Chapter 10

Using Simulation Modeling to Assess Historical Reference Conditions for Vegetation and Fire Regimes for the LANDFIRE Prototype Project

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Introduction

A critical component of the Landscape Fire and Resource Management Planning Tools Prototype Project, or LANDFIRE Prototype Project, was the development of a nationally consistent method for estimating historical reference conditions for vegetation composition and structure and wildland fire regimes. These estimates of past vegetation composition and condition are used as a baseline for evaluating current landscape conditions in terms of ecological departure from historical conditions (Landres and others 1999). Simulated historical fire regime characteristics provide managers with information for designing and evaluating hazardous fuel treatments in which the objective is to restore landscapes to near-historical reference conditions (Keane and Rollins, Ch. 3). In LANDFIRE, simulated historical conditions are used to characterize the departure of current landscapes using Fire Regime Condition Class (FRCC) calculations (Hann and Bunnell 2001) and other measures of ecological departure (Holsinger and others, Ch. 11). Previously, Schmidt and others (2002) produced fire regime and departure information on a nationwide basis at a 1-km resolution; this effort used existing broad-scale spatial data and a rule-based approach to assign fire regimes and FRCC to mapped biophysical settings across the United States. The LANDFIRE Prototype methods used the Landscape Succession Model version 4.0 (LANDSUMv4), a spatially explicit fire and vegetation dynamics simulation model, to simulate disturbance and succession dynamics over a simulation period of thousands of years (Keane and others 2006). The model uses pathways of successional transitions and disturbance effects stratified by unique biophysical settings, called potential vegetation types (PVTs), across the simulation landscape to produce estimates of historical reference conditions for fire frequency, fire severity, and vegetation conditions. This chapter describes the model and how it was used to generate historical reference conditions of vegetation and fire regimes for the LANDFIRE Prototype Project.

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Background

Estimating reference conditions for vegetation and fire regimes—The non-equilibrium paradigm of disturbance ecology maintains that ecosystems are not static, and natural disturbance regimes create temporal and spatial variability in the structure and composition of most ecosystems (Picket and White 1985). Within this framework, therefore, reference conditions should be defined in terms of a range of conditions over space and time rather than in terms of a static set of conditions. For the LANDFIRE Prototype, we described reference conditions for vegetation by the quantification of the temporal fluctuations in vegetation characteristics (defined by dominant species and stand structure) prior to Euro-American settlement, specifically from 1600 to 1900 A.D. (Keane and Rollins, Ch. 3). Fire regimes describe fire characteristics over time (Baker 1992) and are often defined in terms of fire frequency, size, pattern, seasonality, intensity, and severity (Agee 1993; Heinselman 1981). In the LANDFIRE Prototype, we described fire regimes by their frequency and severity because these metrics influence vegetation composition and structure across landscapes and have been used in the majority of fire regime studies (Barrett and others 1991; Brown and others 1994; Keane and others 2003; Morgan and others 2001; Rollins and others 2004) and management planning activities. We used the point-based mean fire return interval (MFRI; in years) to quantify fire frequency. Fire severity is defined as the effect on overstory vegetation, and we use three categories to describe fire severity: 1) non-lethal surface fires, 2) mixed-severity fires, and 3) stand-replacing fires. A non-lethal surface fire kills few individuals (< 10 percent) in the overstory (Schimdt and others 2002), whereas stand-replacing fires kill the majority (> 90 percent) of the dominant vegetation (Brown 1995; Schmidt and others 2002). Mixed-severity fire regimes contain elements of both non-lethal surface and stand-replacing fires and may be used to describe an area of patchy burn patterns created during one fire event; however, mixed-severity fire regimes can also be used to describe a mix of fire severities occurring over time (Shinneman and Baker 1997). For the LANDFIRE Prototype simulation modeling effort, we used mixed-severity fires to describe single fire events that cause mixed mortality and have moderate effects on overstory vegetation (Schmidt and others 2002).

Since the turn of the twentieth century, human activities such as fire suppression, logging, and grazing of domestic livestock have altered fire regimes and vegetation structure and dynamics in ecosystems across the United States (Baker 1992; Ferry and others 1995; Heinselman 1973; Herron 2001; Keane and others 2002b). In recent years, there has been increasing recognition that information about ecosystem processes and characteristics prior to intensive Euro-American settlement may offer the best reference conditions for managing complex ecosystems to maintain diversity and sustainability (Kaufmann and others 1998; Landres and others 1999; Swanson and others 1994). Furthermore, the increasing occurrence of large, ecosystem-altering fires and escalating fire suppression costs in recent years have shown that managing ecosystems outside of their natural range can be difficult, costly, and devastating to important ecosystem elements. Although historical reference conditions of vegetation and fire dynamics can serve as effective tools for fire planning and management, fire managers in many areas of the country lack the necessary information to develop baseline historical information (Keane and others 2002b; Landres and others 1999; Schmidt and others 2002).

