANDSUMv4. The fire module implemented in LANDSUMv4 is discussed next and it is thoroughly detailed in Keane and others (2002c). Although this module was primarily designed for fire, it can also be used to spread any other disturbance that occurs within one year of simulation.

***Simulating fire ignition and spread*—**The spatial simulation of fire behavior and effects presented a special challenge because of LANDSUMv4's simplistic simulation structure. Some spatial models assume a random or patch-to-patch fire spread (Chew 1997, Kurz and others 2000), which maintains map integrity but misrepresents the dynamics of fire growth (Gardner and others 1999, Keane 2000, Keane and Finney 2003). Wildland fires tend to split patches along topographic, fuel, moisture, or wind gradients and rarely follow patch boundaries (Finney 2001). Inclusion of a detailed mechanistic fire growth model, such as FARSITE (Finney 1998a), into LANDSUMv4 was problematic because it would have required the addition of fine scale fuels and weather input data that would have created an overly complex model that would have required extensive parameterization and computer resources for millennia simulations across the entire nation. The second version of LANDSUM (version 2.0) simulates spatial fire dynamics and its effect on landscape pattern and composition using an approach that balanced simplicity and applicability with realism (Keane and others 2002c). A discussion of the fire spread algorithm follows with all spatial fire input parameters mentioned in this section specified by the user in the Spatial Disturbance Input File (Appendix A.6).

The simulation of fire in LANDSUMv4 is represented by three phases: initiation, spread, and effects (fig. 2). Ignition is stochastically simulated from the fire probabilities assigned to each initial polygon based on its PVT and succession class. The following three-parameter Weibull hazard function is employed to account for fuel buildup (using years since burn –YSB, years) and a no-burn period directly after a fire (REBURN, years).

$$p_f = (fmult)(pscale)(\frac{\beta}{FRI})[\frac{YSB - REBURN}{FRI}]^{(\beta-1)} \qquad (1)$$

where ß is the shape parameter (parameterized at 2.0 for this study), FRI is the fire return interval or the inverse of fire probability as entered in the Scenario Input File (years), and p_f is the probability of fire. We assigned the REBURN variable a value of 3.0 years in the LANDFIRE effort. The probability p_f represented the probability that any point on the landscape would burn in a year and that point is defined by size of the pixel. The p_f was adjusted for scale to account for the size of the polygon and the size of the fire using the following scaling factor (*pscale*):

$$pscale = [\frac{AREA_{pixel}}{AREA_{fire}}][\frac{AREA_{polygon}}{AREA_{pixel}}] \tag{2}$$

where $AREA_{pixel}$ and $AREA_{polygon}$ are the areas of the pixel and polygon (m^2), respectively, and $AREA_{fire}$ is the average fire size as entered in the Spatial Disturbance Input File (Appendix A.6). The first term in the equation scales the probability using the relationship of total area that is burned to the pixel area to account for the point-level fire probabilities. The second term scales the probability to a polygon level because ignition is evaluated on a polygon-by-polygon sequence.

The effect of weather on fire initiation and spread is simulated using a fire multiplier (*fmult*, index from 0-1 in equation 1). The user must decide how many years out of ten there will be a dry, moderate, and wet fire season (specified in the Spatial Disturbance Input File; Appendix A.6). The program calculates the probability of these weather years (p_d, p_m, and p_w for probability of dry, moderate and wet years, respectively) and selects the fire year by generating a random number and comparing it with the cumulative probability distribution. Once a fire year is selected (wet, moderate, dry), the ignition probability is increased by a factor (*fmult*) that is computed from the wet-moderate-dry probabilities under the assumption that the *fmult* for a moderate year is always 1.0 in the simulation. The equation for a wet and dry year multiplier is:

$$fmult_w = \frac{(1 - p_m)}{\kappa (p_d + p_w)} \tag{3}$$

$$fmult_d = \kappa (fmult_w) \tag{4}$$

where the coefficient κ is the increase in size and frequency of fire from a wet to dry year. For the LANDFIRE effort, the factor κ was assigned a value of 100 determined from an analysis of fire occurrence data in Hardy and others (2001) and Schmidt and others (2002). This approach maintains the integrity of the fire occurrence probabilities specified in the Scenario Input File (Appendix A.11) by keeping the long-term average fire frequency probability close to that specified by the user. The user can bypass this entire step by specifying a weather year multiplier for every simulation year in the Fire Year Input File (Appendix A.13).

Other probability functions are available in LANDSUMv4 besides the three-parameter Weibull function detailed above. The model also contains options to use a normal or exponential distribution if these are more appropriate for the ecosystem or landscape. Most studies use the three-parameter Weibull because it was proven effective (Johnson and Gutsell 1994, Johnson and Van Wagner 1985, Keane and others 1996c). We actually used the survivor function of the

Weibull probability equation to compute instantaneous estimates of annual probabilities.

The program generates a random number for each polygon, and if that number is less than p_f, a fire is started in that polygon. It is assumed that the fire has an equal chance of starting anywhere within the polygon. The pixel where the fire first starts is randomly determined from the number of pixels within the polygon. The program calculates a cumulative probability distribution for all pixels, selects a random number, and compares the number with the distribution to choose the pixel.

Fire is spread across the landscape at a pixel-level using directional vectors of wind and slope. Wind direction (degrees azimuth) is an input to the model and specified in the Spatial Disturbance Input File (Appendix A.6), but then it is randomly modified within 45 degrees of the input direction for each simulated fire. Wind speed (m sec^{-1}) is also an input parameter that is randomly adjusted within 0.5 times of a user-specified input value for each fire. Slope (percent) is calculated from a digital elevation model (DEM), which is a required input map in LANDSUMv4 (see the Map Input File in Appendix A.4). The number of pixels to spread the fire in eight possible directions (N, NE, E, SE, S, SW, W, NW) is calculated from the following relationship, which was modified from Rothermel (1991).

$$spix = (wind_f)(slope_f) \tag{5}$$

where *spix* is the number of pixels to spread in a direction, $wind_f$ and $slope_f$ are wind and slope factors that are computed from the following equations.

$$wind_f = (1 + 0.125\varpi)(\cos(abs(\theta_s - \theta_w))^{\varpi^{0.6}} \tag{6}$$

$$slope_f = \frac{5}{(1 + 3.5e^{-10\Delta})} \tag{7}$$

where ϖ is wind speed (mph), *abs* is absolute value operator, θ_s is the spread direction, θ_w is the wind direction, and Δ is percent slope (rise over run) (Rothermel 1991). The slope factor applies to only positive slope values (upslope spread). Downslope spread is computed as:

$$slope_f = e^{3(\Delta)^2} \tag{8}$$

These equations were solved for each pixel ignited by the fire, originating from the randomly selected fire start pixel mentioned above. Only those pixels within polygons having assigned fire probabilities in the Scenario Input File (Appendix A.11) less than 0.002 (500 year MFRI) were allowed to burn, except for those patches where p_f was zero, such as in a recently burned patch or rock polygon. Rounding of the computed *spix* to the nearest pixel (pixel size was 30 meters in this study) was stochastically determined from a uniform random number generator.

Initially, fires were allowed to burn until they hit the landscape boundary or an unburnable patch, but this resulted in abnormally high burned areas on the simulated landscapes. Fire spread was then limited by stochastically calculating a maximum fire size (FIRESIZE, ha) for each fire from the following equation:

$$FIRESIZE = \alpha \ln(RN)^{1/\sigma} \tag{9}$$

where α is the magnitude parameter that approximates the average fire size (ha) estimated by the user from sources such as the NIFMID data base (Hardy and others 2001), RN is a random number from a uniform probability distribution (number between zero and one), and σ is a shape parameter estimated as 1.33 for this effort. Both α and σ parameters are specified in the Spatial Disturbance Input File (Appendix A.6). Some users can confuse α, the fire scale parameter in the Weibull function, with average fire size, but the main difference is that α is a fire size equation parameter that is the expected average from the Weibull distribution and is "approximated" by average fire size. A maximum size of the simulated fire is determined by first generating a random number and then solving the above equation. Then, the fire's spread is simulated using the cell percolation approach described above until it reaches the maximum fire size or until it reaches an unburnable boundary such as the edge of the simulation landscape. The program stores the map of burned pixels and the fire size characteristics (see Appendix B.1). The above fire size equation is derived from a heavy-tailed Weibull distribution but there are several other options in LANDSUMv4 including Pareto, Exponential, Uniform, and Logistic distributions (Appendix A.6).

The fire spread cell percolation method detailed above is not the only method available in LANDSUMv4 to simulate fire growth across the landscape. The model also allows two very simplistic, and somewhat adequate, methods of creating fire perimeters to simulate patch dynamics. The simplest method involves using a "cookie cutter" approach where ellipses encompassing the area determined by FIRESIZE in the above equation are placed on the landscape originating at the fire-start pixel (discussed above). The width and length of the ellipses are specified by an elongation parameter in the Spatial Disturbance Input File (Appendix A.6). There is also a cell automata option where fire is stochastically spread to adjacent pixels based probabilities computed from slope, wind, and fuel loadings (Hargrove and others 2000, Li 2000, 2001). We used only the cell percolation approach in the LANDFIRE effort and found this far superior to all others.

The effect of the fire on the burned polygon is stochastically determined from probabilities of each fire severity type in the Scenario Input File (Appendix A.11). The program cycles through all polygons in the burned area and slices all burned polygons into the sections that burned and sections that did not burn. The unburned and burned polygons retain all characteristics of the mother polygon prior to the fire. The burned polygons get new succession classes, stand ages, and year since fire attributes using the following procedure.

The model retrieves the fire occurrence probabilities for each of these burned polygons for the pre-burn PVT-succession class combination. The fire occurrence probabilities in LANDSUMv4 are usually specified by three fire severity types: stand-replacement, mixed severity, and non-lethal surface fires. This set of probabilities is assigned to each mapped polygon based on PVT and succession class. The inverse of the sum of these probabilities is used as the mean fire return interval in Equation 1. In calculating fire effects, these three probabilities for the pre-burn polygon's PVT-succession class combination are relativized (scaled from 0.0 to 1.0) and a random number is compared to the cumulative relativized probability distribution to stochastically select the severity of the fire to simulate. A slight chance (0.01 probability) that the polygon would not burn was also included in the cumulative probability distribution in earlier versions of LANDSUM. The selected fire severity would then determine the appropriate successional pathway (fig. 1). The disturbance effects for the PVT-succession class are determined from the information specified in the Disturbance Input File

(Appendix A.8) for the old polygon's PVT-succession class. These new burned polygons are added to the end of the polygon list. Succession is not modeled for any polygon that was burned during that year of simulation.

The above algorithms for spatially simulating fire on the simulation landscape can also be used for any other disturbance process in LANDSUMv4. Any number of disturbances can be added to the Spatial Disturbance Input File (Appendix A.8) as long as data exists to quantify all input parameters and the disturbance has effects that are manifest in the same year of simulation. An example of a disturbance that might be considered for spatial simulation would be mountain pine beetle epidemic where the spread and mortality must be simulated within a year of simulation. This may be true for some lower elevation landscapes but it takes much longer for beetles to spread in high elevation pine stands.

Model Execution

LANDSUMv4 is a command line program that is initiated at the DOS command prompt by entering the program name (landsumv4) and then the name of an input file (Appendix A.1), called a Driver Input File (Appendix A.2), which contains the file pathnames of several other files that contain input parameters and initial values. All LANDSUMv4 input files are ASCII text files that are organized by simulation task and are structured by unique formats (see Appendix A.2-A.13). The Simulation Input File (Appendix A.11) contains user specifications for general simulation parameters including simulation time span, output options, random number options, age initialization options, and fire code specifications (Appendix A.3). A flowchart illustrating the steps needed for LANDSUMv4 execution is shown in figure 3 for reference throughout the following sections.

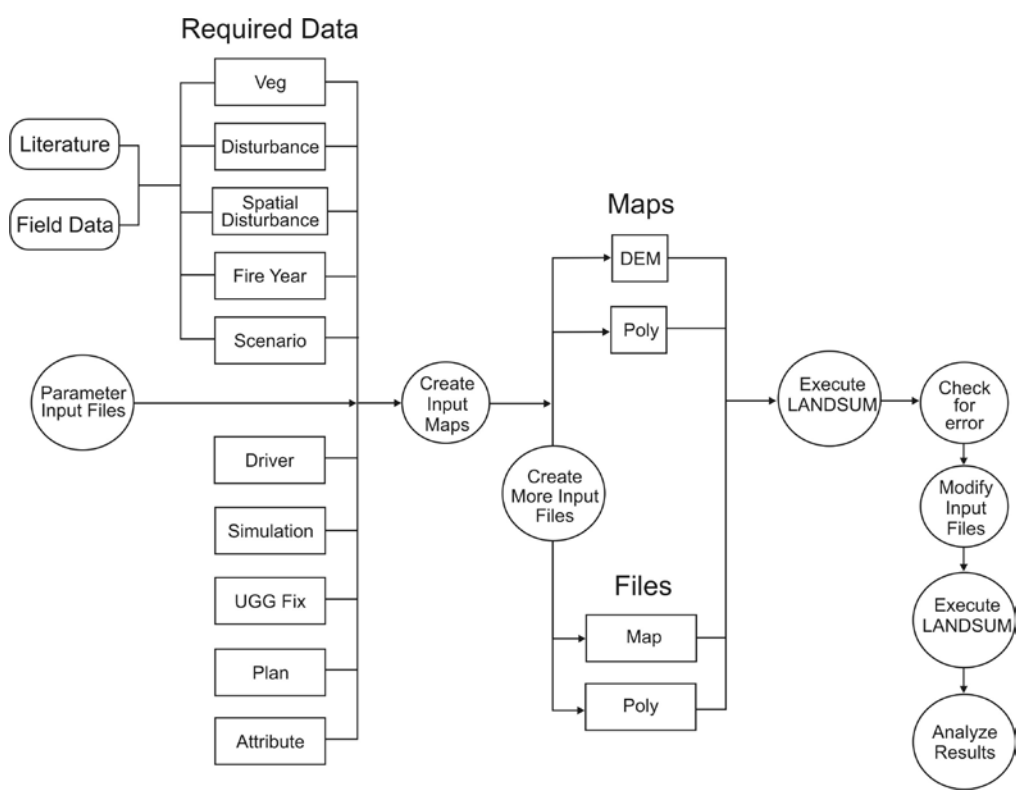
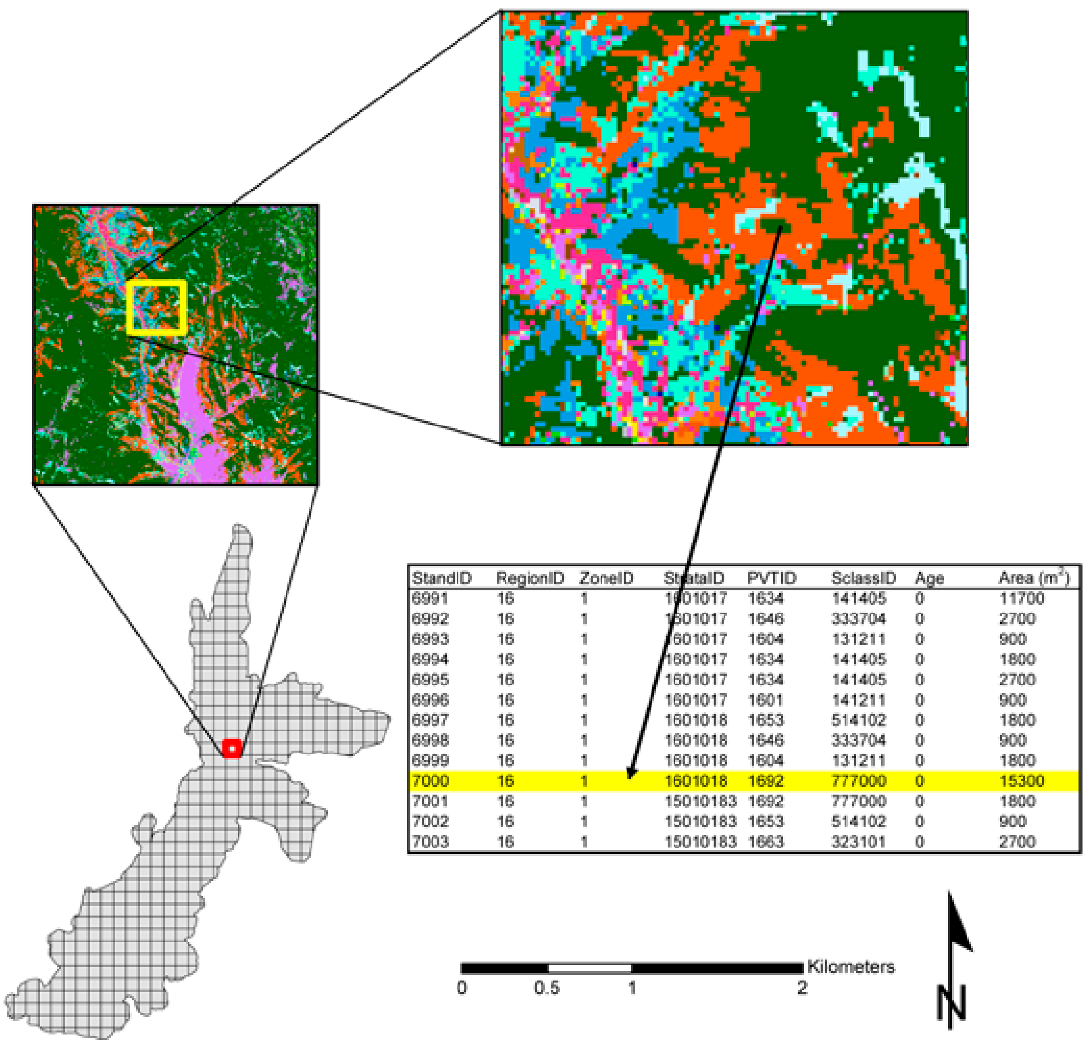


Figure 3—A flowchart showing the steps needed to parameterize and initialize LANDSUMv4 for execution on a landscape.

Creating simulation maps—Only two digital maps are needed for input to LANDSUMv4 (fig. 3). These maps are input into LANDSUMv4 in the ARC/INFO ASCII GRID format. The extent of the simulation landscape in LANDSUMv4 is defined by the DEM (Digital Elevation Model) Input Layer and landscape composition is described by the Polygon Input Layer. An error will occur if these layers are not congruent; the model uses the DEM to spatially define the simulation landscape. During the initialization phase, the model will create a raster map of memory locations for each pixel on the landscape and each memory location will have all descriptive parameters for that pixel including succession age, time since last fire, cover type and structural stage. All output maps and spatial simulations are created from this memory location map. It is important that all pixels within the simulation landscape have values for PVT and succession class because these values are needed in the simulation of fire spread. The DEM layer can be created from any digital elevation model (DEM) and a good source is the EROS Data Center's National Elevation Database (NED, www.usgs.eros.gov).

The Polygon Input Layer can be created from many sources. A digitized stand map with PVT, cover type, and structural stage attributes is perhaps the best source, but it can also be created from satellite imagery and gradient modeling (fig. 4 illustrative diagram) (Keane and others 2002a). The Polygon Input File



StandID	RegionID	ZoneID	StrataID	PVTID	SclassID	Age	Area (m^2)
6991	16	1	1601017	1634	141405	0	11700
6992	16	1	1601017	1646	333704	0	2700
6993	16	1	1601017	1604	131211	0	900
6994	16	1	1601017	1634	141405	0	1800
6995	16	1	1601017	1634	141405	0	2700
6996	16	1	1601017	1601	141211	0	900
6997	16	1	1601018	1653	514102	0	1800
6998	16	1	1601018	1646	333704	0	900
6999	16	1	1601018	1604	131211	0	1800
7000	16	1	1601018	1692	777000	0	15300
7001	16	1	15010183	1692	777000	0	1800
7002	16	1	15010183	1653	514102	0	900
7003	16	1	15010183	1663	323101	0	2700

Figure 4—An example of a simulation landscape with mapped polygons and the associated list of those polygons.

(Appendix A.5) is created from the Polygon Input Layer by creating an ASCII file where each line is a polygon on the simulation landscape (in the Polygon Input Layer) and each polygon is given a set of attributes. The first set of attributes is used to stratify simulation results so that predictions can be summarized by specific land areas or management units. The first stratification is the region code that represents the region of the country for which the succession pathways and disturbances parameters were developed (fig. 4). The next attribute is the management zone that is used to further delineate areas on the simulation landscape based on management objectives (for example, wilderness, roadless, and wildland urban interface). The third stratification parameter is generic and can be used for any purpose including finer geographical divisions or land use allotments. In the LANDFIRE prototype project, we used this stratification as the spatial landscape reporting unit for mapping FRCC to describe historical fluctuations in succession class (Pratt and others, in press).