The importance and challenges of estimating historical reference conditions for vegetation have been widely recognized by the scientific and land management communities (Kaufmann and others 1998; Landres and others 1999; Moore and others 1999; Swanson and others 1994; Veblen 2003). There are several types of data that may be used to estimate historical fire regimes and vegetation conditions including 1) time series data, 2) spatial series data, and 3) simulated data. Time series data are based on actual data from one location over a long period of time. Time series data used in estimating historical vegetation characteristics may come from historical imagery, historical documents, or dendroecological data. Information about historical fire regimes, on the other hand, is often gathered from fire scars, charcoal sediments in lakes, bogs, or soils, or post-fire tree establishment dates from tree ring analysis (Kaufmann and others 1994, 1998; Keane and others 2004; Swanson and others 1994). Time series data have the benefit of being based on the evidence of actual fires, but are often difficult to obtain. Furthermore, the data generally describe fire regimes or vegetation over small spatial extents or short temporal spans and cannot be extrapolated consistently across broad areas. Historical vegetation conditions and fire regimes may also be estimated for a geographic region from spatial series of data (imagery or otherwise) collected on several similar landscapes within a geographic region (Hessburg and others 1999). Inferences about conditions for the larger region are predicated on the assumption that the sampled landscapes represent the range of possible conditions over time for the entire region. This assumption may be tenuous, however, as variations in disturbance histories between sites may obscure historical patterns when extrapolated over the entire region. Furthermore, an adequate amount of data to fully describe the range of possible conditions may be difficult to obtain, and data may not be equally available for all ecosystems and regions. Simulation modeling provides an alternative for estimating historical fire regimes and vegetation conditions. This approach substitutes data modeled over long simulation periods for actual historical data. Although the parameters used in the models are based on available data, simulation modeling is necessarily a simplification of the actual processes occurring in ecosystems. Simulated results represent only an estimate of actual historical conditions. Nevertheless, simulation modeling has several advantages: 1) models can integrate the limited data available and extrapolate over larger areas, 2) simulation modeling can be applied over large areas consistently and comprehensively, and 3) models can be used to simulate a broad range of potential conditions rather than merely the actual conditions experienced, which represent only one possible scenario.

Simulation modeling—Given the LANDFIRE objective of creating a robust methodology for estimating historical reference conditions consistently and comprehensively across the nation, simulation modeling, despite limitations, proves the best source for estimating historical fire regimes and vegetation conditions. A class of simulation models, called landscape fire succession models (LFSMs), simulate fire and vegetation dynamics in the spatial domain (Keane and others 2004), and several existing LFSMs have the potential to generate estimates of historical fire regimes and vegetation conditions over time (for reviews of existing models see Baker 1989, Gardner and others 1999, Keane and others 2004, and Mladenoff and Baker 1999). Keane and others (2004) identified four separate components essential for simulating fire and vegetation dynamics in LFSMs: 1) vegetation succession, 2) fire ignition, 3) fire spread, and 4) fire effects. For each of these components, the complexity of the approach and the scale of application may differ from model to model and must be considered when selecting a model for a particular use (Keane and others 2004).

LANDSUMv4—We selected LANDSUMv4 as the landscape fire succession model for LANDFIRE because of the minimal number of inputs required and its generalized structure, which allowed it to be portable, flexible, and robust with respect to geographic area, ecosystem, and disturbance regime (Keane and others 2002a; Keane and others 2006). More complex models, such as Fire-BGC (Keane and others 1996) and LANDIS (Mladenoff and others 1996), would likely have generated more realistic landscape simulations, but the required extensive parameterization would likely have been difficult to implement for every ecosystem and landscape in the United States. Also, to generate sufficient time series (especially for landscapes with infrequent fires), complex models such as these would have required prohibitively long execution times. Less complex models, such as TELSA (Kurz and others1999) or SIMPPLLE (Chew and others 2004), would have been easy to parameterize, but these models do not adequately simulate the spatial dynamics of fire spread and effects so that variation in landscape structure can be assessed. LANDSUMv4 provided a good balance between the realism of more complex models and the simplicity of less complex models.

LANDSUMv4 is a spatial state-and-transition patch-level succession model combined with a spatially explicit disturbance model that simulates fire growth using a cell-to-cell spread method (Keane and others 2002a). The model is based on vegetation pathways developed for each PVT on the simulation landscape with user-defined transition times for succession events and user-defined probabilities for disturbance events and their effects (see Long and others, Ch. 9 for details on pathway development). A PVT identifies a distinct biophysical setting that supports a unique and stable climax plant community under a constant climate regime (see Keane and Rollins, Ch. 3; Long and others, Ch. 6; and Frescino and Rollins, Ch. 7 for detailed information on the role of PVT in the LANDFIRE Prototype). Succession classes, which are defined by the combination of the dominant species, or cover type (CT), and the stand structure, or structural stage (SS) (see Long and others, Ch. 6; Zhu and others, Ch. 8; and Long and others, Ch. 9 for descriptions of the CTs and SSs used in the LANDFIRE Prototype), serve as discrete stages along the pathways. The pathways are applied across the landscape to mapped patches and their associated PVTs and succession classes. In the model, patches (also referred to as polygons or stands) are spatially contiguous areas having homogenous attributes of PVT, CT, SS, and age (Keane and others 2006).

LANDUSMv4 operates at an annual time–step, and, for each year, the model first simulates disturbance (fig. 1). The model iterates through all the patches in the landscape and, for each patch, cycles through all possible disturbances for the current PVT/succession class for that patch and stochastically determines if a disturbance occurs. Once a disturbance is modeled for a particular patch, the simulation year is over for that patch and no further disturbances or succession can occur.

There are two different disturbance categories in LANDSUMv4: non-fire, or aspatial, and fire, or spatial. Non-fire disturbances are simulated in two steps: initiation and effects. Initiation is based on probabilities defined in the vegetation pathways. Effects are then modeled as a change in succession class based on a second set of probabilities, also defined in the vegetation pathways, unique to the succession class/disturbance combination. A disturbance effect can have multiple pathways; in other words, a patch can transition to any one of several succession classes following a disturbance. The probabilities for all pathways from a particular succession class/disturbance combination must total one.

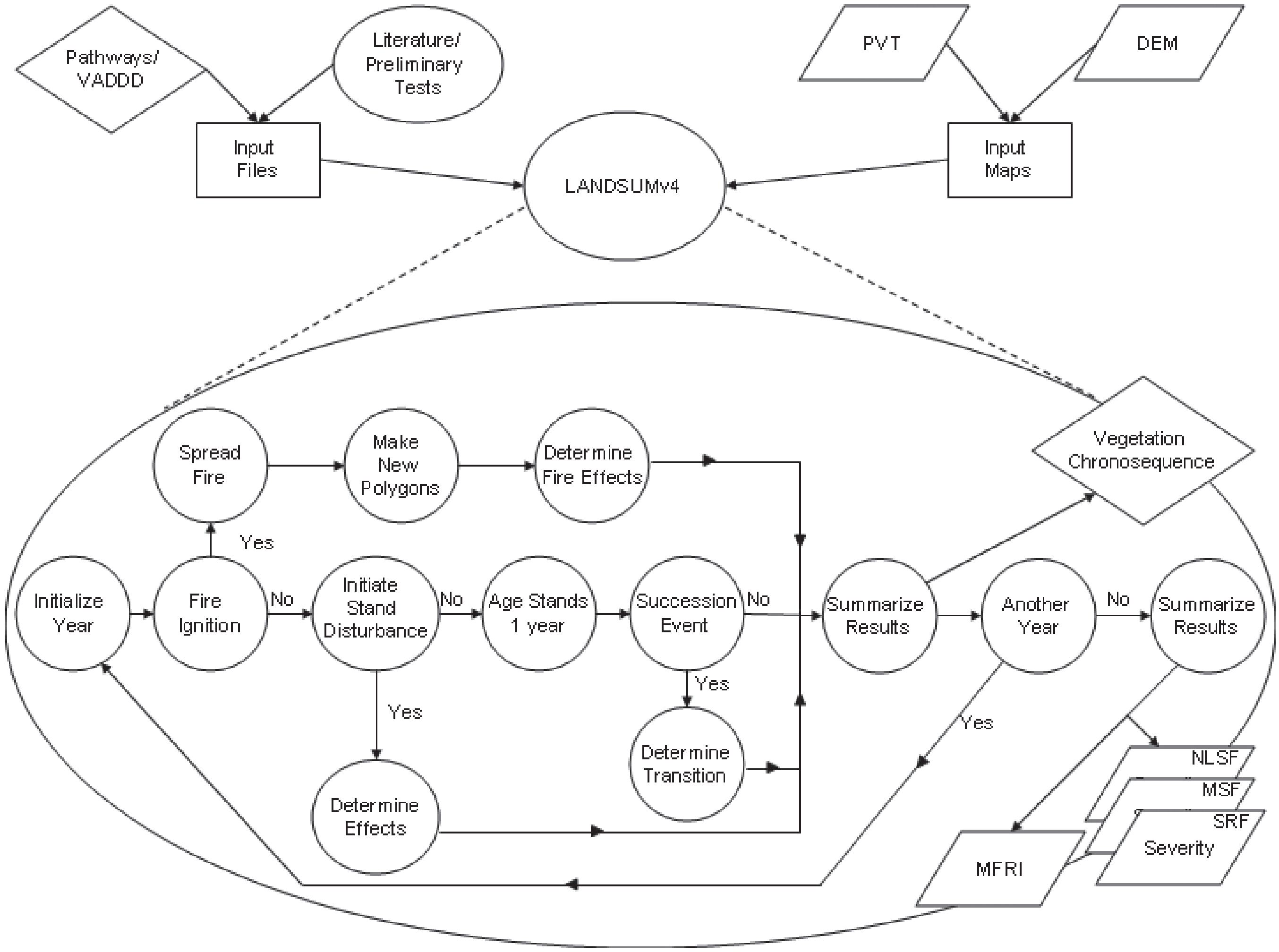

Figure 1—Flow diagram showing the LANDSUMv4 modeling process. Information from vegetation pathway models, parameters estimated from literature and preliminary testing, an elevation map, and a potential vegetation type (PVT) map are used to make the input files and input maps for the model. Each model year, LANDSUMv4 begins by simulating disturbances. Fire is simulated in three steps (ignition, spread, and effects) and results in the creation of new patches on the landscape. Other disturbances are simulated at the stand level and are simulated in two steps (initiation and effects). For stands where no disturbances are modeled, the stand ages one year and a succession event is modeled based on transition times. Summaries of the area occupied by each PVT/succession class combination are output to a tabular file every reporting year, and fire regime characteristics (mean fire return interval [MFRI], non-lethal surface fires [NLSF], mixed-severity fires [MSF], and stand-replacing fires [SRF]) are output to maps at the end of the simulation.