The next set of attributes concern those variables used to model succession and disturbance: PVT, succession class, and succession age. These values are usually modeled from other GIS layers using topography, remotely sensed imagery, and other biophysical layers (Keane and others 2002a) and then assigned to mapped polygons using various GIS techniques (Keane and others 2000). The succession age presents a special challenge because it is difficult to obtain stand age from remotely sensed imagery or biophysical layers. Therefore, the user has the option of simulating a realistic succession age inside LANDSUMv4 by specifying a zero for this polygon attribute. The simulated succession age can be computed as 1) a midpoint of the beginning and ending age assigned to the PVT-succession class combination (see the Simulating Succession section); 2) a randomly selected age between the beginning and ending succession class time span; or 3) the beginning age for that succession class (this option is specified in the Simulation Input File, Appendix A.3). The last polygon attribute is the initial area (m^2) of the polygon, which is used to check for discontinuities in the Initial Polygon Map.

The most important polygon attributes are potential vegetation type (PVT) and succession class. As mentioned, a PVT identifies a distinct biophysical setting that supports a unique and stable climax plant community under a constant climate regime in the absence of disturbance (Daubenmire 1966, Fischer and Bradley 1987, Pfister and Arno 1980). A PVT is usually identified in the field by overstory and understory indicator plants. These plants indicate a biophysical setting where, in the absence of disturbance, a unique plant community will persist. The PVT concept is used as a framework for simulating succession in LANDSUMv4. It is hypothesized that, if a unique climax community is supported by this biophysical setting when there are no disturbances, then there should be a unique set of successional pathways that converge on this unique plant community (Arno and others 1985, Steele 1984). And, each of these pathways originates from a specific disturbance(s).

There are three ways to stratify LANDSUMv4 parameters and results within a simulation. First, each polygon and each successional parameter is assigned a region code. The region code was designed for the LANDFIRE project where the region refers to the mapping zone that was used to stratify the entire United States. Another use for the region code in LANDFIRE is to assign variants of succession pathways for a PVT across large regions. Some simulation landscapes are so large that the successional dynamics for a Douglas-fir PVT, for example, are different across regions on that landscape. Therefore, the user has the option of stratifying succession parameters for one PVT over different regions of the landscape. The next stratification field is the management zone (see Disturbance Simulation section). The management zone is used to assign a disturbance scenario to different parts of the landscape. An area on the landscape that is in wilderness, for example, might get a different set of disturbance probabilities than another zone that is actively managed for timber production. All polygons are assigned a management zone in the Polygon Input File (Appendix A.5) and the simulation scenarios are assigned to each management zone in the Management Plan Input File (see Disturbance Simulation section and Appendix A.10). The last stratification field is called the landscape stratum and is assigned to a polygon in any strategy desired by the user. The landscape strata have no intrinsic use in most LANDSUMv4 applications, but, as mentioned, it is used in LANDFIRE to spatially define areas to summarize landscape fluctuations in succession classes.

Creating input files—There are two types of input files in LANDSUMv4: scenario files and description files. Scenario files describe various aspects that are unique to the simulation while the description files portray site or polygon existing conditions. Scenario files reflect a particular simulation application, while the description files must accurately describe mapped or measured ecological conditions and characteristics.

All input and output files in LANDSUMv4 are in ASCII format and are space or comma delimited. This is often referred to as text format. Each input or output ASCII file is configured as a vertical or horizontal file. Vertical files contain only one input value per line with a descriptor of that input value following the number. Horizontal files contain more than one value per line and resemble a table. In general, LANDSUMv4 input files are both vertical and horizontal, while all output files are only horizontal. The horizontal file structure is used for efficiency while the vertical file structure is used for ease of development, greater understanding, and error management. Files in LANDSUMv4 are also cycling or discrete. Cycling files contain the same format that is cycled downward or repeated for each similar instance on the next line or set of lines. For example, disturbance parameters are cycled vertically for each PVT on the landscape. Discrete files do not cycle and always contain a discrete number of vertical records.

The first line of every LANDSUMv4 input file is called a title line and is used to describe the file and its origins. There are 256 characters available to craft a descriptive title that can uniquely identify the file while it is being viewed within a text editor. The title line should describe who, what, when, where, and why the file was developed. For example, one header might have the project for which the file was developed, who developed the file, when the file was developed (version), where the data were taken (data sources), and why this file was used for this particular simulation scenario.

The Polygon Input File (fig. 3, Appendix A.5) is a horizontal, cycling ASCII file that contains the list of all polygons on the landscape with values for each of the stratification, simulation, and area variables. The simulation landscape is composed of polygons defined by groups of pixels of the same PVT and succession class, and the number of polygons on the landscape dictates the speed of model execution. As mentioned, LANDSUMv4 simulations are performed at the polygon-level, which means succession and disturbance processes (except for fire) are simulated stand-by-stand in the order of the polygons in the input list. For example, all non-fire disturbances are evaluated for the first stand, then for the second stand, and so on. So, the more stands that are in the polygon list, the longer LANDSUMv4 will take to run. The initial list of polygons is input to the model using the Polygon Input File and it is important that this list reflects the diversity of vegetation on the landscape with the minimal number of polygons. In LANDFIRE, we defined polygons by unique clusters of PVT-succession class combinations. But, long polygon lists will mean long LANDSUMv4 execution times. The simulation of fire across the landscape will dissect these initial polygons to create new ones and therefore the number of polygons will increase throughout simulation time. So, long simulation periods coupled with frequent fire regimes will always result in long execution times.

The Map Input File (fig. 3, Appendix A.4) contains all the geo-referenced coordinates and map specifications (upper X and Y coordinates, missing value number, cell size, number rows, and number columns) for the input and output maps. The program compares these parameters to those specified in the header of the input maps in ASCII format (ARCGRID) to ensure consistency. The program also has an option where a small box within the simulation landscape can be specified, and all output maps generated from the model will be confined to the specified box.

The Spatial Disturbance Input File (Appendix A.6) contains all parameters to simulate the spread of any disturbance across a landscape (fig. 3, 4). Any number of disturbances can be specified in this file, but only fire was spatially simulated in LANDFIRE. A set of parameters are used to simulate the initiation of the disturbance (for example, fire ignition) and another set are used to calculate the size of the disturbance. The user must also select the spread algorithm: cell automata, cell spread (suggested), and "cookie cutter" techniques. Wind speed and direction are specified in this file to account for wind effects on spread, and a distribution of wet, normal, and dry weather years is specified to account for climate effects on fire ignition. The user can also specify the weather year (wet, dry, normal) by simulation year in the Fire Year Input File (Appendix A.13) for the LANDSUMv4 model.

Succession parameters are entered in the Vegetation Input File (Appendix A.7) and disturbance effects parameters are entered in the Disturbance Input File (Appendix A.8). The beginning and ending year of a succession class, along with the next transitional succession class, are specified in the Vegetation Input File by PVT to deterministically simulate succession. The effects of a disturbance are specified in the Disturbance Input File including the succession class that the polygon would transition to if a disturbance were initiated and the succession age or increment this polygon would receive. All these effects parameters are stratified by PVT and succession class.

Disturbance occurrence probabilities are specified in the Scenario Input File (Appendix A.11) by PVT and succession class. These probabilities reflect the chance that a polygon will experience a disturbance in any given year. There can be multiple scenarios contained in this file to reflect the change in climate and land use over time. Each scenario is assigned to a management zone and a simulation time period in the Management Plan Input File (Appendix A.10). A management zone is a region in the simulation landscape where historical or current disturbance probabilities would be significantly different because of changes over time or changes in land use.

Two input files in LANDSUMv4 allow the assignment of additional attributes to polygons. The Vegetation Fix Input File (Appendix A.9) allows the user to assign more consistent succession classes to polygons that have been assigned the wrong succession class for its PVT. The program scans all polygons for errors in the Polygon Input File, and if it finds a succession class that does not belong in a PVT based on information in the Vegetation Input File, it then scans the Vegetation Fix Input File for the appropriate fix for that situation. The fix is only for the current simulation and the program does not fix the Polygon Input File. The Attribute Input File (Appendix A.12) allows the user to assign up to five attributes to combinations of PVT and succession class. Examples of attributes include fuel models, canopy bulk density, hiding cover, and canopy cover. The cover type and structural stage attributes (two characteristics that define a succession class; see discussions above) are also assigned in the Vegetation Attribute File. These attributes can be mapped over the simulation, or the area of these attributes can be summarized in generated output.

Other simulation characteristics—There are a number of other algorithms used in LANDSUMv4 simulations that deserve mentioning as they are important to the interpretation of the results. The random number generation is perhaps the most critical computation in this stochastic model and several random number generators are available in LANDSUMv4 and are specified in the Simulation Input File (Appendix A.3). However, these random number generators all generate the same random number sequence so run-to-run variations are not possible. The system default random number generator is used to generate entirely different random number streams across simulation runs but some system random number generators are not always statistically random. The random number scheme (same or different random numbers across simulations) and generator (see Appendix A.3 and the Simulation Input File) are selected according to the simulation objective. If the evaluation of alternative management scenarios is desired, then the same random number scheme should be used. However, if the variation between simulations needs to be quantified, then a different random number sequence should be used for each run using the system generator.

One of the most difficult tasks in preparing a LANDSUMv4 simulation is the development of the Polygon Input File (Appendix A.5) and Initial Polygon Map (Appendix A.4). Often, the GIS synthesis of cover type, structural stage, and PVT maps into a polygon layer results in some polygons having successional class assignments that are not present in the successional pathways for that polygon's PVT. This is a common problem and, in previous LANDSUM versions, it took a long time to rectify these illogical combinations because the misfits had to be dealt with one at a time (Keane and others 1996a, Keane and others 1996b). This required that new versions of the PVT and vegetation input maps be developed where pixels were modified so that the PVT-succession classes were congruent. This version of LANDSUMv4 has the ability of assigning a new succession class to an illogical succession class inside the model so that new maps need not be developed and time is saved in the initialization phase. This is done with parameters found in the Vegetation Fix Input File (Appendix A.9) where each illogical PVT-succession class combination found during the error scanning process (see next section) is entered into the file along with the new succession class assignment. This routine also allows for the stochastic assignment of multiple valid succession classes for each illogical combination. For example, a Douglas-fir PVT might have a succession class that has a white pine cover type that is not found in the Douglas-fir pathway. The user may reassign all white pine succession classes to ponderosa pine, or the user may decide to reassign 50 percent of the white pine polygons to ponderosa pine and 50 percent to lodgepole pine. See Appendix A.9 for details. To help facilitate the process, all illogical combinations are written to the end of the Error Output File (see next section) and this can be used to start the development of the Vegetation Fix Input File.

Model Output

Results generated from LANDSUMv4 can be summarized in tabular ASCII files and mapped into grid layers in the ARC/INFO Grid format (fig. 3). Most tabular results summarize total area (m^2) by simulation year, project, region, management zone, landscape strata, PVT, and succession class. Simulation data are summarized in five different tabular formats and written to separate files as specified in the Simulation Input File (Appendix A.3): landscape, disturbance, fire, and LANDFIRE summaries. Model output is written to these files at user-specified intervals, such as every 20 or 100 years, and the user enters a year to start printing simulation results (see Simulation Input File). For example, the user could start printing results at year 250 and print those results every 20 years until year 5,000. This is especially handy if the user does not want to include the first couple of simulation centuries to allow a period for the model to come into equilibrium (see Recommendations section).

Two output files are essential for evaluating the validity of LANDSUMv4 executions and these files should be examined after every simulation. The Echo Output File contains a summary of all input parameters specified for all input files (fig. 3). This file should be examined to detect if any parameters are in error or if the parameters were not input to the model correctly. The Error Output File contains all warnings and errors the program encountered as it was performing a scan of the input parameters. LANDSUMv4 conducts a thorough error scan by comparing all input parameters across files to ensure no errors will be encountered during the simulation. Warnings are issued if the input parameters are inconsistent across or within files but these inconsistencies do not prevent a successful execution. An error issued in the Error Output File must be fixed for the model to initiate a simulation.

All other LANDSUMv4 output files are formatted to be used as input to statistical programs or database software for further analysis (see Appendix B.1). Output to these files is generated at a simulation year interval specified in the Simulation Input File (Appendix A.3). The user can also select the files to be generated in the Simulation Input File. The Polygon Output File generates a list of polygons present on the simulation landscape and writes the attributes of each polygon including region, zone, PVT, and succession class, and the simulated area (m^2) by simulation year. This output file can be used as a Polygon Input File for any output year. The Landscape Output File summarizes simulated landscape area (m^2) at each output year by region, management zone, PVT, and succession class. The Disturbance Output File summarizes the estimated area (m^2) affected by each disturbance stratified by region, management zone, PVT, and succession class. The Fire Output File is a file that contains the starting coordinate, PVT of the starting pixel, weather year, and fire size of every fire simulated on the landscape. The LANDFIRE Output File generates summaries of simulated area (m^2) for all succession classes by the region, zone, strata, and PVT stratifications (as specified in the Vegetation Attribute Input File; Appendix A.7). Formats for these files are detailed in Appendix B.1.

Spatial data layers or digital maps are another form of output generated by LANDSUMv4. The model can generate up to 13 digital data layers in the ARC/INFO ASCII GRID format for the same simulation years as printed in the tabular output of the above files (specified in the Simulation Input File, see Appendix A.3). The desired output layers are specified in the Map Input File as a pathname; the word "none" or "NONE" is entered if that particular layer is not desired. The Polygon Output Map is a layer where each pixel is assigned a unique polygon number that can be cross-referenced with the Polygon Output File. The Fire Output Map is a fire atlas of the number of times each pixel has been burned during the simulation. The Succession Class Output Map has each pixel assigned a succession class and the Cover Type and Structural Stage Output Maps have each pixel assigned the cover type or structural stage code specified for that PVT-successional class combination in the Attribute Input File (Appendix A.12). The Disturbance Output Map has the unique disturbance code assigned to each pixel for each disturbance simulated for that year of execution. There is also an output map where each unique combination of PVT and succession class is assigned to a pixel (PVT-Class Output Map). The Age Output Map has the succession age of each pixel on the simulation landscape. Last, the user can generate five output maps from the five attributes specified for each PVT-succession class combination in the Attribute Input File (Appendix A.12). These maps can be especially useful in understanding the behavior of the model and for estimating the range and variation of patch dynamics (for example, size, shape).

Methods

The Test Landscapes

The two landscapes that were used to demonstrate, test, and explore the model are from the two prototype areas in the LANDFIRE prototype project (Pratt and others, in press) (fig. 5). Square landscapes approximately 100,000 ha were taken from the Central Utah prototype area and the Northern Rockies prototype area (fig. 5). A PVT layer was created from a statistical model using biophysical process layers (Holsinger and others, in press), and cover type and structural stage layers were computed from a merging of satellite imagery (Landsat 7 Thematic Mapper), biophysical modeling, and pattern analysis (Zhu and others, in press). The PVT, cover type, and structural stage layers were combined using standard GIS techniques to create polygons of contiguous pixels of similar PVT-cover type-structural stage combinations. The cover type-structural stage combinations were then assigned succession classes based on those defined in the successional pathways (discussed next). Both test landscapes were not stratified by management zones or regions for simplicity.

Successional pathways were constructed by LANDFIRE personnel for every PVT in both prototype areas (Long and others, in press). These pathways include all successional development trajectories with linked disturbance paths. All succession and disturbance parameters were quantified from existing data or study results found in the literature, and if no data were available, the parameters were estimated from the most similar succession class or disturbance type using opinions from local experts. Only one simulation scenario was employed for both areas and it was an historical scenario that attempts to simulate landscape dynamics prior to the turn of the 20th century (circa 1600 to 1900 AD). Fire occurrence probabilities were estimated from a host of fire history studies for both areas. Documentation of the succession and disturbance parameters are presented in Long and others (in press).

The fire size parameters were estimated from a summary of the NIFMID database for both areas (Hardy and others 2001, Schmidt and others 2002). The fire climate (wet, moderate, and dry years per decade) was estimated from the

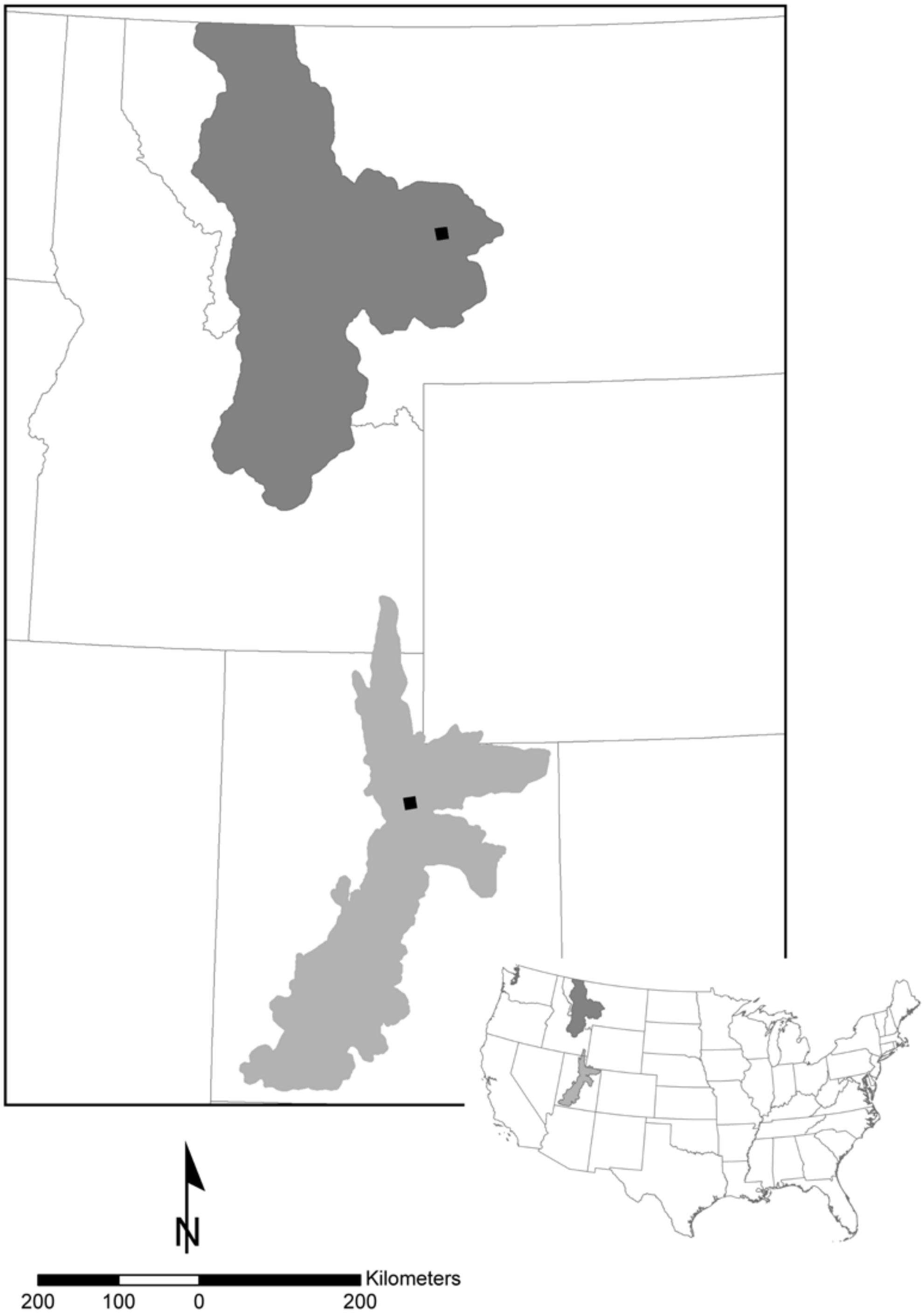


Figure 5—The two prototype areas used in the LANDFIRE project and the test simulation landscapes within these prototype areas that were selected for model demonstration.

distribution of the Palmer Drought Severity Index (PDSI) over a century long weather record as estimated from tree chronologies where years with an average PDSI less than –2.99 were considered dry fire years, 1.99 to –2.99 were considered normal years, and those with PDSI above 1.99 were considered wet years.