Fire disturbances are modeled in three steps: ignition, spread, and effects. Like non-fire disturbances, fire ignitions are based on probabilities in the pathways, but the probabilities are adjusted to account for fuel build-up (probability increases with increased time since last fire) and a no-burn period following a fire (Keane and others 2006). The probability is then further adjusted using a fire weather multiplier and a scaling factor based on patch size and average fire size (Keane and others 2006). Once a fire has ignited, the model calculates the size of the fire and then, based on wind and slope vectors, spreads this burned area over the landscape until it has reached the calculated fire size or reaches an unburnable boundary (Keane and others 2002a; Keane and others 2006). The model limits the fire size estimate using a minimum fire size of 1 ha and a maximum fire size equal to the size of the simulation landscape, which, for the LANDFIRE Prototype, was 20,000 ha (see the *Methods* section below for details on the LANDFIRE simulation landscape) (Keane and others 2006). The fire spread is independent of patch boundaries, thus fires can divide patches and create new patches. Fire effects are then simulated at the patch level for each of the new patches created by the fire. The model stochastically determines the fire severity based on the probabilities for each fire severity type (non-lethal surface, mixed-severity, and stand-replacing fire) in the vegetation pathways. Finally, the model determines the post-fire succession class based on probabilities assigned to the pre-fire succession class/severity combination.

For those patches where no disturbances occurred, the model simulates succession. LANDSUMv4 implements a multiple pathway succession approach using unique sets of succession pathways for each PVT. This approach assumes that all pathways of successional development will eventually converge to a stable or climax plant community (PVT) in the absence of disturbance (Arno and others 1985; Cattelino and others 1979; Davis and others 1980; Kessell and Fischer 1981; Noble and Slatyer 1977; Steele 1984). Each simulation year, all undisturbed patches advance one year in age, and when a patch reaches the final age for the current succession class (defined in the pathways), the patch transitions to a new succession class. A succession event can result in the patch transitioning to any one of several classes defined in the vegetation pathways (Long and others, Ch. 9), and the model stochastically determines which pathway succession follows.

The LANDFIRE Prototype was conducted for two broad study areas or mapping zones: one in the central Utah highlands and the other in the northern Rocky Mountains (referred to as Zone 16 and Zone 19, respectively; see Rollins and others, Ch. 2 for description of the two study areas). In this chapter, we describe the use of the LANDSUMV4 simulation model to generate estimates of historical reference conditions for vegetation composition and structure and wildland fire regimes for the LANDFIRE Prototype (for more information on the use of models in simulating historical fire regimes and vegetation and the LANDSUMv4 model, see Keane and others 2004 and Keane and others 2006). Whereas the fire regime data form a final LANDFIRE product (Rollins and others, Ch. 2), the data on reference condition vegetation served as an interim product used to determine ecological departure (this chapter describes only the LANDSUMv4 simulation process; for information on how departure was estimated using the LANDSUMv4 output, see Holsinger and others, Ch. 11). In this chapter, we outline the preliminary testing and analyses used to parameterize and initialize LANDSUMv4 in addition to the final methods used to simulate historical chronosequences (time series) and fire regimes for each mapping zone. We present the results from each mapping zone, a discussion of the benefits and limitations of our approach, and recommendations for estimating vegetation and fire regime reference conditions for LANDFIRE's national implementation.

Methods

The LANDFIRE Prototype Project involved many sequential steps, intermediate products, and interdependent processes. Please see appendix 2-A in Rollins and others, Ch. 2 for a detailed outline of the procedures followed to create the entire suite of LANDFIRE Prototype products. This chapter focuses specifically on the procedure for modeling historical vegetation and fire regimes in the LANDFIRE Prototype Project.

We prepared the inputs for LANDSUMv4 from several key pieces of data, including a PVT map, a digital elevation model (DEM), succession pathways containing probabilities for disturbance events and effects, and times and transitions for succession events (fig. 1). Frescino and Rollins (Ch. 7) developed the PVT map using a suite of biophysical gradient layers (Holsinger and others, Ch. 5) and predictive landscape modeling. We obtained the DEM from the National Elevation Database (NED; ned.usgs.gov). Local experts developed the succession pathways for each PVT based on extensive literature review and experience (Long and others, Ch. 9). They prepared and tested these pathways with the aid of a simple aspatial state-and-transition model, the Vegetation Dynamics Development Tool or VDDT (Beukema and others 2003; Kurz and others 1999), before converting them for use in LANDSUMv4. We determined the model parameters through a combination of literature review, expert opinion, and exploratory analysis. We partitioned each zone into a series of 20,000 ha simulation landscapes and divided the landscapes into discrete 81 ha reporting units for summarizing statistics (fig. 2). Succession and disturbance were then simulated for each landscape using LANDSUMv4. The total simulation time for Zone 16 was 4,500 years, but because of temporal autocorrelation in the vegetation output, the simulation time for Zone 19 was extended to 10,500 years. The model produced maps of fire severity and mean fire return interval, which were processed in a global information system (GIS) to create the final fire

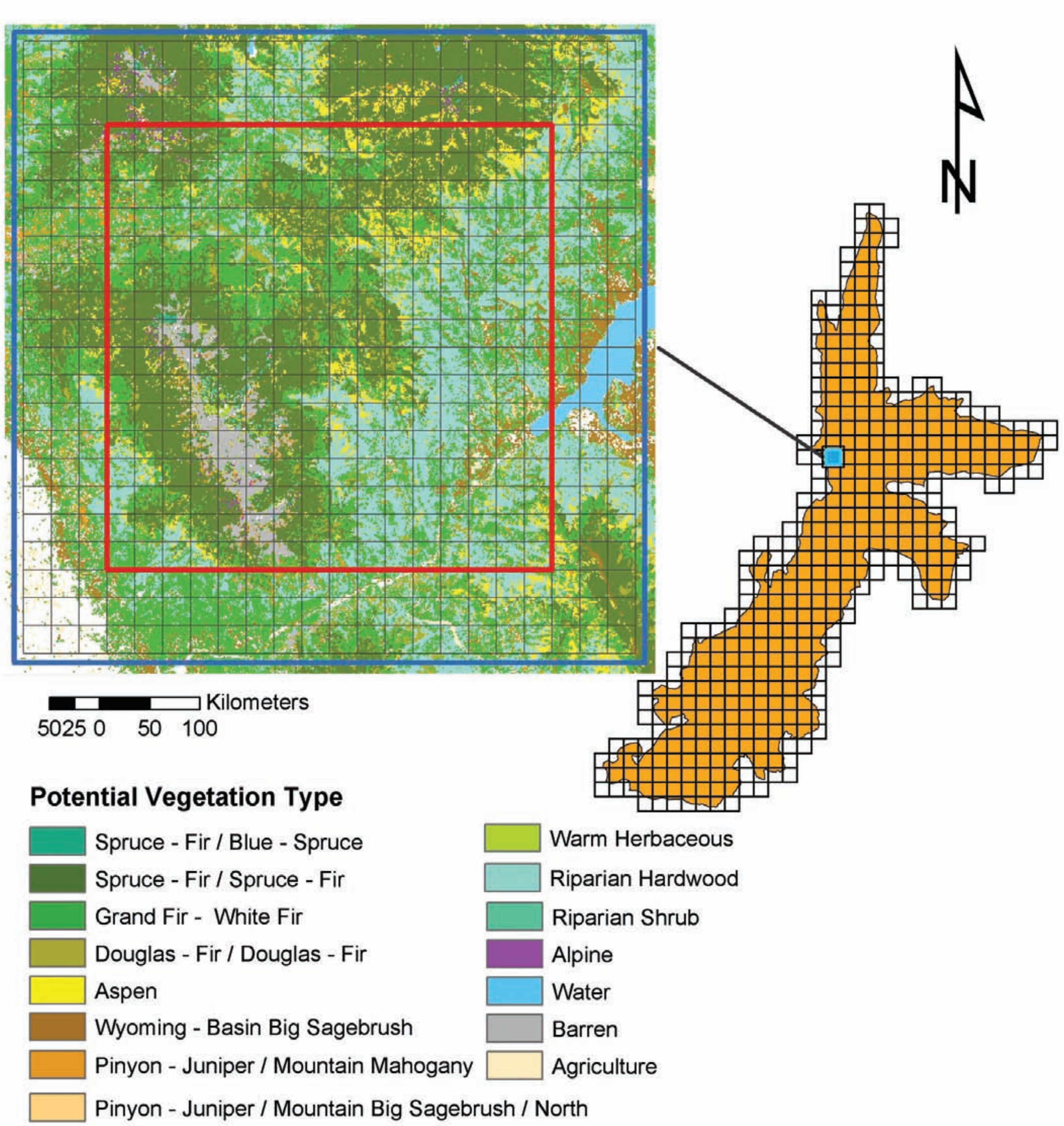

Figure 2—The simulation landscapes for LANDFIRE consisted of a 20,000-ha context area and a 3-km buffer. Each mapping zone was divided into a series of simulation landscapes, and each simulation landscape was further divided into reporting units. Here, Zone 16 is divided into 427 context landscapes. One context landscape (boundary shown in red) with buffer (boundary shown in blue) is displayed with a PVT background and the 900-m by 900-m reporting units. Stand boundaries for the initial map were determined by a spatial overlay of the PVT and reporting unit boundaries.

regime maps for each zone. Statistical summaries of vegetation composition by PVT were computed for each reporting unit for every reporting year. These summaries comprised the reference conditions that Holsinger and others (Ch. 11) then used in subsequent LANDFIRE processes to calculate ecological departure and FRCC. The following sections detail methods for 1) designing the simulation landscape, 2) preparing the input maps, 3) preparing the input files, 4) parameterizing the model, and 5) processing the output data.

Designing the Simulation Landscape

Before preparing the LANDSUMv4 input files, we had to determine the most appropriate size and shape of the simulation area and the landscape reporting units. In designing the simulation landscape, we aimed to balance the need for model efficiency with that of obtaining realistic simulation results. The main factor influencing simulation time is the number of patches on the simulation landscape, and the number of patches increases exponentially throughout the simulation period because fire creates new patches throughout the simulation. In general, use of smaller simulation landscapes increases model efficiency, whereas use of larger landscapes better represents fire's long-term effects on vegetation composition (Keane and others 2002a).