Model Demonstration

The demonstration of the LANDSUMv4 model was completed for the two areas to illustrate the wide range of spatial and tabular outputs available to the user. First, a typical application of LANDSUMv4 was simulated for the test landscapes where the initial polygon map was created by assigning the most dominant succession class for each PVT to all pixels associated with that PVT in the PVT map. The most dominant succession class was determined by a GIS summary of the succession class layer described in the previous section. The most common succession class was used because previous investigations into LANDSUMv4 behavior showed that the model comes into equilibrium with the input parameters much quicker if the input landscape is simplified and the current conditions (cover type and structural stage layers developed from recent satellite imagery) were NOT used as the initial polygon map. This is primarily because the current composition and structure of succession classes (today's landscapes) are quite dissimilar from distributions on historical landscapes thereby extending the time required to achieve equilibrium behavior (Keane and others 2002c). The layer was then converted to a polygon layer by identifying contiguous pixels of identical PVTs using standard GIS techniques. A polygon list was then created from the polygon map using the PVT and dominant succession class as the vegetation attributes. The model was executed for 1,000 years with maps and files being printed every 50 years to demonstrate the scope of LANDSUMv4 output. All generated map files were brought into ARC/INFO GIS to create the digital maps. Tabular results, output in the ASCII files, were imported into the SAS statistical package to create examples of LANDSUMv4 simulation results. Simulated map outputs were also imported into the FRAGSTATS program (McGarigal and Marks 1995) to describe landscape structure in terms of descriptive statistics (Keane and others 2002c)

The LANDSUMv4 model was then applied to the two test landscapes using the LANDFIRE protocols to demonstrate how the model was used to calculate an index of departure (Keane and Rollins, in press). The entire landscape was initialized to the most dominant succession class for each PVT from the LANDFIRE vegetation maps. All historical LANDFIRE pathways were used to simulate succession and LANDFIRE historical scenario files were used to simulate fire dynamics (Pratt and others, in press). The test landscape was stratified into landscape reporting units (sub-landscapes) to demonstrate the scale dependency of LANDSUMv4 output. The resultant LANDFIRE Output File (Appendix B.1) was used as the historical reference file in the LANDFIRE statistical analysis program, called HRVSTAT, to compute an index of departure from the current conditions. The HRVSTAT program compares the current conditions with the range and variation of historical conditions using standard parametric metrics. An index between 0 and 100 is calculated that rates the degree of departure of the current conditions from historical conditions using probability distributions. The current landscape conditions for the test landscape, quantified from the set of LANDFIRE vegetation maps that were created from satellite imagery (Zhu and others, in press), were summarized from the LANDFIRE vegetation data layers into a data file similar in structure to the LANDFIRE Output File using GIS techniques. Various graphs and tables were generated to illustrate this intensive LANDFIRE analysis process. These data were also used to compute Fire Regime Condition Class (FRCC) using the methods outlined in Hann (2004).

Sensitivity Analysis

A comprehensive analysis of the sensitivity of LANDSUMv4 output to several important input parameters was conducted to develop the simulation strategy for the LANDFIRE project. Keane and others (2002c), Pratt and others (in press), and Keane and others (2004a) had previously performed an extensive sensitivity analysis on LANDSUM version 2.0 to detect the importance of a small set of input parameters on patch metrics and fire regimes simulated from landscapes in the northern Rocky Mountains. Results from those studies allowed us to narrow our sensitivity analysis to a limited set of LANDSUMv4 parameters, called test parameters, that we felt were important to LANDFIRE concerns (table 1). The sensitivity analysis performed here differed from previous LANDSUM efforts in that burned area was used as the diagnostic variable rather than landscape structure (patch dynamics). It was important to identify if the sensitivity of certain input parameters was different across landscape structure and composition, and it was also important to detect sensitivity changes from previous studies using the LANDFIRE input parameters and initial data. Three values were assigned to each of the test parameters to encompass the full range of valid values for that variable.

We evaluated the effect of two fire parameters, wind speed and landscape size, on the behavior of LANDSUMv4 simulations using simulated burned area as the diagnostic variable (table 1). This detailed sensitivity analysis was performed to judge the sensitivity of altering levels of four explanatory factors on only one response variable - percent area burned on the simulation landscape. The four factors in this sensitivity analysis were: (1) average fire size (ha) which we termed **fire size**; (2) **frequency scalar** - a multiplier of the expected mean of the Weibull fire size distribution taken from the Spatial Disturbance Input File fire size parameters (values of the scalar variable less than 1.0 decrease fire frequency, whereas values greater than 1.0 increase the frequency); (3) **wind speed** (m sec^{-1}); and (4) simulation **landscape size** (ha). Each factor has three levels as detailed in table 1.

We ran the model for each combination of sensitivity factors on six different landscapes that were called sites in the statistical analysis (fig. 6). Site was considered a random effect nested within the landscape size factor. Percent area burned was calculated for 500 time intervals where model output was printed every 20 years for a 10,000 year simulation (10,000 / 20 = 500 analysis units). To achieve independence across these time intervals, the analysis units were averaged for every five time periods for a total of 100 sample observations. To study the effects of altering the levels of each factor, a partially hierarchical

Table 1. The levels for each factor used in the sensitivity analysis. The factors are: fire size - average fire size; frequency scalar - ratio of ignition to fire size; wind speed - wind speed at mid-flame length at time of fires, and landscape size - area of simulation landscape (ha).

Factor	Level 1	Level 2	Level 3
Fire size (ha)	25.0	50	75
Frequency Scalar	0.75	1.00	1.25
Wind Speed (m sec^{-1})	1.0	5.0	25.0
Landscape Size (ha)	50,000 (50k)	100,000 (100k)	200,000 (200k)

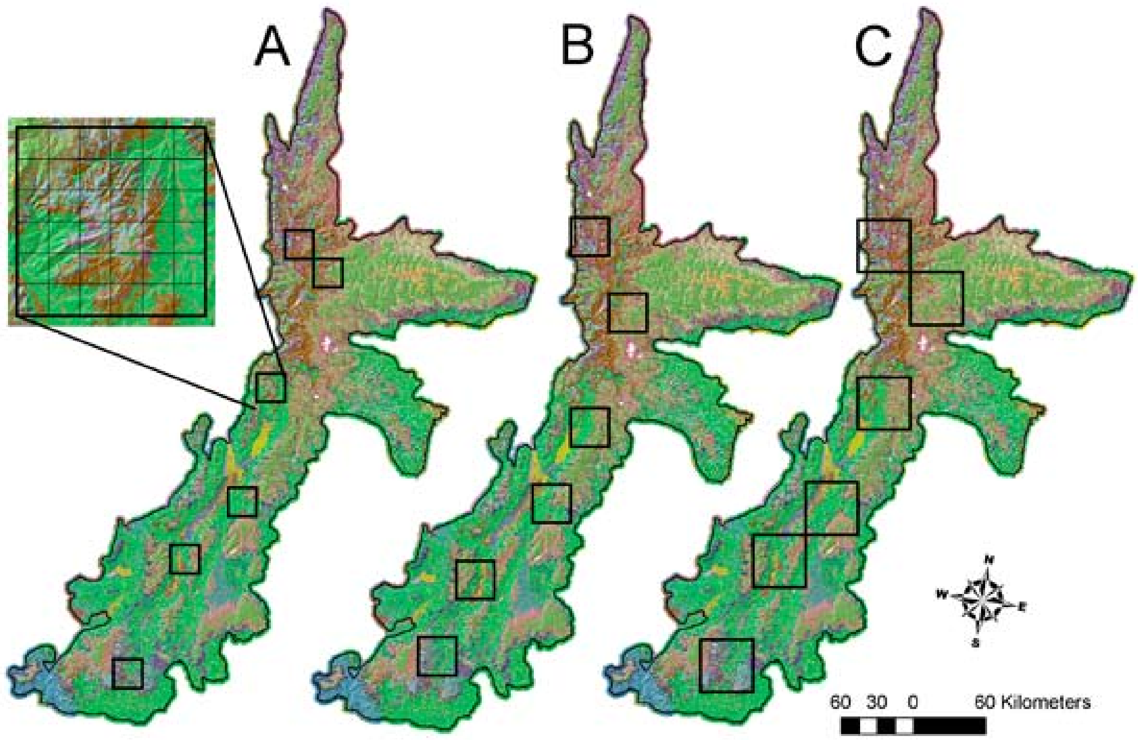


Figure 6—The six landscapes used as sites to test the sensitivity of LANDSUMv4 input parameters across various ecosystems and topography. Each landscape has three sizes: A) 50,000 ha (50k), B) 100,000 ha (100k), and C) 200,000 ha (200k).

ANACOVA was performed where the covariate was time. Interactions up to four ways were initially examined. Calculations were performed using S-plus 6.2 and SPSS 10.

Results

Model Demonstration

A set of simulation results from LANDSUMv4 generated from the two test landscapes are shown in figure 7. These simulation results portray the temporal dynamics of the three most dominant successional classes over the 1000 years of simulation for the Zone 16 (fig. 7A, 7B, and 7C) and Zone 19 (figs. 7D, 7E, and 7F) demonstration landscapes (fig. 5). Graphs of cover type, structural stage, disturbance type, and fuel model dynamics could also have been easily created along with a host of other landscape characteristics (Appendices A.3 and A.4). These graphs illustrate the range and variation of estimated species composition on the historical test landscapes. The temporal dynamics of simulated burned area are shown in figure 7G for the Zone 16 landscape and figure 7H for the Zone 19 demonstration landscape. Note the large fire years are more frequent on the Zone 16 landscape.

Maps of estimated cover types for four simulation years during the 1,000 year simulation are shown in figure 8 for both demonstration landscapes. Cover types were used because there were fewer mapped entities than succession classes, which made the map legend easier to read and understand. Fire perimeters can be seen in the later simulation years. Fire regime maps generated by LANDSUMv4 from all fires that occurred during the simulation, shown in figure 9, illustrate the

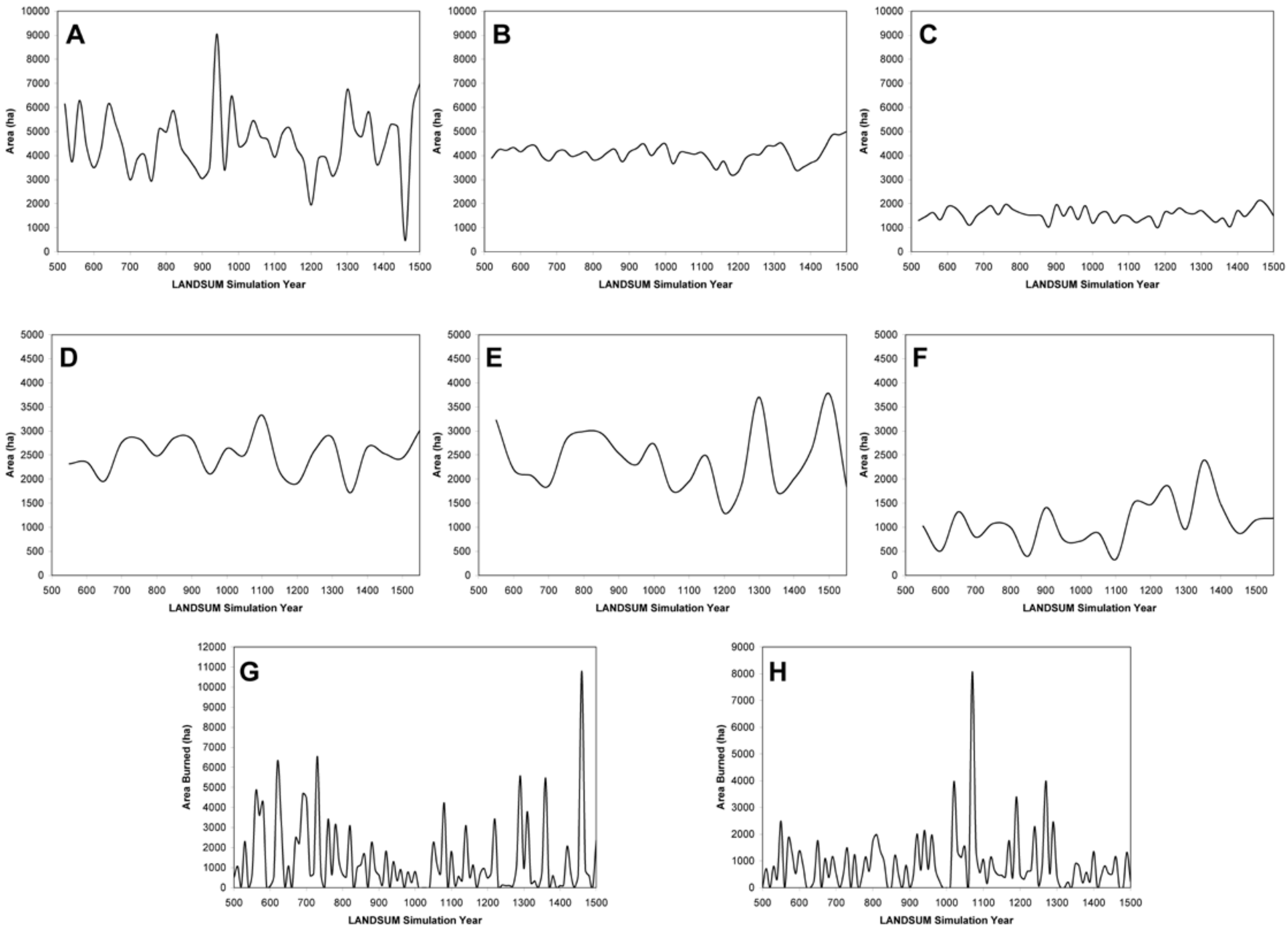


Figure 7—LANDSUMv4 output generated from a typical application of LANDSUMv4 for the two test landscapes using historical disturbance parameters. Graphs of the extent of three dominant succession classes on the historical landscape showing range and variation of landscape composition for the Zone 16 test landscape: A) Aspen-Birch HCLH, B) Douglas-fir HCHH, C) Lodgepole pine LCHH, and the Zone 19 test landscape: D) Douglas-fir LCHH, E) native perennial bunchgrass grasslands HCHH, F) big sagebrush HCLH. Graph of area burned across the historical simulation era for the Zone 16 landscape (G) and the Zone 19 landscape (H). Structural stage names are defined as: LCLH-low cover low height early succession stage, HCLH-high cover low height mid-seral stage, HCHH-high cover high height late succession stage, LCHH-low cover high height disturbance maintained late succession stage

severity and frequency of fire across the simulation landscape. A fire frequency map (fig. 9A) depicts the mean fire interval for each pixel calculated by dividing the number of fires experienced by each pixel by the simulation length (1,000 years). Three fire severity maps were generated for each demonstration landscape: percent of non-lethal surface fire (fig. 9B), mixed severity fire (fig. 9C) and stand-replacement fire (fig. 9D), for each pixel across all 1,000 years of simulation. The three maps can be combined to illustrate the mix of fire severities that occur across the simulated landscape.

The LANDFIRE prototype project used the LANDSUMv4 model to generate a time series of historical conditions to evaluate against the condition of current landscapes. A demonstration of this LANDFIRE application of LANDSUMv4 is shown in figure 10. First, a map showing a measure of departure of current

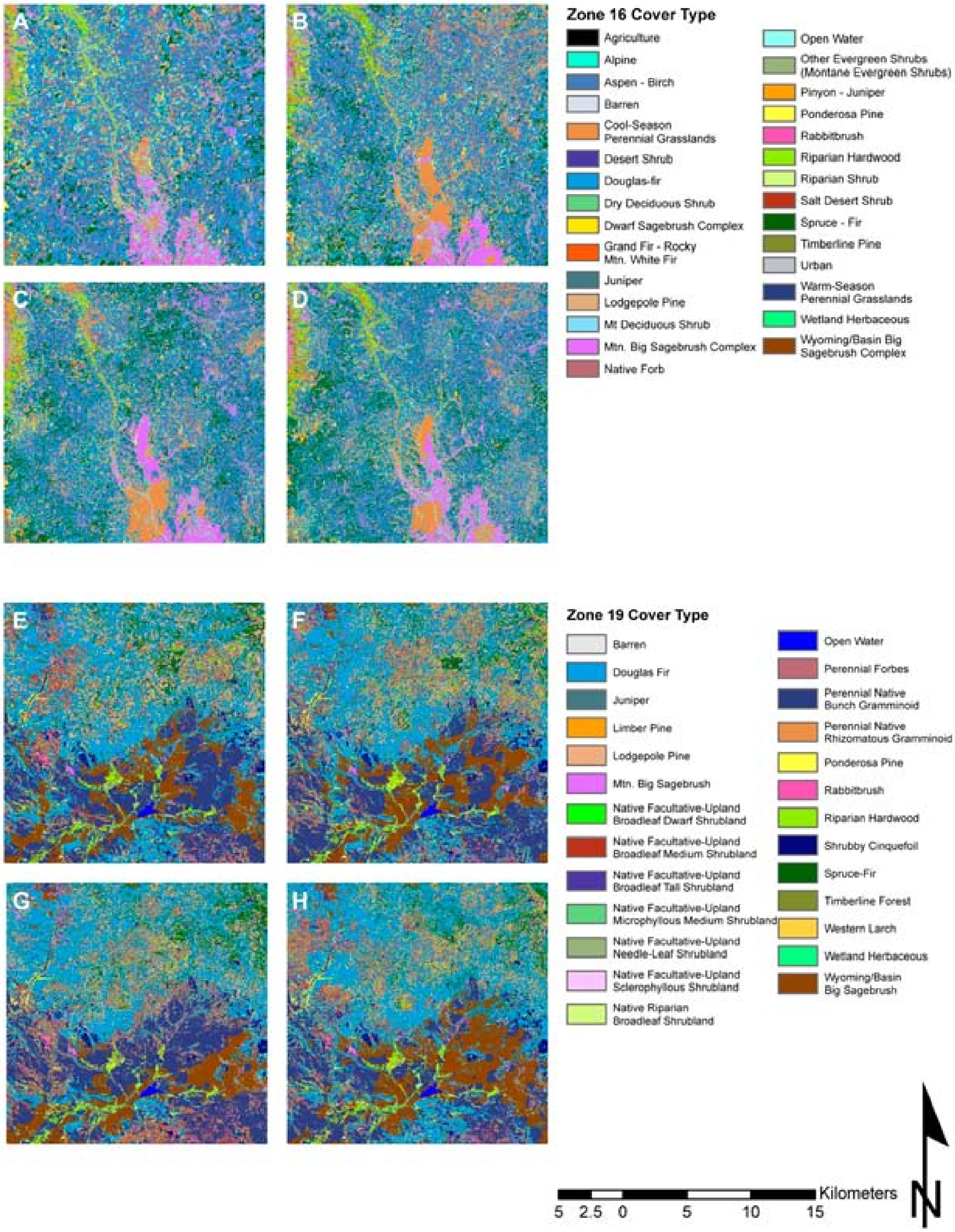


Figure 8—Digital maps of cover type at four simulation years: A-200 year, B-400 year, C-600 year, D-800 year for the Zone 16 demonstration landscape and E-200 year, F-400 year, G-600 year, 4-800 year for the Zone 19 demonstration landscape.

landscape composition from simulated historical ranges and variability of landscape composition (figs. 7A to 7F) for 1 km^2 landscapes within the Zone 16 and Zone 19 (fig. 10A). This departure was calculated using the computer program HRVSTAT detailed in Holsinger and others (in press). Next, an observed significance level