Size and shape of the simulation landscape—The simulation landscape for the LANDFIRE Prototype consisted of the area of interest — or context area — for which vegetation conditions were summarized and a simulation buffer surrounding this area, which was not included in the summaries. The LANDFIRE Prototype required a simulation landscape (context area surrounded by a simulation buffer) that allowed for realistic simulations of fire and vegetation while at the same time minimized 1) the edge effect, 2) the amount of simulation time, 3) the area of overlap between simulations (thus minimizing total computing time for the entire zone), and 4) the total number of simulations required to complete a mapping zone. Previous analysis of the model showed that the effect of both landscape shape and size on fire spread and patch dynamics (Keane and others 2002a) was significant. Circular or square landscapes resulted in the most realistic simulation of fire spread, while narrow, linear landscapes tended to underestimate fire spread. We selected square-shaped simulation landscapes over circular shapes for the LANDFIRE Prototype to simplify GIS processing and to decrease overlap between simulation landscapes.

Keane and others (2002a) also found that use of smaller landscapes led to the overestimation of mean fire return intervals. This overestimation results from the inability of fires to immigrate from outside the landscape into the edges of the simulation area; therefore, fewer fires than expected occur near the edges. With smaller landscapes, this "edge effect" impacts a greater proportion of the simulation landscape than with larger landscapes. The edge effect can also be decreased by adding a buffer zone around the context area to provide a place from which fires can spread into the context area. The ideal simulation area size may depend on both the size of the context area and the size of fires. Keane and others (2002a) recommend a total simulation area of 8 to 10 times the size of the context area for a 2,500-ha context landscape; however, the appropriate size is highly dependent on landscape complexity. Although larger landscapes and larger buffers minimized edge effects, they increased simulation times. We determined that a 20,000-ha context box with a 3-km buffer offered a reasonable compromise between minimal edge effects and manageable simulation times. In addition, all other LANDFIRE maps (such as DEM and PVT) were produced with a 3-km buffer around the zone boundary; therefore, the maximum buffer size that was available at the edges of the zone was only 3 km. We used a 14,400-m x 14,400-m (20,736 ha) context area to allow the 30-m pixels to nest within the landscape and simplify GIS processing. With the 3-km buffer on all sides, the simulation landscape was 20,400 m x 20,400 m (41,616 ha). We divided the entire mapping zone into a series of adjacent 20,000-ha boxes with 3-km buffers where buffer areas overlapped adjacent context areas (fig. 3).

Size and shape of the landscape reporting units—Landscape reporting units define the area on the ground into which the vegetation conditions are summarized and are used in subsequent modeling to calculate departure and FRCC (Holsinger and others, Ch. 11). For LANDSUMv4, the simulation landscape must be stratified into reporting units because ecological departure and FRCC are spatial and not point measurements. Although reporting units have no impact on the LANDSUMv4 simulations, the size and shape of these reporting units is important when summarizing the LANDSUMv4 output for use in departure calculations (see Holsinger and others, Ch.11 for a complete discussion of the considerations relevant to selecting landscape reporting units for departure calculations). For LANDFIRE, the selection of an appropriate landscape reporting unit must include