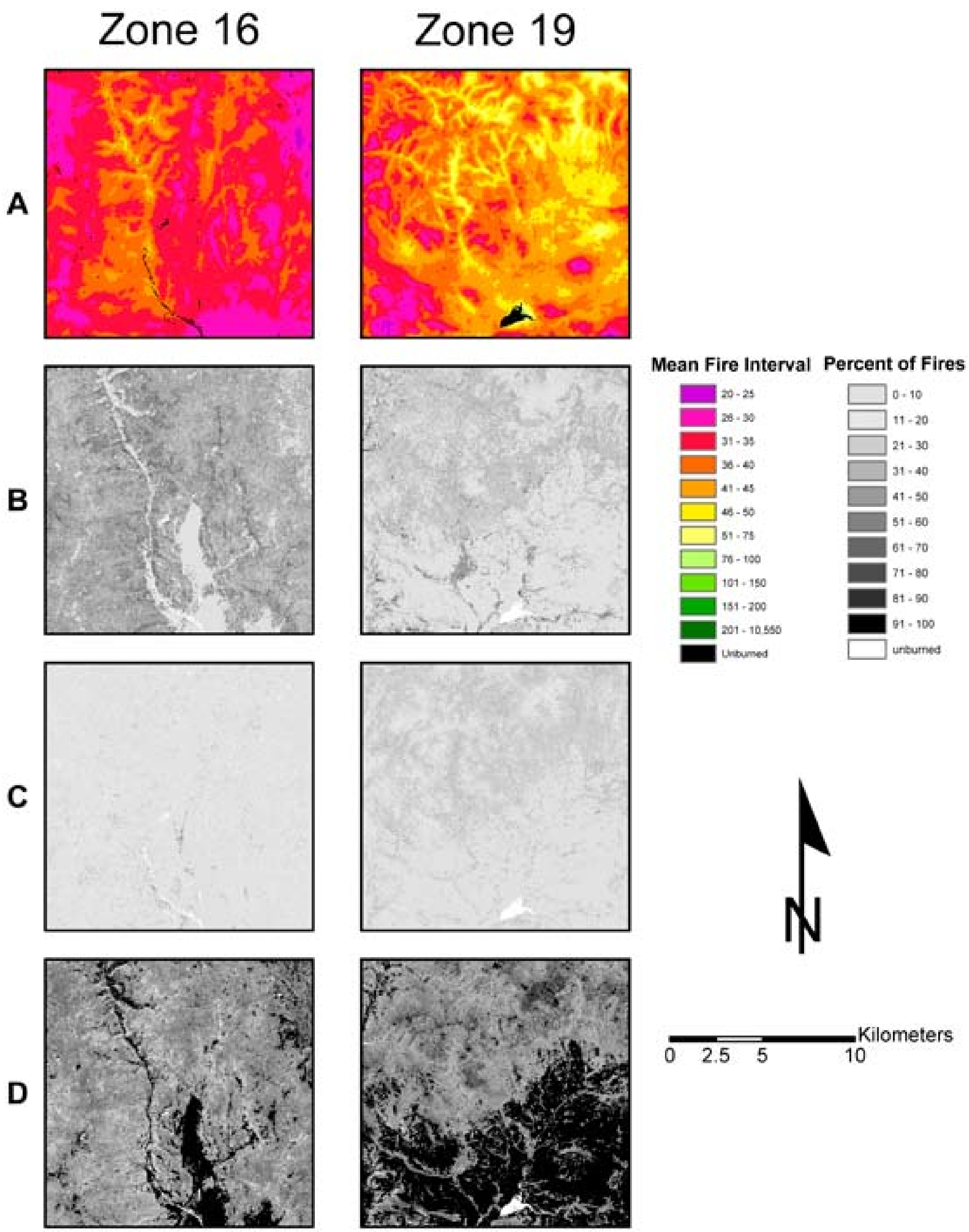


Figure 9—Digital maps of fire regime characteristics generated for Zone 16 and Zone 19: A) mean fire interval in years; B) percent of non-lethal surface fire; C) percent of mixed-severity fire; and D) percent of stand replacement fire.

is shown in figure 10B for each of the 1 km^2 landscapes where values are probability values that assess if the departure from simulated historical conditions in figure 10A is statistically significant. Figure 10C depicts the FRCC (Fire Regime Condition Class) calculated from methods presented in Hann (2004) (Holsinger and others, in press). This FRCC index will be used to guide the prioritization and implementation of fuel treatments across the nation.

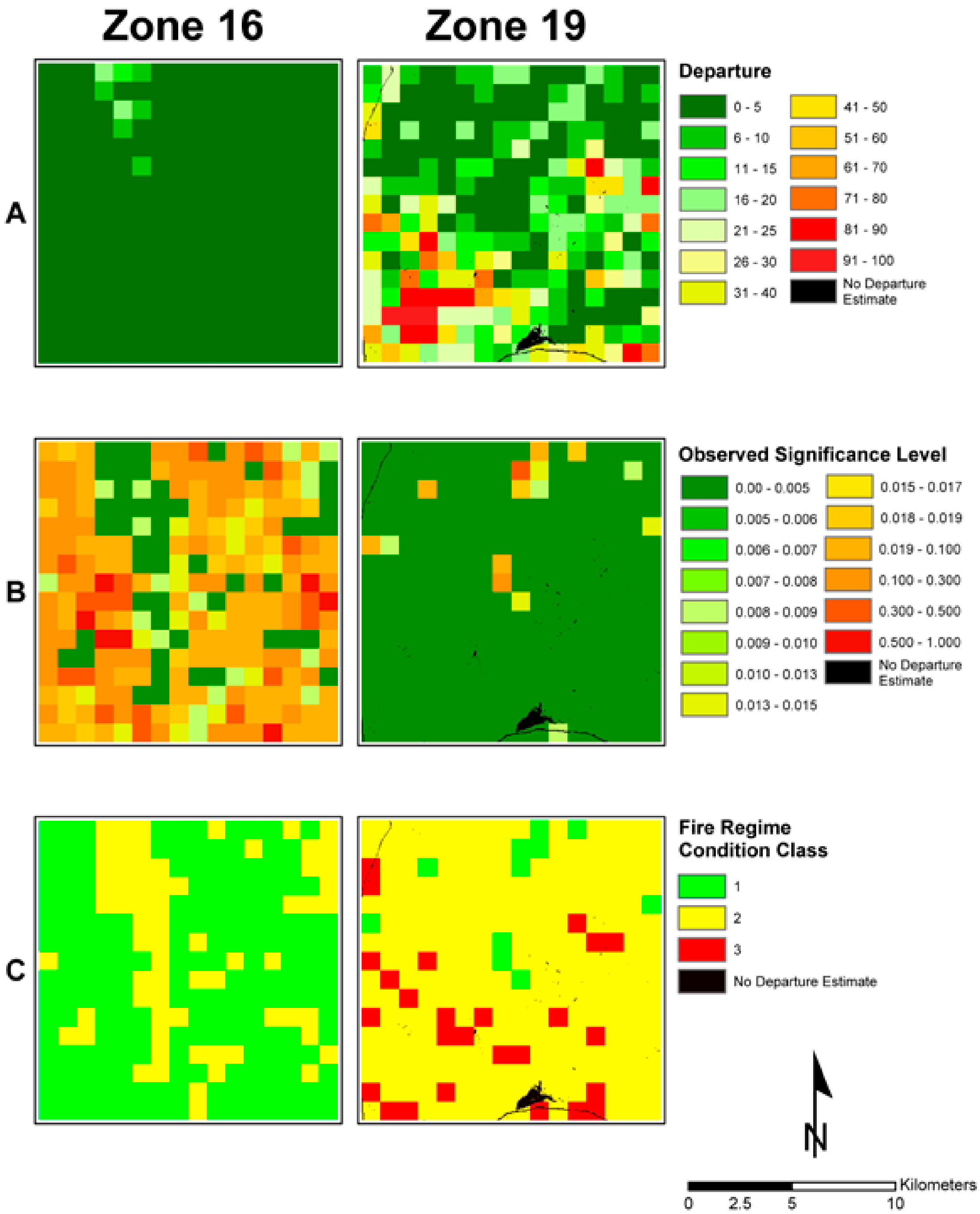


Figure 10—Demonstration of the use of LANDSUMv4 for calculating departure measures using the HRVSTAT program for Zone 16 and Zone 19: A) departure index; B) observed significance level; and C) Fire Regime Condition Class.

Sensitivity Analysis

Results of the sensitivity analysis show the complex influences of input parameters on area burned. Results of the partially hierarchical ANACOVA (table 2) reveal that there is only one highly significant (p-value<0.0005) interaction, wind speed and fire size. The interaction between fire size and frequency scalar was marginally significant (p-value=.049). Due to the insignificance of most of

Table 2. The analysis of covariance (ANACOVA) of the four sensitivity analysis factors and their interactions. The abbreviations mean: df-degrees of freedom, MS-mean sum of squares, F-ratio, p-value-probability value for significance. Most of the interactions are insignificant while the main effects are highly significant except for Landscape size (**bold numbers** signify significance p<0.05). The term (Site) indicates the interaction of simulation landscape. See table 1 for description of factors.

Source	df	MS	F	p-value
Analysis Factors				
Landscape size	2	4065	0.185	0.833
Fire size	2	3871	143.4	**<0.0005**
Frequency scalar	2	34466	1148.89	**<0.0005**
Wind speed	2	12197	369.6	**<0.0005**
Factor Interactions				
Landscape size x Fire size	4	1	0.056	0.994
Landscape size x Freq scalar	4	10	0.33	0.856
Landscape size x Wind speed	4	4	0.114	0.977
Fire size x Freq scalar	4	7	2.54	0.049
Fire size x Wind speed	4	87	34.5	**<0.0005**
Freq scalar x Wind speed	4	1	0.14	0.967
Landscape size x Fire size x Freq scalar	8	1	0.44	0.890
Landscape size x Fire size x Wind speed	8	2	0.89	0.531
Landscape size x Freq scalar x Wind speed	8	1	0.21	0.988
Fire size x Freq scalar x Wind speed	8	3	1.35	0.226
Fire size x Freq scalar x Wind speed x 16 Landscape size	2	1.47	0.1221	
Time	1	124	494.0	**<0.0005**
Landscape size (Site)	15	21939		
Fire size x Landscape size (Site)	30	27		
Frequency scalar x Landscape size (Site)	30	33		
Wind speed x Landscape size (Site)	30	33		
Fire size x Freq scalar x Landscape size (Site)	60	3		
Fire size x Wind speed x Landscape size (Site)	60	3		
Freq scalar x Wind speed x Landscape size (Site)	60	4		
Fire size x Freq scalar x Wind speed x Landscape size (Site)	120	1		
Error	48113	.252		
Total	48599			

the interactions and the desire to examine the main effects, the interactions were dropped from the model.

The results of the main effects ANACOVA in table 3 show that the effect of landscape size is insignificant (p-value=0.882) for percent area burned. The remaining main effects and time are all highly significant (p-value<.0005). The most significant effect is from the frequency scalar factor where changes in the frequency scalar had the largest effect on percent area burned. Wind speed was also highly significant; therefore varying the levels of wind speed will also have a large effect on percent area burned. Although fire size is highly significant, the

Table 3. Results of the ANACOVA main effects only. The factor with the largest effect on percent area burned was frequency scalar followed by wind speed. Although the effect of scale was significant, the F ratio is much smaller. There does not appear to be a significant effect from landscape size. **Bold numbers** represent significance (p<0.05)

Source	df	MS	F	p-value
Landscape size	2	4065	0.127	0.882
Fire size	2	3871	18.98	**<0.0005**
Frequency scalar	2	34466	565.0	**<0.0005**
Wind speed	2	12197	370.0	**<0.0005**
Time	1	124	452.0	**<0.0005**
Landscape size (Site)	15	31939		
Fire size x Landscape size (Site)	30	204		
Frequency scalar x Landscape size (Site)	30	61		
Wind speed x Landscape size (Site)	30	33		
Error	48576	.247		
Total	48600			

Table 4. Results of the multiple comparisons for the factors fire size, frequency scalar, and wind speed. All of the differences for each level were highly significant (p<0.05).

Variable	Treatment Levels	Mean Diff	95% Confidence Interval for Difference	p-value
Fire size	25 vs 50	0.621	(.606,.637)	<.0001
	25 vs 75	0.964	(.952,.977)	<.0001
	50 vs 75	0.343	(.331,.356)	<.0001
Frequency	0.75 vs 1.00	1.54	(1.52,1.55)	<.0001
Scalar	0.75 vs 1.25	2.92	(2.90,2.93)	<.0001
	1.00 vs 1.25	1.38	(1.36,1.39)	<.0001
Wind speed	1 vs 5	-0.158	(-.173,-.142)	<.0001
	1 vs 25	-1.58	(-1.59,-1.56)	<.0001
	5 vs 25	-1.42	(-1.43,-1.40)	<.0001

F ratio for this factor is much smaller. Therefore, the effects of varying the levels of fire size do not have as large of an effect on percent area burned as do the frequency scalar and wind speed.

Multiple comparisons were performed for fire size, frequency-scalar and wind speed using Bonferroni tests (table 4). All of the multiple comparisons were highly significant implying that all of the treatment levels were significantly different from one another. The largest differences occurred for the frequency scalar factor. Within this factor, the difference between the scalars 0.75 and 1.25 was the greatest. Based on the multiple comparisons and the ANACOVA table for the main effects, percent area burned is most sensitive to varying levels of the frequency scalar variable. The differences between the 0.75 and 1.25 levels were the most significant, and, therefore the model will be most sensitive to varying these levels of the factor. The wind speed factor appears to have the second highest effect on percent area burned (-1.58 in table 4) based on the significance of the ANACOVA model (tables 2 and 3). However, the mean

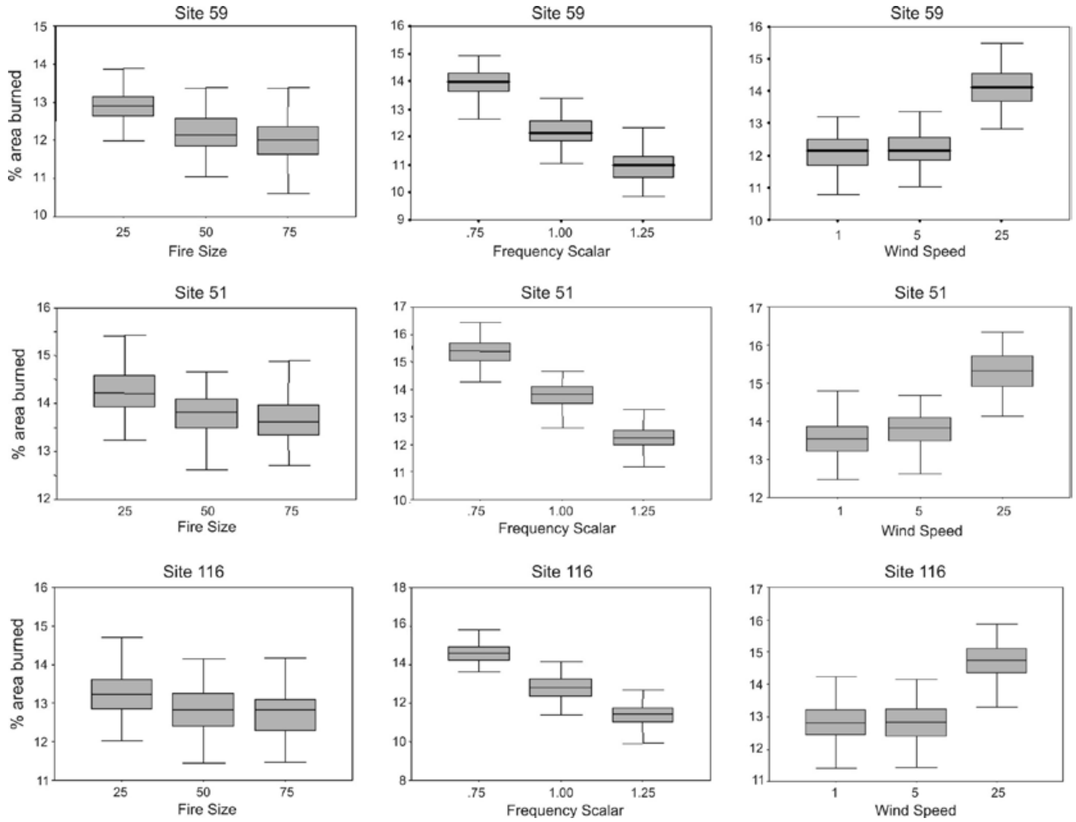


Figure 11—Side by side box plots of the sensitivity analysis factors of fire size, frequency scalar and wind speed. The remaining variables not in the box plot are held at level 2. The box plots reveal that varying the level of the frequency scalar has the largest effect on percent area burned. The box plots also reveal the large difference between the 25 level of wind speed versus the 1 and 5 level of wind speed.

difference, although significant, between 1 and 5 was quite small compared to the differences between 1 and 25 and 5 and 25. The factor that has the least effect, although highly significant, on percent area burned is the fire size factor. Figure 11 shows side by side box plots of the factors fire size, frequency scalar and wind speed at three different simulation sites where each site had three different-sized landscapes. The box plots reveal that varying levels of frequency scalar has the largest effect on the response variable—percent area burned. Also evident is the large difference in the percent area burned for the wind speed level 25 versus wind speed levels 1 or 5.

Discussion

The LANDSUMv4 model seems to be a viable vehicle for simulating historical fire and vegetation time series to use as reference to compare with current conditions as a means of locating, prioritizing and implementing future fuel treatments. We feel the model is a good compromise between simplicity and realism for generating historical chronosequences. Other models with more detailed simulations of fire spread and vegetation development require prohibitively long simulation times and difficult parameterization. For instance, simulating fire spread at hourly time steps using weather, wind, and fuels dramatically increases simulation times especially if the simulating time span were 5,000 years. LANDSUMv4 has a simple state-and-transition pathway model to simulate succession, and a simple cell percolation model to simulate fire spread. This reduces execution time and allows the simulation of large landscapes over long time spans to get temporally deep simulated chronosequences.

Even with it's simplicity of design, the LANDSUMv4 model, in its current form, is quite difficult to initialize, parameterize, and execute because it is a command-line program linked to a set of 14 ASCII input files (fig. 2). The C program is available on this CD, or it can be downloaded from a number of web sites including www.frames.nbii.gov, www.landfire.gov, and www.fire.org in the near future. Current efforts are underway to simplify the input and output structure of LANDSUMv4 and to provide a user-friendly front-end to easily specify simulation options. Moreover, the model is constantly being improved and revised to incorporate the latest simulation technology and research findings.

Sensitivity Analysis

The effects of altering levels of fire size, frequency scalar, and wind speed are highly significant but the effect of landscape size on percent area burned appears insignificant in our analysis (table 2, fig. 11). Most of the interactions between the factors proved to be insignificant, implying that the effect of one of the factors is not dependent on the level of another factor. This means it is very important that the input fire return intervals (in other words, fire probabilities) reflect realistic conditions and that realistic wind speeds and fire size parameters be used since they have a large impact on the area burned. We suggest that these parameters be initially estimated using any available data, and then iteratively adjusted as the results from the model (area burned) are compared with actual field measurements or expert opinion. Fortunately, there does not appear to be a significant effect of landscape size so the size of the simulation landscape can be selected to match computer resources for increasing efficiency and reducing simulation time.

Other sensitivity analyses on previous versions of LANDSUM also emphasize the importance of selecting important landscape characteristics for simulation. Keane and others (2002c) note that the shape and orientation of the landscape is critical for determining realistic fire regimes given the input values of wind speed and direction. They also found that there should be a simulation buffer around the target simulation landscape to ensure that immigrating fires are allowed to burn onto the target simulation landscape thereby reducing edge effect. Moreover, they found that output interval should be long enough to minimize temporal autocorrelation but large enough so that there is not an overabundance of redundant simulation years in the record. The LANDFIRE prototype project also performed a variety of sensitivity analyses on different landscapes and found roughly the same results (Pratt and others, in press). Fire size and probability input parameters remain the most sensitive and most important in a LANDSUMv4 simulation, whereas succession class time span is less important.

Model Parameterization

The quantification of succession and disturbance parameters in LANDSUMv4 is a difficult task. Because LANDSUMv4 is a spatial model that simulates spatial dynamics on landscapes composed of multiple PVTs, it is often hard for the user to determine the effect of a parameter or parameter set on model results. Moreover, previously measured disturbance and succession parameters are rare in the literature and there are scant field data for the many PVTs and landscapes across the United States, so these parameters are often quantified through an iterative process where the results of the model are used to set the parameter value. The user selects a starting value for the parameter, often taken from the next most similar succession class, and runs the model with this first estimate. Model results are evaluated and the parameter is modified if results disagree with experience. What is needed is a simplistic modeling platform that allows the testing and revision of model parameters without all the complexity of LANDSUMv4.

Model parameterization tool—One product of the Columbia River Basin Project (Hann and others 1998) was the VDDT (Vegetation Dynamics Development Tool) model that simulates succession and fire for one PVT in a non-spatial domain (Beukema and Kurz 1998). The VDDT model was built so that users could quickly prototype succession pathways for simulating succession and disturbance to determine the effect of management scenarios across the Columbia River Basin. VDDT serves as an excellent model building tool for LANDSUMv4 pathways.

VDDT allows the user to easily build and validate fire and successional parameters by comparing predictions against professional opinions and real historical data (Long and others, in press). It has an extensive graphical user interface that allows the quick and simple modification of parameters to determine their effect on PVT simulations. VDDT can also be used as a primary modeling tool, but since spatial relationships, such as fire spread, are NOT included in VDDT simulations, the results cannot be summarized to spatial units and the variability simulated by VDDT will tend to be underestimated over time. A spatial version of VDDT, called TELSA, simulates fire spread across the landscape but at resolutions coarser than LANDSUMv4 (Kurz and others 1999).

Fire occurrence probabilities—Both VDDT and LANDSUMv4 use fire probabilities to simulate fire processes. The input fire probabilities are point estimates of fire return interval. They do NOT describe the spatial aspect of fire regimes such as fire rotation or cycle. They only describe the probability that a fire will burn at a point on the landscape over long time spans. An example would be the number of times Rip Van Winkle got burned during his 20 year sleep. These fire probabilities are not fire ignition probabilities. They represent a one-dimensional statistic of fire occurrence over time and they do not infer other fire regime characteristics such as fire size, pattern, severity, and seasonality.

It is best if the fire probabilities are stratified by the three main fire severity types: non-lethal surface fires, mixed severity fires, and stand-replacement fires. Non-lethal surface fires burn surface fuels at low intensities but do not kill many overstory trees. Stand-replacement burns kill the majority of the dominant vegetation, often trees and shrubs (greater than 90 percent mortality). These fires include both lethal surface fires and active crown fires. Mixed severity burns contain elements of both non-lethal surface and stand-replacement fires mixed in time and space and include passive crown fires, patchy stand-replacement burns, and mixed severity underburns. Other types of severity classes exist, such as ground fires (in other words, smoldering fire burning extensive duff layers), but their effects must be manifest by changes in the successional pathways. The sum of the probabilities for these three fire types would equal the fire return probability, and the inverse would be the fire interval.

The two models use fire probabilities quite differently during simulation. VDDT uses the fire probabilities to determine how many points burn each year using the probability as a proportion. For example, a 0.1 fire return probability would translate into 10 percent of the points on the simulation landscape burning each year, but the size of the landscape is unknown. Since VDDT does not integrate the complex processes of spread and ignition with climate and fuels, much of the annual variation in burn size and severity is lost so the simulated time series will often underestimate landscape variability in fire. LANDSUMv4 uses the fire return probabilities to calculate an ignition probability for each landscape pixel by multiplying the probability by the pixel size divided by mean fire size. Once an ignition is simulated, the fire is spread across the landscape based on wind, slope, and climate. This approach is better able to describe the variability of fire effects and pattern because of the spatial implementation, but it is still a crude approximation of actual fire dynamics because it does not include fuels, weather, and moisture conditions.

Estimating fire occurrence probabilities—Since very few studies have measured fire probabilities on the landscape as they are defined and used in this model, we must find a way to approximate these parameters from other sources. These sources may measure the fire probabilities using methods that may limit the use of probabilities as model parameters. We suggest that the user always compare the simulation results with observed conditions or expert opinion to ensure these parameters are acceptable. If not, parameters should be modified so that results fit with expectations.

Fire history studies remain our major source for estimating fire parameters, especially fire return interval, in the modeling efforts. A review and summary of the fire history literature is an excellent method for approximating these elusive model parameters. But, there are some problems of scale and analysis in the data collected in fire history studies that the user must account for when estimating fire probabilities. First, many fire history studies are usually conducted in small areas within a highly complex landscape. Topographical features and their orientation, coupled with predominant wind patterns, can influence fire history within small study areas. For example, study areas on the lee side of large lakes or rock fields will tend to underestimate fire frequency while study areas adjacent to highly flammable ecosystems, such as grasslands on Native American travel routes, may tend to overestimate fire frequency. Second, fire intervals are often determined from dating fire scarred trees and the scar years are compared across a certain number of trees to determine if that year was a fire year. This threshold number of trees is very important to the detection and identification of fire years. It is difficult to determine if a tree did NOT scar because the fire did not visit the tree or because the fuels were insufficient for generating a scarring fire. So, the computed fire return interval is dependent not only on the number of trees used to identify a fire year, but also the number of fire scarred trees sampled within the study area. Again, fire scars are point measures of fire history and do not integrate spatial interactions of fire spread. Therefore, when using fire history studies to estimate fire occurrence probabilities, the user should adjust fire return intervals to reflect point level data using one of the following techniques.

Most fire history studies report mean fire intervals (MFI) from the fire dates recorded on scarred trees. Again, reported MFIs are estimated from a cluster of trees at a stand level and mostly describe non-lethal surface fire, and sometimes mixed severity fire, frequencies. Fire history studies in stand-replacement fire ecosystems determine the fire rotation from the extent of successional communities on the landscape. The assumption is that the proportional distribution of age classes on the landscape can be used to approximate a probability distribution that can then be used to approximate MFI. The MFI derived from each type of fire history study is quite different in its interpretation but either can be used as a starting point in the quantification of fire model parameters in the LANDFIRE and FRCC efforts. MFIs from most field studies are estimated using clusters of trees at a stand level (frequency often called a Composite Fire Interval), not "point" data from a single tree. Second, most data come from relatively small sample sites (sites less than an acre in size, which increases the likelihood that a given fire burned most of the sample site). Third, the stand MFI for a given PVT is assumed to be representative for the PVT as a whole. Together, these assumptions suggest that stand MFIs can be used to estimate fire parameters in the models, regardless of landscape size.

Fire history studies are missing for many ecosystems and regions of the United States. Often, the only way to estimate fire and succession parameters in these regions is by expert opinion, sometimes euphemistically called the "Delphi" approach. This remains a viable method of approximating fire probabilities, but it should be augmented with a feedback process to ensure realistic model results. In this feedback process, the local experts estimate fire and succession parameters to the best of their abilities. These parameters are then fed into computer models, such as VDDT, and simulation results are compared with the expert's expectations. Parameters are adjusted if needed and new results are generated. The process would stop once results agree with the expert's experience. If fire probabilities are unknown for an ecosystem, the local experts can estimate a set of starting fire probabilities, and the run the models continually adjusting the fire probabilities until results concurred with observed landscapes.

Most fire history studies document fire events over a very short time interval of about three to five centuries. The climate and human land use during this time was quite unique and therefore the fire regime documented by these fire history studies may be only applicable to this period. However, we often use the documented fire regime parameters and simulate fire over longer time spans than the fire parameters capture. This has obvious limitations and results generated from thousand year simulation runs must recognize that the parameters used to describe the fire regime were static and quantified from data taken from a small slice of history.

One problem with the design of LANDSUMv4 fire simulation is that the point-level estimate of fire occurrence probabilities (Scenario Input File) are not closely linked to the simulated process of fire spread. As a result, the final fire frequency map created by a LANDSUMv4 simulation may reflect more fire than the map of the input fire probabilities (see figure 9A for an example). This is primarily because more fire starts are simulated in high fire frequency environments, typically at lower, drier elevations, and these starts will spread uphill and down-wind to burn what are typically low fire frequency environments. Subtle differences in landscape orientation, shape, topography, and prevailing wind will dictate spatial fire regimes. Because the fire probabilities are estimated from studies that do not quantify landscape relationships, it is difficult, at this time, to fully integrate fire spread with ignition and get realistic results.

Fire size parameterization—Good historical data may be even more difficult to obtain for quantifying the fire size distribution in the Spatial Distribution File (average fire size and fire size parameter, Appendix A.6). While fire scars or pollen records may be used to reconstruct historical fire frequencies, they have limited use for reconstructing historic fire perimeters or fire sizes. Fire atlases have been compiled for some ecosystems, but the temporal record is relatively short (see Rollins and others 2001 for example). Fire size data for the last one or two decades remain our only source of estimating historical fire size (Hardy and others 2001, Schmidt and others 2002). The NIFMID database is probably the most important data source for fire size descriptions. However, these data reflect fire size distributions during the active fire suppression era where fire size distributions are probably not representative of historical conditions. Moreover, the NIFMID data have many problems, including double reporting of fires and the absence of many small fires (Schmidt and others 2002).

The two fire size parameters strongly influence fire and vegetation dynamics. A consistent methodology for setting these parameters to achieve appropriate fire frequencies is important. As we discussed, the historical data available for estimating these parameters is limited. We recommend using these estimates as a starting point for the average fire size parameter. While this estimate is likely to be larger than the historical average fire size, the average fire size modeled in LANDSUMv4 is also likely to be larger. Due to scale and model efficiency, no fires smaller than 1 ha are modeled. This removes a portion of the left end of the fire size distribution curve, which is where the largest numbers of fires occur, and thus increases the mean fire size. With this in mind, we recommend starting with the NIFMID estimate for the average fire size and setting the fire-size distribution parameter to 1/2 to 1/3 of this value and then running the model on several test landscapes and varying both parameters until the simulated average fire size approaches the NIFMID estimate and the fire frequencies simulated for each PVT approach the probabilities set in the pathways.

Another possible source of information regarding historic average fire sizes may be the expert opinion of the vegetation modelers who develop the succession pathways (Long and others, in press). Presumably the people developing the pathways have good familiarity with the ecosystem and may have some estimate of fire size based on their experience and the literature review they conducted to develop the pathways that could be used along with the NIFMID information to establish a starting point for the average fire size parameter. Simulated fire return intervals should always be compared with the probabilities entered in the Scenario Input File to ensure that they are within 10 to 20 percent; the simulated fire frequencies should approach the fire frequencies that parameterize the model.

Recommendations—The following are some recommendations for estimating the fire probability and size parameters in the LANDSUMv4 and VDDT models.

- Use fire history studies as guidelines or starting points for estimating fire probabilities. Incrementally adjust these parameters to agree with observed conditions.
- Use the model as the estimation tool when no fire history data are available. Guess approximate values of fire probabilities and run the model to determine if landscape composition agrees with expectations. Repeat process until results are realistic.
- Separate fire probabilities into the three fire severity types if possible. Use the effects of that fire type as guidelines for deciding if a fire severity type is warranted.
- Document sources of all parameters used in the model pathways. Define the temporal and spatial scales and confine the interpretation of model results to that scale.

- Interpret the results from VDDT differently than LANDSUMv4 in that VDDT will always have significantly less variation than that observed on the landscape because of the lack of spatial dynamics.

Simulation Issues and Limitations

***Issues of fire simulation*—**The most important limitation of the LANDSUMv4 model is absence of the close linkage between fuels, weather, and topography when estimating fire effects and pattern. Since fuel moistures are not computed, it is difficult to stop simulated fires from spreading into those stands that tend to be moist for many parts of the year, such as spruce fir forests. As a result, the model tends to overestimate the number of fires in mesic communities because fire is constantly spreading into these areas from surrounding flammable communities. Because LANDSUMv4 does not integrate the spatial distribution of fuel loading, fuel moisture, and daily weather, the pattern and severity of fire may not be entirely accurate. Use of LANDSUMv4 results to generate spatial statistics or metrics for describing HRV of landscape structure may not be as realistic as using the annual succession class distributions for describing HRV of landscape composition. Limitations of the LANDSUMv4 model must be recognized while interpreting simulated time series of landscape pattern metrics.

Even if the there were good historical data to estimate the fire parameters, there would still be differences between simulated fire regimes and actual historical fire regimes. It is difficult to simulate fire regimes from two sets of independent fire parameters (fire occurrence probabilities and fire size distributions). Fire, like many natural processes, is complex and any attempt to model it is necessarily a simplification of the actual processes. Fire operates at many different spatial and temporal scales and its occurrence is influenced by many factors, such as vegetation, weather, wind, and topography, which also operate at different spatial and temporal scales. As a result of this complexity, it is difficult to realistically simulate fire without building overly complex models that would be difficult to parameterize and inefficient to run for large landscapes over long simulation periods. Fire simulation in LANDSUMv4 incorporates mainly coarse scale processes. The weather parameters in the model function at a yearly time step and are generalized for the entire simulation landscape. The model does not incorporate daily or localized weather information. Wind speed and direction are also parameterized for the entire zone and then varied by time step, and not locally for each fire event. Integrating fine scale processes of weather or fuel into the model would make the model computational intensive and would dramatically reduce the efficiency of the model runs. Therefore, results of each LANDSUMv4 simulation should be compared with expert experience and any available data to determine if output is reasonable because of the overly simplistic model algorithms. If not, then the parameters should be adjusted to more closely approximate reality.

Mixed fire regimes present a special problem in the LANDSUMv4 modeling efforts. Mixed severity fire regimes have elements of both non-lethal surface fires and stand-replacement fires mixed in space and time. Technically, mixed severity fires should only be included as a separate fire type with associated probability in these models if their effects are significantly different from the other two severity types. This is difficult to assess since mixed severity regimes can create many small patches of tree mortality inside a simulated polygon. Therefore, the spatial grain of the mixed severity fire should always be more than the minimum polygon size to properly simulate mixed severity fire effects, especially in the LANDSUMv4 modeling effort.

The relationship between the average fire size and fire size distribution parameters can cause some confusion and problems in parameterization and interpretation of model results. The average fire size is the average size of the fire on the simulation landscape and it is used to scale the point estimate of fire probability to the polygon level. The fire size distribution parameter is a constant in the fire size distribution equation that determines the ultimate size of a simulated fire. This parameter is often approximated from the average fire size, but in LANDSUMv4 simulations, it often turns out to be about a third of the average fire size to match observed fire regimes. We recommend that the average fire size be determined from available data, and then the fire size distribution parameter be estimated using calibration techniques. The model should be executed and fire statistics from the Fire Output File (Appendix B.1) should be inspected to determine if the fire size distribution parameter should be altered to obtain more realistic fire regime simulations.

Issues of landscape simulation—Much of the LANDSUMv4 modeling is about balancing realistic simulations of fire and vegetation dynamics with the often opposing goal of computational and logistical efficiency. This struggle becomes more important as simulation landscapes increase in size and complexity. We found simulation times tend to increase exponentially with increasing landscape size but the use of larger simulation landscapes are logistically simpler and may produce better simulation results. There is probably some size landscape at which the model becomes efficient and overall processing time is optimized. We found the 100,000 to 250,000 ha landscapes work well but this may change with topographic and succession pathway complexity and as computer technology improves.

One of the problems with defining simulation landscapes is that the landscape edges create artificial boundaries across which fire cannot burn. In real landscapes, water, rock or topography may create real boundaries and influence fire spread, but our simulation landscapes did not follow natural boundaries and may cut right through areas of constant vegetation or topography through which the fire would naturally spread. Another problem is that areas near the edge of the landscape have a limited number of surrounding pixels from which a fire can spread into them. This problem is exacerbated by wind direction, because fire is only spread by wind and slope, and wind direction is at a constant direction and speed for the entire simulation. This means, all things being equal, pixels near the direction where the wind is originating (south and west edges, for example) have the lowest probability of burning while those near direction where the wind is blowing (the north and east for example) have the highest probability of burning (fig. 12A).

The best way to mitigate the edge effects in a LANDSUMv4 simulation is to surround the simulation landscape with a buffer (fig. 12). A buffer is created by making the simulation landscape larger and then stratifying the results into two categories – the buffer and the context area where both comprise the simulation landscape. The LANDFIRE prototype project used a 3-km buffer area around each 20,000 ha context area to create the final simulation landscape. If the buffer area is large enough, the relative position of pixels within the landscape will not influence the chance of burning and fire frequency will be determined by fire probabilities, adjacency, and topography. Areas of overlap, that is, those areas that were simulated twice (once as part of the buffer and once as part of the context area), are useful for examining how the buffers are functioning because fire probabilities and topography are constant between the two runs but the

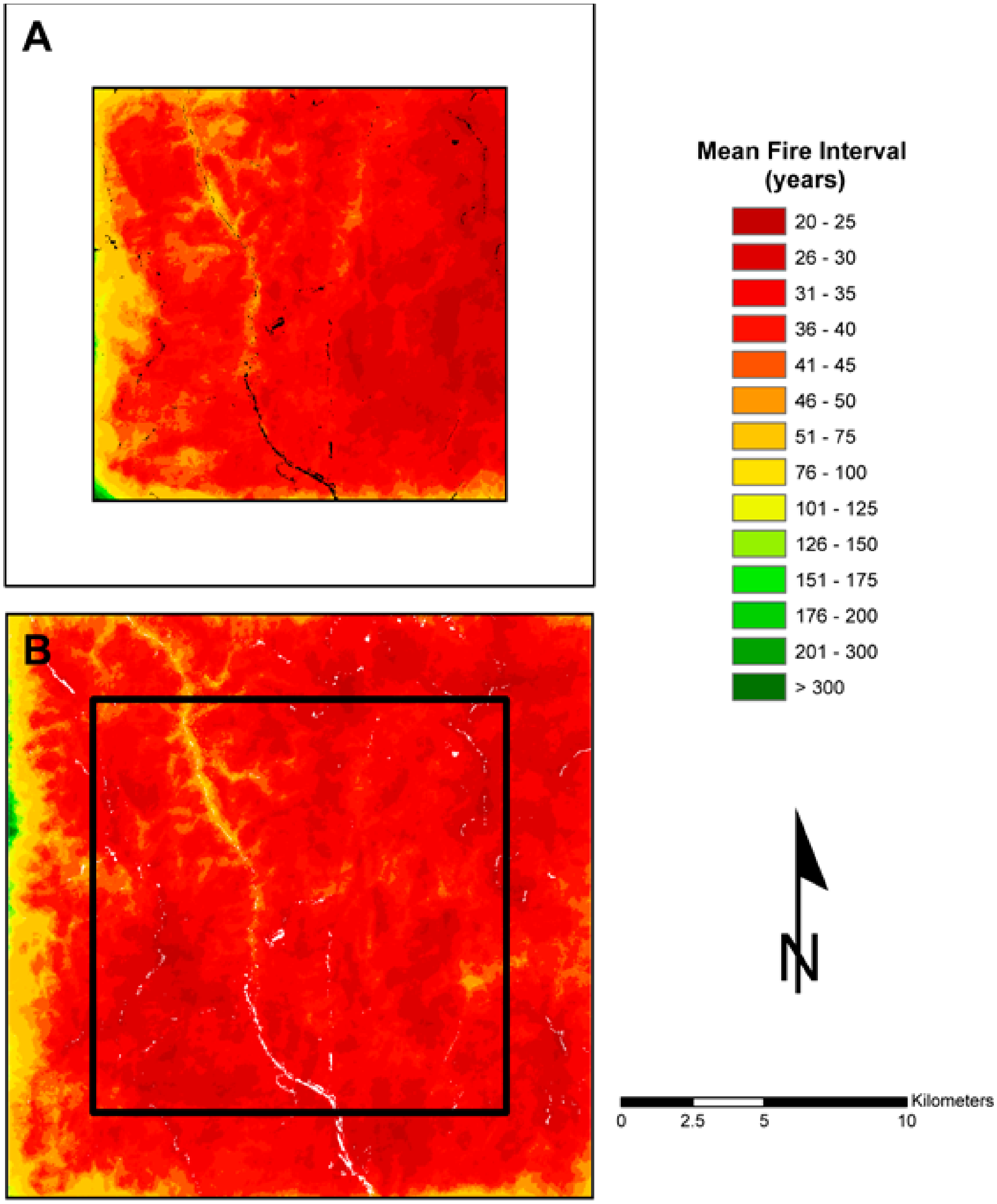


Figure 12—An example of fire regime simulation results for the Zone 16 test landscape showing the effect of edges on fire frequency across the landscape. A) fire frequency without a landscape buffer and B) fire regime for the same landscape with a 3 km buffer.

relative position of the pixels within the larger simulation landscape changes. Fire should not be underestimated in the leeward buffer region, as most fires burn in from the windward regions. If the buffer is large enough, fire should not be underestimated in the context area because the buffer should provide an adequate source for fires to burn in from the windward side. So if the buffer is adequate, the fire frequency in the leeward buffer region should not be substantially different from the fire frequency for this same region when it is part of the context area. Each landscape is unique, so buffers will be different for each setting. The user should always inspect fire regime maps to determine if the buffer is large enough to minimize edge effects in the context landscape, keeping in mind that simulation time increases exponentially as landscapes get larger.