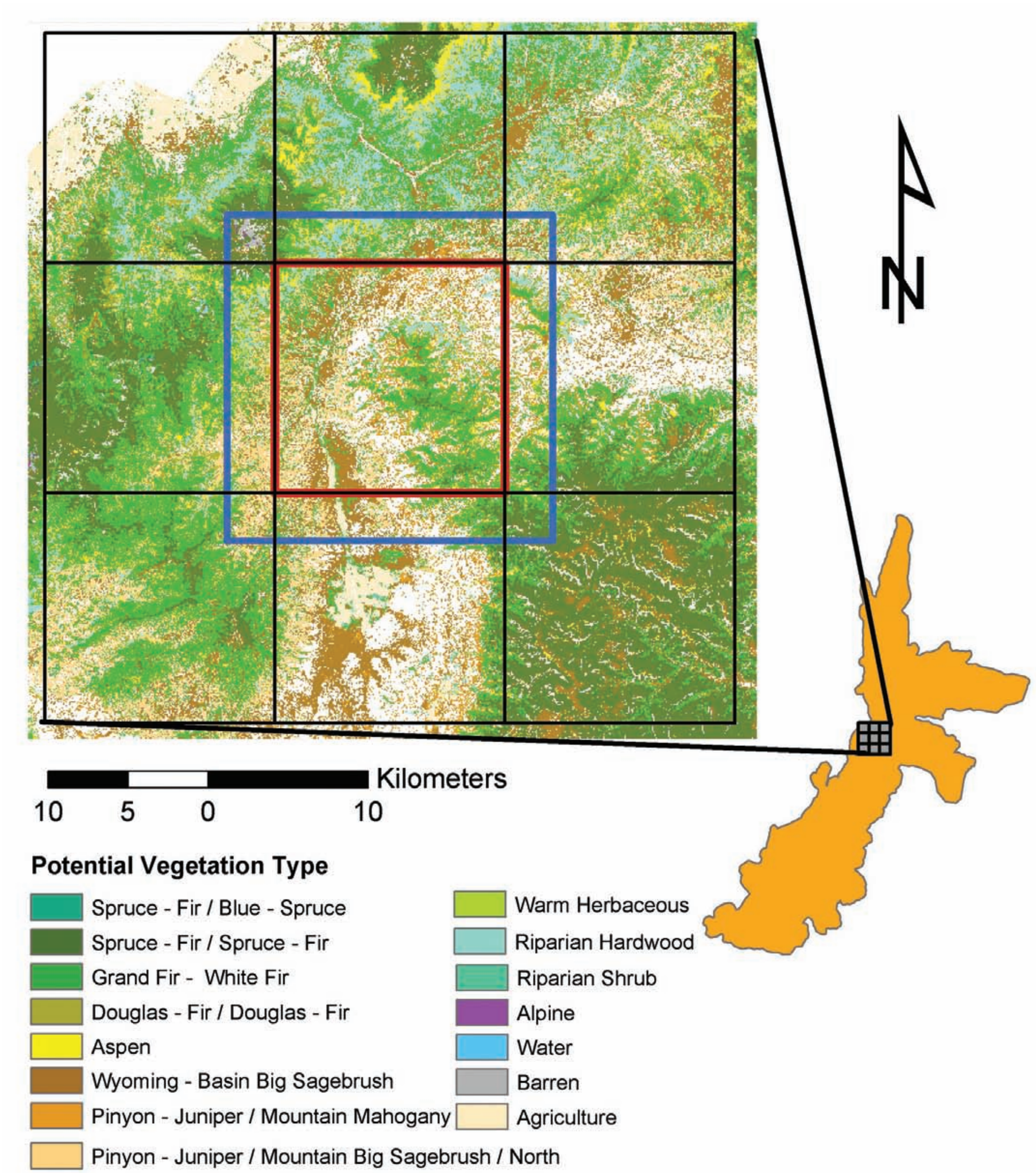

Figure 3—A series of nine 20,000-ha context areas in Zone 16 shown with potential vegetation type in the background. The 3-km buffer area (in blue) is shown for the center context area (in red). Notice that the 3-km buffer area overlaps adjacent context areas. The total simulation landscape (context area + buffer) is 40,000 ha.

consideration of scale from both an ecological standpoint and a management standpoint. The most desirable landscape extent is one that is small enough to detect subtle changes resulting from land management actions (such as fuel treatments) but large enough to capture important ecological patterns and processes (such as fire, migration, and climate) in the correct spatial context. Other studies have used watersheds or ownerships to delineate reporting units. These units are highly variable in size, however, which complicates the comparability of departure estimates across reporting units. Furthermore, 4th and 5th order Hydrologic Unit Codes (HUCs) were too large for our purposes, and the spatial data for 6th order HUCs were at that time incomplete for both prototype zones as well as for many areas across the nation. We chose reasonably small, uniform squares of 900 m by 900 m (or 81 ha) as reporting units (fig. 2) based on the need for ecological and managerial relevance, national consistency, and computational efficiency. Furthermore, we chose the 900-m box so that the 30-m pixels of the LANDFIRE vegetation layers would nest perfectly inside and reporting unit boundaries would therefore not split pixels.

Preparing Input Maps

A map of patch boundaries and a map of elevation are the only spatial inputs required for the model. The elevation map was derived directly from the DEM map obtained from NED and required no additional processing, whereas the map of patch boundaries had to be created. As mentioned above, patches in LANDSUMv4 are spatially contiguous areas that have identical PVT, CT, and structure. In addition, each patch can belong to only a single reporting unit. Succession and disturbance input parameters are stratified by PVT, and PVT distributions remain constant for any given landscape throughout the simulation.

In LANDSUMv4 simulations, overall processing time increases dramatically with the number of patches on the initial landscape. To minimize the number of patches on the initial landscape, we used only PVT and reporting units to determine our initial patch boundaries (fig. 2) and assigned a single value for each of the other patch attributes. Before the PVT map could be used to determine patch boundaries, however, we had to rectify the PVT, CT, and SS maps.

In the LANDFIRE Prototype, vegetation conditions, whether current or reference, were defined by PVT, CT, and SS. The reference conditions were generated by LANDSUMv4, and the current conditions were defined by mapped existing vegetation composition and structure (Frescino and Rollins, Ch. 7; Zhu and others, Ch. 8; Holsinger and others, Ch. 11). The succession pathways in LANDSUMv4 were based on the assumption that there is a unique set of succession classes (CT and SS combinations) that can occur naturally within a PVT. All of these succession classes were included as modeled states and thus had some probability of occurring in the historical reference conditions. When LANDSUMv4 output is compared to current conditions, succession classes that cannot occur in the reference conditions will tend to increase departure when calculating FRCC. These succession classes may appear in the current conditions because of exotic or invasive species or as a result of mapping errors in the independently created PVT, cover, or structure maps. Mismatches that are the result of mapping errors and not the result of exotic species must be corrected so that there is ecological consistency between a given PVT and the CTs and SSs that occur therein.

To ensure this ecological consistency, we performed a spatial overlay of the PVT, cover, and structure maps along with confidence layers to identify and correct such mismatches. The confidence layers (associated with each LANDFIRE vegetation layer) report a percentage of confidence in the predicted vegetation attribute for a pixel based on the rules that were used to classify it (Earth Satellite Corporation 2003; Frescino and Rollins, Ch. 7). A value of zero represents the lowest confidence whereas a value of 100 represents the highest confidence. For Zone 16, the only confidence layer available was that associated with the CT map (Zhu and others, Ch. 8). Succession classes that did not occur in the vegetation pathways and that included a CT not considered an exotic species were assumed to result from errors in the PVT or CT maps. The confidence layer information was then used to determine whether the PVT or CT should be changed. If the CT confidence was 50 percent or greater, the PVT was changed; otherwise, the CT was changed. For Zone 19, we had confidence layers for both the PVT and CT maps (Frescino and others, Ch. 7; Zhu and others, Ch. 8), so if the PVT confidence was greater than the CT confidence, the CT was changed; otherwise, the PVT was changed. Following all reassignments, the PVT, CT, and SS maps were recoded to reflect the changes. We then used the rectified PVT map as input for LANDSUMv4 and the rectified PVT, CT, and SS maps to define current conditions.