Another key to efficient and accurate simulations is a consistent methodology for testing the pathways and parameters established for the simulation landscape. LANDSUMv4 has an extensive error checking routine that scans the input data for inconsistencies between the various input files that could cause problems during simulation. However, there may be problems with the input data that the model does not recognize as an inconsistency but may cause unexpected results. For example, differences in the way the VDDT and LANDSUMv4 simulate succession can lead to problems where the pathways did not function in LANDSUMv4 the same way they functioned in VDDT. And while the LANDSUMv4 model has undergone an extensive debugging process, it is always possible that some new, unique circumstance will arise in a new map zone that will cause unexpected results in LANDSUMv4. We recommend a thorough quality control process for the pathways once they are completed by the vegetation modelers. Ideally this could be done as a series of queries in a database environment that would check for consistencies between the ending age of one class and the beginning age of the subsequent class, as well as check that the next age or age increment applied by a disturbance results in an age that is within the age range of the resulting class. Once the pathways have passed this process, they should then be simulated and vegetation and fire regime information should be summarized for these test simulations and reviewed for any unexpected results. If there are any suspicious results, further analysis should be done to determine the reason for such results and whether they make sense ecologically.

It appears that a significant number of simulation years are required before the trends in succession classes stabilize and the annual simulations achieve some level of equilibrium. This stabilization time may take upwards of two to three centuries on simple landscapes and over 500 years on complex landscapes. We found that using the current landscape to initialize the historical landscape was inefficient on two levels. First, the current landscape contained too many polygons, and the simulation times increased as these numerous polygons were added by the continual division of polygons by fire. Second, the current landscape is so departed from historical conditions that it takes an excessively long time for this landscape to reach equilibrium. We found that initializing the model by assigning one succession class to each PVT polygon was the most efficient. The one succession class was selected as the most dominant in the VDDT simulations.

Model validation and verification are difficult tasks with landscape models that simulate vegetation and fire dynamics over millennia time spans (Keane and Finney 2003, Keane and others 2004a). There is a lack of spatially explicit historical time series data that are in the right context to compare with model results. Validation data must have many characteristics to be useful for model validation. First, the data must be described in the same format as model output; the mapped data must have the same categories as those simulated by LANDSUMv4. Next, the historical data must be from many time periods. The comparison of one historical map with the simulation results provides only a qualitative or descriptive means of testing and verifying the model. Multiple maps would provide the basis for an objective statistical comparison. And, since LANDSUMv4 does not replicate historical fire sequences because it is a stochastic model, it would be difficult to compare past fire patterns with corresponding simulated patterns. Last, the data must be incorporated into maps that describe historical conditions across the entire landscape. Because of these limitations, we could find no historical data sets to comprehensively validate LANDSUMv4. This leaves validation of the pathway and disturbance parameters as the only way to verify the model is producing realistic results. Stage and others (1995) performed an extensive validation of succession parameters for the pathways in the Interior Columbia River Basin Ecosystem Management Project using the FVS stand growth model and found greater than 80 percent accuracy (Stage 1997). Keane and others (2002c) compared simulated fire area and pattern statistics from a 1,000 year LANDSUM run to the historical fire atlas created by Rollins and others (2001) and found excellent agreement between the distributions of fire size and patch shape.

VDDT vs LANDSUMv4—VDDT does not simulate spatial relationships so none of the output should be interpreted in that context. There are options in the model that infer that spatial results can indeed be simulated into "number of pixels" or "area in PVT". In fact, these are misleading and contrary to model assumptions. It is suggested that the user interpret the number of pixels to be points on the landscape, and assume that the landscape can be any size. Most VDDT results are summarized in graphs or tables of percent of the landscape by modeled units (for example, cover type, structural stage, and disturbance type). These results should be interpreted as percent of points on the landscape rather than percent of area occupied by modeled elements. This is because most disturbances, especially fire, have a critical spread spatial component, and if spread isn't modeled, simulation results really shouldn't be summarized by area measures. That doesn't mean VDDT simulations are "wrong," rather, the VDDT simulations are coarser approximations of what is happening in the real world. These VDDT results help us understand the importance of fire parameters to landscape and vegetation dynamics. This approximation can be refined and improved by inserting the VDDT pathways and parameters into the spatial model LANDSUMv4.

There are subtle differences in the way LANDSUMv4 and VDDT simulate succession. The succession age in LANDSUMv4 is an index of vegetation development where polygons with old succession ages are more successionally advanced. VDDT, on the other hand, treats succession age as the age of the oldest plants in the simulated polygon. This difference is important when developing the succession transition ages because LANDSUMv4 defines a succession class with a beginning and ending age whereas VDDT specifies the longevity of that succession class. Another difference is that VDDT has an option that does not allow disturbances, primarily fire, to occur until a user-specified number of years has elapsed. Future versions of LANDSUMv4 will integrate these VDDT characteristics as options in the simulation.

Simulating HRV Issues

Many people feel it may be inappropriate to simulate fire and landscape dynamics over millennial simulation spans while holding climate and fire regimes constant. This would be true if the objective of the fire modeling were to replicate historical fire events. However, the primary purpose of the LANDFIRE modeling efforts is to describe variability in historical landscape dynamics. It is important that the entire range and variation of landscape conditions and processes be documented so that current condition can be compared against a realistic and comprehensive reference database. To accomplish this, field-based fire history study findings were used to parameterize the models even though these results represent a relatively small slice of time (300 to 400 years). The assumption here is that this small temporal span is a good proxy for the creation of reference conditions used in HRV simulation. Since the time slice represents only four or five centuries, it may seem that only 500 years of simulation are needed. However, the sampled fire events that occurred during this time represent only one unique sequence of fire start locations and subsequent fire spread that created the unique landscapes observed today. If these events had happened on a different timetable or in different areas, an entirely new set of landscape conditions would have resulted. It follows then that the documentation of landscape conditions from only historical records would tend to underestimate the variability of conditions that that landscape could have experienced in the past and will experience in the future. As a result, we attempted to approximate the entire range of conditions by simulating the static historical fire regime for thousands of years. We assumed that 3,000 to 5,000 years are long enough to contain enough fires to approximate the variability of conditions that the historical test landscape (fig. 5) would have experienced, but this time span is likely to be longer for landscapes with infrequent fires (we used 10,000 years in LANDFIRE Zone 19). We believe this is the best way to simulate historical reference conditions because it allows future landscapes to have variable fire ignitions and fire patterns. If only the last 300 years were used as reference conditions, then the future fire regimes would have to replicate the same ignition pattern and timing for the landscapes to be within bounds.

The complexity of PVT pathways can influence the comparison of historical dynamics to current conditions and ultimately affect the computation of departure. Pathways with a large number of succession classes have more elements to compare with current conditions and, as a result, the departure may be underestimated. Departure from a five succession class pathway, for example, would be greater than departure from a 40 class pathway because the large number of near zero values for the majority of succession class pairs tends to lower departure estimates. Departure estimation is best when succession pathway complexity is somewhat equal across all simulation landscape PVTs.

The size of the landscape unit for reporting simulated historical time sequences and computing departure within the simulation landscape is a critical question that still needs to be answered with further research. The LANDFIRE prototype effort divided the simulation landscape into a 900 meter grid to create 81 hectare reporting units. This size was selected so that it could be matched to a similar 1 km coarse scale effort (Hardy and others 2001) and not because it made ecological sense (fig. 10A). It is difficult to determine the optimum size of a simulation landscape reporting unit because of subtle differences in topography, climate, and vegetation across large regions. Current efforts are underway to develop guidelines for determining the appropriate reporting unit size and shape and preliminary results indicate that an appropriate landscape size may be between 10 and 20 km^2. In the meantime, it is probably best to match the reporting unit size with the management objectives. For example, watershed boundaries might be appropriate for the selection of fuels treatment prioritization if the management plans are stratified by watersheds.

Historical time series are autocorrelated in space and time. Any pixel on the landscape is ultimately dependent on the status of the surrounding pixels as fire spreads across the landscape. The instantaneous status of any landscape is dependent on the landscape composition and structure of the previous year. In addition, the extent of any succession class is related to the extent of all other classes; the increase in one succession class must result in the corresponding decrease of one or more succession classes on the landscape. It is important to minimize the mentioned autocorrelation in the historical time series by selecting an output reporting interval that is long enough to reduce the interdependencies of time, space, and succession class. This reporting interval will vary by landscape depending on fire frequency and succession transition times. The LANDFIRE prototype effort used 50 year reporting intervals to minimize autocorrelation for their simulations (Pratt and others, in press).

Many types of LANDSUMv4 output can be used to describe the historical variability for a multitude of management objectives. For example, simulated historical maps of fire frequency and severity can be compared with current fire atlases to estimate departure in terms of fire regime. Fuel models can be assigned to the PVT-succession class combinations in the Attribute Input File (Appendix A.12) to generate historical chronosequences of fuels to compare with current fuel maps. This comparison would be especially valuable if reduction of fire hazard were an important management objective. Similarly, hiding cover, thermal cover, or forage value can be assigned to PVT-succession class combinations to estimate historical variation in wildlife habitat. Mountain pine beetle and other insect and disease disturbance fluctuations can be simulated for comparison to current epidemics.

Historical scenarios might not be the only scenario used to compute departure and summarize HRV for simulation landscapes. Other scenarios can be developed and implemented into the Scenario Input File (Appendix A.11) to generate a time series for a completely different set of reference conditions. For example, the invasion of exotics may be so extensive that most of the landscape is departed from historical conditions. Therefore, the exotics can be included as disturbances in the Scenario Input File so that a more contemporary reference condition can be used. Or, historical reference conditions may not be a viable target for some heavily managed areas, so the fire probabilities in the Scenario Input File can be modified to reflect a fire suppression program.

Conclusions

The landscape fire succession model LANDSUMv4 appears to be a useful tool to simulate the range and variation of historical landscape dynamics. These landscape dynamics can be used as reference to evaluate the departure of current landscapes to historical conditions to prioritize and design treatment areas for land management.

Although simulation modeling in general, and the LANDSUMv4 model in particular, has several important limitations, it is still a useful and perhaps the only viable approach for generating historical reference conditions of vegetation and fire across large areas and ultimately the nation. First, LANDSUMv4 can generate this information in a consistent manner across all areas in the nation. While data coverage on actual historical conditions is limited in spatial extent, simulation modeling can estimate the reference conditions everywhere. This is not to say that the simulated conditions are intended to replace actual historical data where it exists, but rather to provide information where it is currently lacking. In addition to increasing the spatial coverage of historical reference conditions, simulation modeling can increase the temporal depth. Historical data often represents a narrow slice of time. This has obvious limitations and results generated from thousand year simulation runs must recognize that the parameters used to describe the fire regime and climate were static and quantified from data taken from a small slice of history.

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Appendix A.1 – LANDSUMv4 Model Execution

This appendix A describes the methods and procedures needed to develop the input data files for executing the weather summary model LANDSUMV4. The LANDSUMV4 model requires several tabular input files and two map files for its execution. The tabular files must be in ASCII format. All tabular input files should have an extension of “in” (for example, driver.in) to signify input files.

The program is executed via a command on the command line:

```
landsumv4 <DriverFile>
```

Where landsumv4 is the program name and DriverFile is the main file that drives the execution (see Appendix A.2, Figures 2, 3).

The LANDSUMv4 model can be found on this CD or downloaded from three web sites. The LANDFIRE project web site (www.landfire.gov) contains the source code and the executable for LANDSUMv4. It is compiled for a PC to work in a DOS window. The user can take the source code and compile LANDSUMv4 on any platform since the code is ANSI C++. The FRAMES website (www.frames.nbii.gov) also has the executable file but not the source code. Last, the program is available on the Missoula Fire Sciences Laboratory website (www.firelab.org).

The LANDSUMv4 program was primarily designed for execution on a personal computer within a DOS window.

The remaining sub-appendices in Appendix A describe the input files to LANDSUMv4. All input and output files in LANDSUMv4 are in ASCII format and are space and column delimited. This is often referred to as text format. Each input or output ASCII file is configured as a vertical or horizontal file. Vertical files contain only one input value per line with a descriptor of that input value following the number. Horizontal files contain more than one value per line and resemble a table. In general, LANDSUMv4 input files are both vertical and horizontal, while all output files are only horizontal. The horizontal file structure is used for efficiency while the vertical file structure is used for ease of development, greater understanding, and error management. Files in LANDSUMv4 are also cycling or discrete. Cycling files contain the same format that is cycled downward or repeated for each similar instance on the next line or set of lines. For example, site parameters are cycled vertically for each site on the landscape. Discrete files do not cycle and always contain a discrete number of vertical records. The first line of every LANDSUMv4 input file is called a title line and is used to describe the file and its origins. There are 256 characters available to craft a descriptive title that can uniquely identify the file while it is being viewed within a text editor. The title line should describe who, what, when, where, and why the file was developed. For example, one header might have the project for which the file was developed, who developed the file, when the file was developed, where the data were taken (data sources), and why this file was used for this particular simulation scenario.

Appendix A.2 – The Driver Input File

This Driver Input File is a vertical discrete scenario file that contains the names of all input and output files involved in LANDSUMV4 execution. Each file is listed as an entire pathname. The order of these files is absolutely critical. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable and UNITS is the units of this variable.

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for identifying landsum driver file	None
echo	2	256	Echo file: contains summary of all input data	None
error	3	256	Error file: contains errors, warnings encountered during init	None
sim	4	256	Simulation file: contains specific simulation criteria	None
mapfile	5	256	Map file: contains all input,output parms for generating a map	None
polyfile	6	256	Polygon file:list of polygons on landscape with attributes	None
spatdist	7	256	Spatial disturbance file: parameters to simulate spatial dist	None
vegfile	8	256	Veg file: Contains all vegetation succession parameters	None
distfile	9	256	Disturbance file: contains disturbance parameters	None
vegfix	10	256	Vegfix file: fixes in inconsistencies between maps and files	None
mgtfile	11	256	Management file: instructions for assigning scenarios to zones	None
scenfile	12	256	Scenario file: probability parms by disturbance for scenario	None
attfile	13	256	Attribute file: a set attributes for each PVT, ct, ss combo	None
firefile	14	256	Fire year file:fire year severity assignments for sim years	None
ostand	15	256	Output stand file: same as the input polygon file	None
oland	16	256	Output Landscape file: summarizes landscape by PVT, CT, SS	None
odist	17	256	Output Disturbance file: summarizes disturb by PVT, CT, SS	None
ofire	18	256	Output Fire file: output of individual fires on landscape	None
olandfire	19	256	Output LANDFIRE file: contains output for HRV computataion	None

The first line in this file is a title or file header for reference. The next 19 lines specify filenames that are entered as full pathnames. All pathnames in this file should start in column one and proceed left to right without blank spaces or commas (valid file names). It is recommended that a space be placed after the file name and then a descriptive statement be written to describe the filename such as who created it and so on. There are 256 characters allowed on these records. Be sure to identify the entire pathname including the directory structure up to the root directory (for example, C: is the root directory on a personal computer). There are some important options in driver file development. First, if you put "NONE" or "none" for any output filename, then no output will be written. The word NONE means that no output need be written for that topic.

The next two lines in this file specify important output filenames (also called pathnames) that are printed from LANDSUMv4 and allow the user to check if the input data are entered correctly into LANDSUMv4. The first pathname (***echo***) is used to identify the filename containing a dump of all the input values from all other input files. This file is important because it allows the user to check if the data were read into LANDSUMv4 correctly. The second pathname represents the ***error*** file that contains any error or warning messages that LANDSUMv4 found when it compared the input data across files and across the maps.

The next eleven lines specify pathnames that describe LANDSUMv4 input files that contain the input parameters and conditions needed to run the model. The formats for all these files are discussed in this Appendix A. The ***simfile*** contains all general simulation parameters that are used to govern the LANDSUMv4 execution such as number of years, output intervals, and output formats. The ***mapfile*** contains the list of pathnames that specify the input and output map filenames and the general mapping attributes for those output map files such as pixel size, starting coordinates, and number of rows and columns. The ***polygonfile*** is a pathname that contains all the polygons, and their associated attributes, that comprise the simulation landscape. The ***spatdistfile*** identifies the pathname where spatial parameters are stored to simulate the spread of fire across a landscape. The ***vegfile*** and the ***distfile*** are pathnames of files that contain the vegetation succession parameters and the disturbance pathway parameters, respectively. The ***vegfix*** pathname specifies a file that contains all the temporary fixes for inconsistencies between the vegetation succession parameters, polygon attributes, and the input polygon map. The ***mgtfile*** pathname identifies a file that contains all the time and space specifications for the disturbance occurrence parameters that are in the following ***scenfile*** (the pathname for all the management scenario disturbance probabilities)***.*** This scenario file contains the probabilities of disturbances by succession class and PVT (Potential Vegetation Type). The ***attfile*** pathname is a file where the user specifies up to five attributes, such as fuel model and cover type, for all PVT-succession class combinations. The ***firefile*** is where the user can specify the weather years (dry, moist, wet) for each year of simulation.

The last five lines are pathnames for LANDSUMv4 output. Output from LANDSUMv4 is the area (m^2) by region, zone, strata, PVT, succession class, then disturbance. The ***ostand*** file is a list of the polygons and their attributes by each simulation year output interval. The ***oland*** file summarizes this polygon list by region, zone, strata, PVT, and succession class and prints it every output year. The ***odist*** file is the same as the ***oland*** file but includes an additional stratification of disturbance for that year. The ***ofire*** file contains a list of all fires by year, PVT, and map coordinate. The last file, ***olandfire***, contains output that is specifically formatted for the LANDFIRE project to compute the historical range and variation of landscape composition.

An example of the Driver file is shown below:

```
LANDSUMv4 Driver file: driver_112.in     20 Jan 04 11:12:04 Tuesday lh
c:\landsum\landfire\test2\outfiles\echo_112.out      Echo file: contains summary of all input data
c:\landsum\landfire\test2\outfiles\error_112.out     Error file: contains all errors, warnings during initialization
c:\landsum\landfire\test2\infiles\sim_112.in         Simulation file: contains specific simulation criteria
c:\landsum\landfire\test2\infiles\map_p20kha.in      Map file: contains all map input output parameters a map
c:\landsum\landfire\test2\infiles\poly_p20kha.in     Polygon file: contains list of polygons
c:\landsum\landfire\test2\infiles\spatdist_112.in    Spatial disturbance file: contains spatial disturb parms
c:\landsum\landfire\test2\infiles\veg_z16.in         Veg file: Contains all vegetation succession parameters
c:\landsum\landfire\test2\infiles\dist_z16.in        Disturbance file: contains disturbance parameter
c:\landsum\landfire\test2\infiles\vegfix.in          Vegfix file: contains all fixes between maps and files
c:\landsum\landfire\test2\infiles\plan.in            Management plan file: instructions for assigning scenarios
c:\landsum\landfire\test2\infiles\scen_z16.in        Scenario file: contains probability of occurrence parms
c:\landsum\landfire\test2\infiles\attrib_z16.in      Attribute file: contains a set of attributes for PVT, ct, ss
NONE
NONE                             Output stand file: same as the input polygon file except it is output
NONE                             Output Landscape file: summarizes landscape by PVT, CT, SS stratification
NONE                             Output Disturbance file: summarizes all disturbances by PVT, CT, SS, and zone
NONE                             Output Fire file: contains output of individual fires on landscape
c:\landsum\landfire\test2\\outfiles\landfire_112.stat Output LANDFIRE file: contains output for HRV computataion in
LANDFIRE
```

Appendix A.3 – The Simulation Input File

This Simulation Input File is also a vertical discrete scenario file that contains general simulation information about a LANDSUMv4 run. Again, the order of these parameters is important and the user must document the file origin in the titleline. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable.

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
verbose	2	1	Verbose flag:(0-no messages, 1-limited messages, 2-full messages)	None
simyear	3	5	Number of years to simulate succession	years
attrib	4	1	Number of attributes in the Attribute file	None
projID	5	10	Project ID code for specific simulation parameters	None
ageinit	6	1	Age init option (0-use age, 1-Random, 2-midpoint , 3-beg age)	None
outint	7	5	Interval (yrs) to print results to output maps and tabular files	Years
outbegyr	8	5	Year to start printing output results to maps and tabular files	Years
firebeg	9	5	Starting code for fire disturbances	Code
fireend	10	5	Ending code for fire disturbances	Code
ostand	11	1	Tabular results: Stand Summary (0=none, 1=partial, 2=full)	None
oland	12	1	Tabular results: Landscape Summary (0=none, 1=partial, 2=full)	None
odist	13	1	Tabular results: Disturbance Summary (0=none, 1=partial, 2=full)	None
ofire	14	1	Tabular results: FIRE Summary (0=none, 1=partial, 2=full)	None
olandfire	15	1	Tabular results: LANDFIRE (0=none,1=sclass,2=ct 3=ss,4=att1,…	None
distopt	16	1	Disturb option(0-include all dist, 1-exclude all dist, 2-exclude all but fire)	
ranscheme	17	1	Random number scheme (0 = different every time, 1 = repeatable)	None
rengen	18	1	Random number generator (0 = system, 1 = Ran1, 2 = Ran2)	None

The variable ***title*** is the line that uniquely identifies this file and should contain information for user reference. The ***verbose*** flag is set to zero if the user doesn't want any messages to be printed to the command line window during program execution; set to one (1) if a limited set of messages are desired so the user knows how long the program has been running; and two (2) if a full set of descriptive messages are to be printed so the user can track the details of a simulation run. The ***simyear*** is the number of years that the user wants to run the model. The ***attrib*** variable signifies the number of attributes that the user has entered in the ***attfile*** for each PVT-succession class combination. The ***projID*** is the identification number for the current simulation project to match the parameters in the vegetation succession file (***vegfile***) and the disturbance file (***distfile***). The ***ageint*** variable identifies how the user wishes to initialize the age of each polygon on the landscape: 0-use the age that is specified in the polygon file (***polyfile***); 1-randomly assign the age between the range specified for that succession class; 2-use the midpoint of that succession class; or 3-use the beginning age for the succession class.

The next set of variables identifies output specifications. The ***outint*** is a variable that specifies the number of years or output interval for printing simulation results for that simulation year. For example, the number 50 would specify that output be printed every 50 years on year 1, 51, 101, and so on. The variable ***outbegyr*** allows the user to specify the year to begin printing output. In LANDFIRE it took about 200-500 years for the model to equilibrate so the number 200 was entered here.

The ***firebeg*** and ***fireend*** variables signify the range of codes used to identify fire disturbances within LANDSUMv4. For example, all fire disturbances in LANDFIRE spanned from 1,000 to 2,000.

The remaining variables allow the user to tailor the output format for greater efficiency in storage and execution. The variables ***ostand, oland, odist,*** and ***ofire*** signify the output formats for the polygon, landscape, disturbance, and fire files (Driver Input File) using the following convention: 0-do not print output; 1-print a summary of the output; or 2-provide the full details in the output. The ***olandfire*** file option allows the user to print the area summary by region, zone, strata, and pvt by the following variables: 1-none; 2-succession class; 2-cover type; 3-structural stage; 4-attribute1; 5-attribute2; 6-attribute 3; 7-attribute4; 8-attribute5; or 9-all possible output variables.

The ***distopt*** variable allows the user to run the model with only succession and no disturbances (option 1), run the model with all disturbances (option 0), and run the model with only fire disturbances (option 2). The random number scheme (***ranscheme***) is a variable for the user to specify that the random numbers are the same across each execution (option 1) or different across all executions (option 0). And last, the ***rangen*** variable specifies the random number generator to use in LANDSUMv4: 0-system random number, 1-random number generator 1, 2-random number generator 2. The system random number generator seems to perform adequately.

An example of the Simulation Input File is show below:

```
LANDSUMv4 -- Test watershed p20kha-112 for Zone 16 -- General simulation parameters -- Keane Fall 2003
2               Verbose flag: (0-no messages, 1-limited messages, 2-full messages during execution)
555             Number of years to simulate succession
0               Number of attributes in the Attribute file
LANDFIRE        Project ID code for specific simulation parameters
1               Age initialization option (0-use age, 1-Random, 2-midpoint, 3-entered beg age in pvt)
3               Interval (yrs) to print results to output maps and tabular files
3               Year to start printing output results to maps and tabular files
1100            Starting code for fire disturbances
1140            Ending code for fire disturbances
0               Tabular results: Stand Summary (0=none, 1=partial, 2=full)
0               Tabular results: Landscape Summary (0=none, 1=partial, 2=full)
0               Tabular results: Disturbance Summary (0=none, 1=partial, 2=full)
0               Tabular results: FIRE Summary (0=none, 1=partial, 2=full)
11              Tabular results: LANDFIRE Summary
0               Disturbance exclusion option (0-include all dist, 1-exclude all dist, 2-exclude all but fire)
0               Random number scheme (0 = different every time, 1 = repeatable random)
0               Random number generator (0 = system, 1 = Ran1, 2 = Ran2)
```

Appendix A.4 – The Map Input File

This Map Input File is another vertical discrete scenario file that contains general spatial information about the input and output maps that are generated from LANDSUMv4. Again, the order of these parameters is important and the user should document the file origin in the titleline. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
pixsize	2	10	Pixel width size of all maps in meters	None
cols	3	10	Number columns (i.e., pixels in a column) in all maps	None
rows	4	10	Number rows (i.e., pixels in a row) in all maps	None
xllcoor	5	15.5	Lower left corner UTM East coordinate of all maps	meters
yllcoor	6	15.5	Lower left corner UTM north coordinate of all maps	meters
nodata	7	10	NODATA value in all maps None	
ulr,ulc	8	10,10	Upper left row,col coordinates for output submap (-999 entire map)	None
lrr,lrc	9	10,10	Lower right row,col coordinates for output submap (-999 entire map)	None
NONE	10		This line is put in for dividine the map names from above	None
demmap	11	256	Input Digital elevation model for landscape	filename
ipolymap	12	256	Input Initial polygon map in pixel or raster form	filename
opolymap	13	256	Output Dynamic polygon output map name (Enter NONE if no output)	filename
ofiremap	14	256	Output cumulative fire map (Enter NONE if no output desired)	filename
oscmap	15	256	Output succession class map(Enter NONE if no output desired)	filename
odistmap	16	256	Output disturbance map (Enter NONE if no output desired)	filename
octmap	17	256	Output Cover type map (Enter NONE if no output desired)	filename
ossmap	18	256	Output structural stage map (Enter NONE if no output desired)	filename
ofyrmap	19	256	Output fire year map (Enter NONE if no output desired)	filename
oagemap	20	256	Output age map (Enter NONE if no output desired) filename	
oatt1map	21	256	Output attribute number 1 map (Enter NONE if no output desired)	filename
oatt2map	22	256	Output attribute number 2 map (Enter NONE if no output desired)	filename
oatt3map	23	256	Output attribute number 3 map (Enter NONE if no output desired)	filename
oatt4map	24	256	Output attribute number 4 map (Enter NONE if no output desired)	filename
oatt5map	25	256	Output attribute number 5 map (Enter NONE if no output desired)	filename
ofrmap	26	256	Output fire regime map prefix (Enter NONE if no output desired)	filename

where ***pixsize*** is the width of the pixel in meters, ***cols*** and ***rows*** are the columns and rows that make up the rectangular input and output map structure. The ***xllcoor*** and ***yllcoor*** are the lower left (southwest) corner coordinates for the easting and northing using a UTM projection. The ***nodata*** variable is the value given in the input maps for missing or no data value available. The ***ulr***, ***ulc***, ***lrr***, and ***lrc*** variables are the upper left (ul, or northwest) and lower right (lr, or southeast) output map coordinates in rows (r) and columns (c). These row and column coordinates allow the user to output only a small section of the simulation landscape. There is another line in this input file but it only serves to separate the map information from the map filename specifications.

The next set of fields are input filenames for the model. There are two input files where the full pathnames should be specified. The ***demmap*** is the digital elevation model map with the above map specifications (pixsize, cols, rows, xllcoor, yllcoor). The ***ipolymap*** is the input polygon map where all pixels are assigned a polygon number. These numbers correspond to the list of polygons in the Polygon Input File (Appendix A.5).

The last set of map filenames are all output filenames. When the user enters a pathname in these lines, the model will write a map to that pathname every time there is an output year (the output year interval is specified in the Simulation Input File in Appendix A.3). The program will append a year number at the end of the pathname to denote the output year that the map represents. If the user does NOT want any of these output maps, the word NONE is specified in columns 1 through 4 and the model will not print this map. The ***opolymap*** is the map containing polygon numbers that can be cross referenced to the output polygon file specified in the Driver Input File (Appendix A.1). The ***ofiremap*** is a map where each pixel is assigned the cumulative number of fires that have occurred up to that simulation year. The ***oscmap*** is an output map that displays current succession classes for that output year. The ***odistmap*** is a map that shows the disturbance ID value for any disturbance that occurred during that output simulation year. The ***octmap*** and ***ossmap*** are maps where the pixels are assigned the cover type ID and structural stage ID values, respectively, and are referenced in the Attribute Input File (Appendix A.12). The ***ofyrmap*** is a map that shows the fires that burned during that output simulation year. The *oagemap* is a map where each pixel is assigned a succession age. The ***oatt1map***, ***oatt2map***, ***oatt3map***, ***oatt4map***, and ***oatt5map*** variables signify five maps that display the values assigned to the succession classes in the Attribute Input File (Appendix A.12). The last output map, ***ofrmap***, is perhaps the most important because it is a prefix that is used for four fire regime maps. The prefix is then assigned a suffix of .freq, .sev1, .sev2, or .sev3 for each of the four maps. The first map is a map of fire frequency where each pixel is assigned a value for the cumulative number of fires across the entire simulation. There are three maps of severity. The .sev1 map represents non-lethal surface fires, the .sev2 map represents mixed severity fires, and the sev3 map represents stand replacement fires. The probability of each of these fire severity types is assigned to the pixels in each of the maps.

An example of the Map Input File is as follows:

```
LANDSUMv4 MAP infile: map_p20kha.in 20 Jan 04 11:12:04 Tuesday lh
30         Pixel size of all maps in meters
397        Number columns (i.e., pixels in a column) in all maps
397        Number rows (i.e., pixels in a row) in all maps
-1448116.625 Xllcorner of all maps in meters
1757702.5 Yllcorner of all maps in meters
-9999      NODATA value in all maps
-999 -999 Upper left row and col coordinates for output submap (-999 means entire map output)
-999 -999 Lower right row and col coordinates for output submap (-999 means entire map output)
Input and output map files -- Enter NONE if you do not want that map
c:\keane\applications\landsum\landfire\test2\inmaps\dem_p20kha.asc      INPUT: Digital elevation model for landscape
c:\keane\applications\landsum\landfire\test2\inmaps\poly_p20kha.asc     INPUT: Initial polygon map (NOT VECTOR)
NONE       OUTPUT: Dynamic polygon output map name in pixel form (NOT VECTOR)
NONE       OUTPUT: Dynamic fire output map
NONE       OUTPUT: Succession class map
NONE       OUTPUT: Disturbance map
NONE       OUTPUT: Cover type map
NONE       OUTPUT: Structural stage map
NONE       OUTPUT: pvtxssxct map
NONE       OUTPUT: Age map
NONE       OUTPUT: Attribute number one
NONE       OUTPUT: Attribute number two
NONE       OUTPUT: Attribute number three
NONE       OUTPUT: Attribute number two
NONE       OUTPUT: Attribute number five
c:\keane\applications\landsum\landfire\test2\outmaps\firereg OUTPUT: Fire regime map prefix
```

Appendix A.5 – The Polygon Input File

The polygon file is a horizontal, cycling, descriptive file that contains a list of all polygons on the simulation landscape defined in the map specified in the Map Input File (Appendix A.4). A set of critical attributes are assigned to each polygon in the list. The polygons in this list must perfectly match all the polygons in the polygon input map specified in the Map Input File. This file is cycling because each line is another polygon.

The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the file in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
colhead	2	256	Column header information for user only-not used in program	None
polyID	3	10	Code that uniquely identifies the polygon	None
regionID	4	10	Unique code for a broad region ID number	None
zoneID	5	10	Stratification code for a zone within a region	None
strataID	6	10	Stratification code for a reporting area within a zone and region	None
pvtID	7	10	Potential vegetation type ID number	None
sclassID	8	10	Succession class ID number	None
age	9	10	Succession age of this polygon	None
area	10	10.2	Area of this polygon in initial polygon map	meters

where the ***polyID*** is a unique identification number assigned to this polygon. Polygon numbers need not be in order or sequential, but, there should not be any repeat ID numbers. Each polygon ID number should exactly cross-reference the polygons mapped in the polygon input map specified in the Map Input File (Appendix A.4).

The next three fields allow the user to hierarchically spatially stratify the polygons by regions, zones, and strata. Regions (***regionID***) are broad stratifications that could represent ownership, ecological sections, or political boundaries. Nested inside regions are zones (***zoneID***) that subdivide regions. Zones might be management zones within ownerships such as wilderness and non-wilderness lands. Last, strata (***strataID***) represent nested divisions of zones. The LANDFIRE effort used regions to represent broad mapping zones (68 zones divided the contiguous United States), then zones represented simulation landscapes within the mapping zones, and last, strata represented the reporting landscapes or units for the calculation of historical departure and fire regime condition class.

The ***pvtID*** identifies the code for the PVT ID number for this polygon as referenced in the Vegetation Input File (Appendix A.7). The ***sclassID*** represents the unique code for the succession class of the polygon within the PVT as defined in the Veg Input File. The ***age*** is the succession age of that polygon. If this attribute is unknown or difficult to estimate, then the user would enter zero and the LANDSUMv4 program will calculate the succession age based on the option specified in the Simulation Input File (Appendix A.3). Last, the ***area*** is a variable that represents the area this polygon contains and should exactly match the area in the Polygon Input Map. This variable is used as a logic check from this polygon list to the polygon input map.

An example of the polygon file is shown below:

```
Polygon input file for LANDSUMv4 demostration Prepared Jan 2 2002

PolyID  RegID  ZID  StrID  PVTID  SClID   Age  Area(m2)
1       16     1    2      1611   131206  0    900
2       16     1    2      1601   141211  0    16200
3       16     1    2      1603   131211  0    900
4       16     1    2      1663   323101  0    900
5       16     1    2      1601   141211  0    900
6       16     1    2      1663   323101  0    3600
7       16     1    2      1601   141211  0    900
8       16     1    2      1663   323101  0    2700
9       16     1    2      1601   141211  0    1800
10      16     1    3      1601   141211  0    900
11      16     1    4      1601   141211  0    2700
12      16     1    5      1601   141211  0    900
13      16     1    5      1601   141211  0    1800
14      16     1    5      1601   141211  0    900
15      16     1    5      1603   131211  0    15619500
```

Appendix A.6 – The Spatial Disturbance Input File

The Spatial Disturbance File is a vertical, cycling, descriptive and scenario file that contains all spatial disturbances that are to be simulated in LANDSUM and the parameters that are needed to simulate these spatial disturbances. Only fire can be simulated with this version of LANDSUMv4, the others are listed and their spatial simulation is included but they haven't been tested. The first two lines of the file define the file. The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line specifies how many disturbances are cycled in this file (***ndist***). Again, only fire is available so the number one is entered. The remaining lines describe each spatial disturbance and they are cycled if the other spatial disturbances were available. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
ndist	2	10	Number of disturbances that are cycled in this file	None
sdistID	3	10	Spatial disturbance ID number(1-fire, 2-beetle, 3-harvest)	None
modID	4	10	Spatial spread model (1-cell automata, 2-Cookie, 3-percolation)	None
nys,nyn,nyw	5 3	10	Number of years that a severe, normal and wet year in a decade	None
fsize	6	10.2	Average fire size for this landscape	Hectares
wsim	7	10	Wind simulation:0-same every year, 1-year, 2-fire, 3-timestep, 4-cell)	
wind	8	10.2	Average wind speed	m/sec
wdir	9	10.2	Average wind direction for a fire event	azimuths
freqequ	10	10	Equation number for frequency probablity equation for occurrence	None
freqa	11	10.2	Parameter 1 for freq equation (Year till it can burn)	Year
freqb	12	10.2	Parameter 2 for freq equation (Approximate fire return interval yrs)	Year
freqc	13	10.2	Parameter 3 for freq equation (shape parm)	None
fsizeequ	14	10	Equation number fire size	None
fsizea	15	10.2	Parameter 1 for fire size equation	m2
fsizeb	16	10.2	Parameter 2 for fire size equation (shape of curve parm)	None
fsizeb	17	10.2	Parameter 3 for fire size equation (shape of curve parm)	None
shape	18	10	Shape pattern (1-triangle, 2-parabolic, 3-circular, 4-rectangle)	None
ecc	19	10.2	Eccentricity or elongation parameter (0.0-10.0)	None
cycle for each disturbance of beetle or harvest				

where ***sdistID*** is the spatial disturbance ID number and the number 1 is wildland fire. Options 2 (beetles) and 3 (timber harvest) have not been fully tested. The variable ***modID*** indicates the spatial spread model to use to simulate the spread of this disturbance. Option 1 is a cell automata model that is very simplistic; option 2 is a cookie cutter method where shapes (specified in following lines) are cut from the landscape to mimic disturbance patches; and option 3 is the fully tested cell percolation approach that uses a mechanistic means to spread fire. Option 3 is available only for fire.

The next three fields identify the distribution of fires over 10 decades and provide a means for the user to impose variation in burned areas over simulation years. When the user specified the number of severe, normal, and wet years (***nys, nyn, nyw***) in a decade, the model will compute multipliers that increase or decrease fire probabilities by an order of magnitude to generate variability across years. For example, if the user specifies 1,1,8 for these variables, then there would be a very low number of severe fire years, but when these years occur, large areas would be burned. A triplet of 3,4,3 would generate the same number of fires each year. Even though the probabilities of fire are modified each year, the annual fire probabilities averaged across the simulation run will be exactly as specified in the Scenario Input File (Appendix A.11).

The variable ***fsize*** identifies the average size (ha) of all fires on the landscape. This value is used to scale the point estimates of fire probabilities in the Scenario Input File to an area basis.

The next three fields concern the simulation of wind. First, the user specifies how wind will be simulated. Option 0 specifies that the wind will be in the same direction and at the same speed each year; option 1 varies wind speed and direction each year; option 2 varies the speed and direction for each fire; option 3 varies wind by simulation time step; and option 4 varies wind speed and direction for each cell. This allows a fully stochastic treatment of wind. Wind speed is varied with the range of half and double wind speed specified in the ***wind*** variable, while wind direction is varied by 45 degrees from the direction specified in the ***wdir*** variable.

The next four fields concern the fire frequency probability computation. The ***freqequ*** is a variable where the ID number of the frequency probability equation is stored. The available probability equations are only 1-Weibull. We have others in LANDSUMv4 but only allow the Weibull in this version. Then, the ***freqa***, ***freqb***, and ***freqc*** are the parameters for the Weibull equation quantified for the simulation landscape. In the Weibull equation, the ***freqa*** parameter is the number of years before the pixel can burn again; ***freqb*** is the fire return interval (inverse of fire probability); and ***freqc*** is the shape parameter (usually 2.0 for most applications).

The fire size equation is described in the next four fields. The ***fsizeequ*** is the equation ID number where options are 1-Pareto, 2-lognormal, 3-exponential, 4-uniform, 5-normal, 6-extreme, 7-Weibull, and 8-logistic. Again, we recommend the Weibull and the parameters that describe that equation: ***fsizea*** is a shape parameter usually set at 3.0; ***fsizeb*** is the inflection of the exponential Weibull equation which is roughly about a third of the average fire size; and ***fsizec*** is not used for this LANDFIRE application.

The last two parameters are used only if the spread model is specified by the user as the cookie cutter approach. The ***shape*** variable is the shape of the patch where options are: 1-triangle, 2-parabolic, 3-circular, 4-rectangle, and ***ecc*** is the eccentricity or elongation parameter that varies from zero (not stretched) to 10 (fully elongated).

An example of the Spatial Disturbance File is:

```
LANDSUM v2.0 - Spatial disturbance parameter file for zone 16, January 2004
1          Number of Disturbances represented in this file
1          Wildand_Fire (1-fire, 2-beetle, 3-harvest)
3          Model of spatial spread simulation (1-cell automata, 2-Cookie cut shapes, 3-cell spread percolation)
0.0 0.0 10.0 Number of years that a severe, normal and wet year occurs in a decade (must add to 10)
50.0       Average fire size for this landscape (ha)
3          Wind simulation: 0-same every year, 1-vary by year, 2-vary by fire, 3-vary by timestep, 4-very by cell)
5          Average wind speed in meters per sec
60.0       Average wind direction for a fire event (azimuths true north)
1          Equation number for frequency probablity equation for occurrence (1-Weibull )
3.000      Value of first parameter for above equation (Year till it can burn )
40.000     Value of second parameter for above equation (Approximate fire return interval yrs)
2.0000     Value of third parameter for above equation (Shape parameter )
7          Equation fire size (1-Pareto, 2-lognormal,3-exponentil, 4-uniform,5-normal,6-extreme,7-Weibull,8-logistic)
1.000      Value first parameter fire size equation (ave fire size ha)
3.000      Value second parameter fire size equation (shape of curve parm)
0.000      Value third parameter fire size equation
2          Shape pattern (not for cell automata) (1-triangle, 2-parabolic, 3-circular, 4-rectangle)
2.0        Eccentricity or elongation parameter (0.0-10.0)
```

Appendix A.7 – The Vegetation Input File

The Vegetation Input File is a horizontal, cycling, descriptive file that contains all the succession parameters for every succession class within a potential vegetation type (PVT). The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

```
VAR          LINE   SIZE    DESCRIPTION                                                    UNITS
------------------------------------------------------------------------------------------------
title           1    256    Title line for reference                                       None
colhead         2    256    Column head line not used in program
None
regionID        3     10    Unique code for a broad region ID number                       None
pvtID           4     10    Potential vegetation type ID number                            None
sclassID        5     10    Succession class ID number                                     None
begyear         6     10    Beginning year of the Succession class                         Year
endyear         7     10    Ending year of the Succession Class                            Year
gotosclass      8     10    Succession class to go to after the current                    None
prob            9   10.2    Prob that sclass will transition to gotosclass                 Prob
------------------------------------------------------------------------------------------------
```

where ***regionID*** is a variable that allows the stratification of succession parameters by PVT for regions of the country, ***pvtID*** is the number of the PVT for the succession parameters, and ***sclassID*** is the number of the succession class.

The next set of fields are the succession parameters. The ***begyear*** and ***endyear*** are the beginning and ending year of the succession class. The difference is the lifespan, in years, of that succession class. After a succession class is aged beyond its lifespan, it would transition to the next succession class (***gotosclass***) with a probability specified in the ***prob*** variable. Most probabilities are set at 1.0 for many succession classes, but occasionally succession will result in a transition to more than one class and the program selects the next succession class based on that probability. An error is printed if the probabilities do not add up to 1.0 across the succession class.

An example of the Vegetation Input File is:

```
Succession parameters for zone 16 July 2004
Project     Region     Pvt    SCLASS    BegYear    EndYear    SCLASS2    Prob
LANDFIRE      16      1601    111201        15         28     121201       1
LANDFIRE      16      1601    121201        28         45     131201       1
LANDFIRE      16      1601    131201        45        515     131211       1
LANDFIRE      16      1601    141201       280        315     131201       1
LANDFIRE      16      1601    111205        15         30     121205       1
LANDFIRE      16      1601    121205        30         60     131205       1
LANDFIRE      16      1601    131205        60        315     131211       1
LANDFIRE      16      1601    141205       187        232     131205       1
LANDFIRE      16      1601    111206        15         30     121206       1
LANDFIRE      16      1601    121206        30         65     131206       1
LANDFIRE      16      1601    131206        65        315     131211       1
LANDFIRE      16      1601    141206       190        240     131206       1
LANDFIRE      16      1601    111211        15         40     121211       1
LANDFIRE      16      1601    121211        40         70     131211       1
LANDFIRE      16      1601    131211        70       9999     131211       1
LANDFIRE      16      1601    141211       267        322     131211       1
LANDFIRE      16      1601    111405        15         25     121405       1
```

LANDFIRE	16	1601	121405	25	50	131405	1
LANDFIRE	16	1601	131405	50	165	131211	1
LANDFIRE	16	1601	141405	107	147	131405	1
LANDFIRE	16	1601	111801	15	45	121801	1
LANDFIRE	16	1601	121801	45	90	131801	1
LANDFIRE	16	1601	131801	90	315	131211	1
LANDFIRE	16	1601	141801	203	248	131801	1
LANDFIRE	16	1601	313301	1	15	111201	0.2
LANDFIRE	16	1601	313301	1	15	111205	0.17
LANDFIRE	16	1601	313301	1	15	111206	0.12
LANDFIRE	16	1601	313301	1	15	111211	0.17
LANDFIRE	16	1601	313301	1	15	111405	0.21
LANDFIRE	16	1601	313301	1	15	111801	0.13
LANDFIRE	16	1601	343704	1	15	111201	0.05
LANDFIRE	16	1601	343704	1	15	111205	0.29
LANDFIRE	16	1601	343704	1	15	111206	0.1
LANDFIRE	16	1601	343704	1	15	111211	0.19
LANDFIRE	16	1601	343704	1	15	111405	0.29
LANDFIRE	16	1601	343704	1	15	111801	0.08
LANDFIRE	16	1601	524102	1	15	111205	0.3
LANDFIRE	16	1601	524102	1	15	111211	0.3
LANDFIRE	16	1601	524102	1	15	111405	0.4

Appendix A.8 – The Disturbance Input File

The Disturbance Input File is a horizontal, cycling, descriptive file that contains all the succession parameters for every succession class within a potential vegetation type (PVT). The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
colhead	2	256	Column head line not used in program	None
regionID	3	10	Unique code for a broad region ID number	None
pvtID	4	10	Potential vegetation type ID number	None
sclassID	5	10	Succession class ID number	None
distID	6	10	Disturbance ID number	None
gotosclass	7	10	Transition succession class ID number	None
prob	8	10.2	Probability that this disturbance will occur	Prob
nextage	9	10	Age to assign to the new transition sclass	Year
ageinc	10	10	Age increment or decrement to add to the current age	Year

where ***regionID*** is a variable that allows the stratification of disturbance parameters by PVT for regions of the country, ***pvtID*** is the number of the PVT for the succession parameters, and ***sclassID*** is the number of the succession class. The ***distID*** number is the number that uniquely identifies this disturbance. If a fire disturbance is specified, the ID number should be referenced to the range specified in the Simulation Input File (Appendix A.3).

The next fields are the disturbance parameters. The ***gotosclass*** is the succession class that the polygon transitions if this disturbance is simulated. The probability of this disturbance occurring is specified in the ***prob*** variable. This is a point estimate of disturbance return interval (inverse of probability). The ***nextage*** variable allows the user to set the succession age of the disturbed polygon to a specific succession age that represents the development of that polygon. Alternatively, the user can increment or decrement (***ageinc***) the disturbed polygon's succession age.

An example of the Disturbance Input File is as follows:

Disturbance parameters for zone 16 July 2004

PROJECT	REGION	PVT	SCLASS	DIST	SCLASS2	PROB	NEXT_AGE	AGE_INC
LANDFIRE	16	1601	131201	1130	131201	1	315	0
LANDFIRE	16	1601	141201	1120	141201	1	280	0
LANDFIRE	16	1601	131201	1120	141201	1	280	0
LANDFIRE	16	1601	121201	1130	141201	1	280	0
LANDFIRE	16	1601	141201	1130	141201	1	280	0
LANDFIRE	16	1601	131201	1210	141201	1	280	0
LANDFIRE	16	1601	131205	1130	131205	1	232	0
LANDFIRE	16	1601	131205	1220	131205	0.75	187	0
LANDFIRE	16	1601	131205	1120	141205	1	187	0
LANDFIRE	16	1601	141205	1120	141205	1	187	0
LANDFIRE	16	1601	131206	1120	141205	0.7143	187	0
LANDFIRE	16	1601	141206	1120	141205	0.4925	187	0
LANDFIRE	16	1601	131211	1120	141205	0.5634	187	0
LANDFIRE	16	1601	141211	1120	141205	0.5634	187	0

Appendix A.9 – The Vegetation Fix Input File

The Vegetation Fix Input File is a horizontal, cycling, descriptive file that contains all fixes for any errors that are encountered when the succession logic and parameters are checked against the Polygon Input File and maps. The user can specify the fixes in this file so that the Input polygon maps need not be changed. The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
colhead	2	256	Column head line not used in program	None
projectID	3	10	Project ID number or alphanumeric	None
regionID	4	10	Unique code for a broad region ID number	None
pvtID	5	10	Potential vegetation type ID number	None
sclassID	6	10	Succession class ID number	None
fixclass	7	10	Succession class to reassign to the pvt for the sclassID	None
prob	8	10.2	Probability that this sclass gets assigned to pvt for the sclassID	Prob

where ***projectID*** represents a name for a project for this fix file. This project would be matched to the project in the Scenario Input File. The ***regionID*** is a variable that allows the stratification of disturbance parameters by PVT for regions of the country. The ***pvtID*** is the number of the PVT for the succession parameters and ***sclassID*** is the number of the succession class that is wrong. The ***fixclass*** is the succession class ID number to assign for the wrong ***sclassID*** for this ***pvtID***. Then, the user can enter a probability of this assignment (***prob***) where a set of assignments can be made for one wrong ***sclassID*** based on these probabilities which must add to one.

An example of the Vegetation Fix Input File is as follows:

```
vegfix.in -- Vegetation correction file for map mismatches -- Keane spring 2003
Project    Region   PVT   SCLASS   TOSCLAS   PROB
LANDFIRE   160000   75     42203     42009   0.5
LANDFIRE   160000   10    264087    264087   0.25
LANDFIRE   160000   10    264087    264087   0.25
LANDFIRE   160000   10    264087    254079   0.25
LANDFIRE   160000   10    264087    264087   0.25
LANDFIRE   160000   10     14080     34081   0.10
LANDFIRE   160000   10     14080    254079   0.20
LANDFIRE   160000   10     14080     54081   0.30
LANDFIRE   160000   10     14080     14080   0.30
LANDFIRE   160000   10     14080     14080   0.10
LANDFIRE   160000   10     34081     34081   1.0
LANDFIRE   160000   10     44081     44081   1.0
LANDFIRE   160000   10     54081    254079   1.0
```

Appendix A.10 – The Management Plan Input File

The Management Plan Input File is a horizontal, cycling, scenario file that specifies which scenario is used for each portion of the simulation landscape during a specific span of years. The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable:

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
colhead	2	256	Column head line not used in program	None
projectID	3	10	Project ID number or alphanumeric	None
regionID	4	10	Unique code for a broad region ID number	None
zoneID	5	10	Stratification code for a zone within a region	None
scenarioID	6	10	Scenario ID number referenced in the Scenario input file	None
startyr	7	10	Starting year of this management plan	Year
endyear	8	10	Ending year of this management plan	Year

The landscape is stratified by region (***regionID***) and zone (***zoneID***), and a scenario (***scenarioID***) that is defined in the Scenario Input File by project (***projectID***) is assigned to each region and zone. This scenario is then used for the span of simulation years specified by ***startyr*** and ***endyr***. For example, lets say the landscape was divided into two regions (public and private lands) and all public lands are further divided into two zones (wilderness and non-wilderness). Then, a let-burn scenario is assigned for the first 100 years of simulation for the public and wilderness lands, and a full fire suppression scenario is assigned to both public non-wilderness and private lands. This file allows the user to target unique scenarios in space and time.

An example of the Management Plan Input File is as follows:

```
LANDSUMv4 Management plan file -- Z16 Test landscape - August 2003
Project    Region    Zone    Scenario    StartYear    EndYear
LANDFIRE     16        1         1            0        10000
LANDFIRE     16        2         2            0        10000
```

Appendix A.11 – The Scenario Input File

The Scenario Input File is another horizontal, cycling, scenario file that specifies the frequency, cost, and benefit of implementing or allowing a disturbance to happen on the landscape. The scenarios are stratified by a project and region. The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable.

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
colhead	2	256	Column head line not used in program	None
projectID	3	10	Project ID number or alphanumeric	None
regionID	3	10	Unique code for a broad region ID number	None
scenarioID	3	10	Scenario ID number referenced in the Scenario input file	None
pvtID	3	10	Potential vegetation type ID number	None
sclassID	3	10	Succession class ID number	None
distID	3	10	Disturbance ID number	None
prob	3	10.2	Probability that this sclass gets assigned to pvt for the sclassID	Prob
cost	3	10	Cost of implementing the proposed disturbance action	$/ha
benefit	3	10	Benefit of implement the proposed disturbance action	$/ha

Each scenario is assigned a project (***projectID***) and area (***regionID***) so that multiple scenarios can be built across space and projects. Scenarios can be stratified by time using the Management Plan Input File. The scenario is given a unique identification number (***scenarioID***) and then each disturbance that can happen on that landscape (***distID***) is given a probability (***prob***) by potential vegetation type (***pvtID***) and succession class (***sclassID***). Disturbances need not be assigned to every combination of PVT and succession class.

The cost of the disturbance (***cost***) and the estimated benefits (***benefit***) are given values in this file (dollars per hectare). Currently, LANDSUMv4 doesn't output any results for the cost-benefit analysis but future versions of the model will have the capability of a full investigation into the financial repercussions of the proposed scenario.

An example of the Scenario Input File is as follows:

```
Scenario Parameters for Zone 16 July 2004
PROJECT    REGION    SCENARIO    PVT    SCLASS    DISTURB    PROB     COST    BENEFITS
LANDFIRE     16          1       1601   111201      1110     0.013     0          0
LANDFIRE     16          1       1601   111205      1110     0.013     0          0
LANDFIRE     16          1       1601   111206      1110     0.01      0          0
LANDFIRE     16          1       1601   111211      1110     0.0025    0          0
LANDFIRE     16          1       1601   111405      1110     0.004     0          0
LANDFIRE     16          1       1601   111801      1110     0.003     0          0
LANDFIRE     16          1       1601   121201      1110     0.0067    0          0
LANDFIRE     16          1       1601   121201      1130     0.02      0          0
LANDFIRE     16          1       1601   121205      1110     0.0067    0          0
LANDFIRE     16          1       1601   121205      1130     0.02      0          0
LANDFIRE     16          1       1601   121206      1130     0.02      0          0
LANDFIRE     16          1       1601   121206      1110     0.0067    0          0
LANDFIRE     16          1       1601   121211      1110     0.003     0          0
LANDFIRE     16          1       1601   121405      1110     0.005     0          0
```

Appendix A.12 – The Attribute Input File

The Attribute Input File is yet another horizontal, cycling, scenario file that specifies up to five attributes for each combination of potential vegetation type and succession class. The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable.

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
colhead	2	256	Column head line not used in program	None
projectID	3	10	Project ID number or alphanumeric	None
regionID	3	10	Unique code for a broad region ID number	None
pvtID	3	10	Potential vegetation type ID number	None
sclassID	3	10	Succession class ID number	None
ctID	3	10	Cover type ID number	None
ssID	3	10	Structural stage ID number	None
att1	3	10	Unique ID number of attribute 1 describing the PVT-ct-ss combo	None
att2	3	10	Unique ID number of attribute 2 describing the PVT-ct-ss combo	None
att3	3	10	Unique ID number of attribute 3 describing the PVT-ct-ss combo	None
att4	3	10	Unique ID number of attribute 4 describing the PVT-ct-ss combo	None
att5	3	10	Unique ID number of attribute 5 describing the PVT-ct-ss combo	None

The attributes can be stratified by simulation project (***projectID***) and by simulation area (***regionID***). But all attributes must be assigned by potential vegetation type (***pvtID***) and succession class (***sclassID***) combinations. If combinations are missed, the program will print an error. The next two fields, cover type (***ctID***) and structural stage (***ssID***), should be entered for most applications, especially if the user desires maps of these variables. The list of five attributes (***att1***, ***att2***, ***att3***, ***att4, att5***) is specified next where each attribute is the quantification of some ecosystem parameter that is sensitive to PVT-succession class pairs. For example, the first two attributes can be the fire behavior fuel model and the NFDRS fuel model, then the next attribute could be an elk habitat value (1-low, 2-moderate, 3-high), the fourth attribute could be snag density, and the last category may be canopy cover class.

An example of the Attribute Input File is:

```
Attribute.in --File for assigning attributes to sclass -- Z16 Landscape -- July 04
Project     Reg   Pvt   SCLASS   Ctype   SS   Fmod   FCC   NFDRS   Nothing   Nothing
LANDFIRE    16    1601  111201   1201    11   10     10    10      10        10
LANDFIRE    16    1601  111205   1205    11   10     10    10      10        10
LANDFIRE    16    1601  111206   1206    11   10     10    10      10        10
LANDFIRE    16    1601  111211   1211    11   10     10    10      10        10
LANDFIRE    16    1601  111405   1405    11   10     10    10      10        10
LANDFIRE    16    1601  111801   1801    11   10     10    10      10        10
LANDFIRE    16    1601  121201   1201    12   10     10    10      10        10
LANDFIRE    16    1601  121205   1205    12   10     10    10      10        10
LANDFIRE    16    1601  121206   1206    12   10     10    10      10        10
LANDFIRE    16    1601  121211   1211    12   10     10    10      10        10
LANDFIRE    16    1601  121405   1405    12   10     10    10      10        10
LANDFIRE    16    1601  121801   1801    12   10     10    10      10        10
LANDFIRE    16    1601  131201   1201    13   10     10    10      10        10
```

Appendix A.13 – The Fire Year Input File

The Fire Year Input File is a horizontal, scenario file that specifies the fire year (severe, normal, wet) for every year of the simulation. The first line of the file is the ***title*** or reference line where anything can be written to describe this file. The second line is a column header line (***colhead***) for ease of entering data. The structure of the file is as follows where VAR is variable name, LINE is line number in file, SIZE is the size of the field in characters or digits, DESCRIPTION is a short description of the variable, and UNITS is the units of this variable.

VAR	LINE	SIZE	DESCRIPTION	UNITS
title	1	256	Title line for reference	None
fmult	2	5.2	Fire multiplier (number from 0 to 1.0; 0.0 is no fires, 1.0 all fire	None

An example of the Fire Year Input File is:

```
Fire multiplier year file -- Z16 Landscape -- July 04
0.1
0.2
0.01
0.9
0.01
0.1
0.1
```

Appendix B.1 – LANDSUMv4 Output File Formats

LANDSUMv4 prints output to five different files as specified in the Simulation Input File (Appendix A.3). Shown here are the formats for those five files.

Output STAND.STAT file structure is:

VARIABLE	COLUMN	SIZE	DESCRIPTION	UNITS
standID	1	10	Polygon keyID	none
regionID	2	10	Landfire Region	None
zoneID	3	10	Management zone	None
strataID	4	10	Polygon stratification code	None
pvtID	5	10	Potential vegetation type	None
sclassID	6	10	Succession class	None
age	7	5	Successional age	Years
area	8	10.1	Area of polygon	m2
year	9	5	Simulation year	Years
lastdistID	10	10	ID of last disturbance	None
ysd	11	5	Years since last disturbance	Years

Missing values are coded with a -1.00

Output FIRE.STAT file structure is:

VARIABLE	COLUMN	SIZE	DESCRIPTION	UNITS
year	1	5	Simulation year	Years
fmult	2	5.2	fire year multiplier	fraction
fireID	3	5	Fire ID number	None
x	4	5	Fire start x coordinate	None
y	5	5	Fire start y coordinate	None
pvtID	6	10	PVT ID code	None
area	7	10.1	Area burned	m2

Missing values are coded with a -1.00

Output LANDSCAPE.STAT file structure is:

VARIABLE	COLUMN	SIZE	DESCRIPTION	UNITS
year	1	5	Simulation year	Years
regionID	2	10	LANDFIRE region	None
zoneID	3	10	Management zone	None
strataID	4	10	Landscape strata	None
pvtID	5	10	Potential vegetation type	None
sclassID	6	10	Succession class (ssxct)	None
coverID	7	5	Cover type ID	None
strucID	8	5	Structural stage ID	None
area	9	10.1	Area in this combination	m2

Missing values are coded with a -1.00

Output ACTION.STAT file structure is:

VARIABLE	COLUMN	SIZE	DESCRIPTION	UNITS
year	1	5	Simulation year	Years
regionID	2	10	LANDFIRE region	None
pvtID	3	10	Potential vegetation type	None
sclassID	4	10	Succession class (ctxss)	None
actionID	5	10	ID number of disturbance	None
area	6	10.1	Cumulative area over interval	m2

Missing values are coded with a -1.00

Output LANDFIRE.STAT file structure is:

VARIABLE	FIELD	SIZE	DESCRIPTION	UNITS
project	1	10	Name of simulation project	Code
region	2	10	Region of country of simulation landscape	Code
year	3	5	Simulation year	year
zone	4	10	Management zone of simulation landscape	Code
strata	5	10	Landscape strata	Code
pvt	6	10	Potential vegetation type	Code
vset	7	5	Variable set: there are eight variable sets 1-succession classes, 2-fire severity types, 3-cover types, 4-structural stages, 5-first user-spec attribute (an example would be fuel model), 6-8-second thru fifth user-specified attributes	
varID	8	10	Code of variables in the specified variable set. For example, a cover type code of 2003 is used in the cover type variable set.	
area	9	10.1	Area occupied on simulation landscape	m2

Missing values are coded with a -1.00

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