Non-vegetated areas (urban, barren, water, snow/ice, and agriculture) presented a special case regarding the rectification of the PVT and CT maps. For Zone 16, we used a mask of all non-vegetated types in making both the PVT and CT maps, ensuring that there was 100 percent agreement between the maps for all non-vegetated types. LANDSUMv4 will not simulate fire occurrence and spread through areas mapped as non-vegetated PVTs. In terms of historical reference conditions, however, some of these non-vegetated PVTs, particularly agriculture and urban, would have historically been vegetation CTs and thus would have experienced wildland fire. Agriculture and urban areas, therefore, serve as unnatural fire breaks and will lower the fire frequency of surrounding pixels, creating an effect similar to that on the edges of the simulation landscape where fire immigration is limited. To remedy this problem for Zone 19, Frescino and others (Ch. 7) predicted a PVT for every pixel on the map rather than masking non-vegetated types before predicting PVTs. In the rectification process described above, we reassigned the water, barren, and snow/ice land covers in the PVT layer to agree with the CT layer because these non-vegetated types occurred historically. The mapped PVTs in areas where the CT was agriculture or urban were not changed; thus, these areas did not act as fire breaks and LANDSUMv4 could simulate fire occurrence and spread according to the vegetation and topography.

Preparing Input Files from the Vegetation Pathways

Many of the key inputs into the LANDSUMv4 model come from the succession pathways developed by the vegetation modelers (Long and others, Ch 9). The modelers used the VDDT model to develop and test the vegetation pathways and stored the results of the VDDT modeling process in the Vegetation and Disturbance Dynamics Database (VADDD; Long and others, Ch. 9). This database was structured to store all vegetation and disturbance dynamics information used as input to LANDSUMv4 (see appendix 10-A for a description of VADDD, VADDD tables, and the fields within). The VADDD served as the primary reference for the codes and labels for all map unit classifications developed in LANDFIRE, including PVT, CT, and SS. In addition, this database was designed to efficiently check for errors in the succession and disturbance information prior to input into simulation modeling and to provide a standardized set of LANDSUMv4 parameters for subsequent applications of the model in different settings.

We converted the vegetation pathways developed in VDDT to the appropriate LANDSUMv4 files through the use of a custom software program, V2L. In addition to the spatial quality of LANDSUMV4, there are subtle differences between the way VDDT and LANDSUMv4 simulate succession and disturbance, including 1) partitioning disturbance and effects probabilities, 2) implementing multiple pathway succession, and 3) tracking patch age (Keane and others 2006; Kurz and others 1999). Most of these differences are rectified by the V2L program, but careful scrutiny was required to ensure that the pathways developed in VDDT functioned as intended in LANDSUMv4.

Parameterizing the Model

Many parameters must be set by the user prior to running LANDSUMv4. Previous research using the model has shown that simulation time, reporting interval, and fire spread parameters are important factors affecting simulation results (Keane and others 2002a; Keane and others 2003). In this section, we discuss the preliminary testing conducted to determine several key parameters, including simulation time parameters and fire ignition and spread parameters (for a list of all model parameters and associated values for the LANDFIRE Prototype, see appendix 10-B).

Simulation time parameters—Simulation time parameters for the model include 1) reporting interval, 2) total simulation time, and 3) initialization time. The reporting interval determines how often (in years) LANDSUMv4 reports vegetation conditions and fire characteristics across the landscape over the simulation period and the number of samples available for quantifying historical reference conditions. The selection of the reporting interval was largely driven by the need to reduce temporal autocorrelation in the LANDSUMv4 output so that each reporting interval represented an independent observation for calculating departure (Holsinger and others, Ch. 11; Steele and others, in preparation). After preliminary analysis, we selected a 20-year reporting interval for Zone 16. Following the Zone 16 runs, however, we determined that a 20-year reporting interval resulted in autocorrelation between observations, so we extended the reporting interval to 50 years for Zone 19 (see Holsinger and others, Ch. 11 for details on temporal autocorrelation in the reference conditions data).

The initialization period represents the number of years it takes the initial simulation landscape to reach equilibrium, and this initial simulation period is excluded from subsequent analysis. Keane and others (2002a) found that it took approximately 200 years for succession class distributions to reach equilibrium, whereas Keane and others (2003) found that the landscape MFRI stabilized after the first 200 – 400 years of simulation. In our exploratory analysis for Zone 16, we found that successional development had a distinct trend for the first 250 to 500 years and then stabilized around a mean with expected variations (Keane and others 2002a). As a result, we specified a 500-year initialization period for both Zone 16 and Zone 19.

The total simulation period needed to be long enough to adequately capture the full range of vegetation conditions and fire regime characteristics and produce an adequate chronosequence to quantify historical vegetation conditions for subsequent departure calculations. In addition, extreme fire events, though rare, have a disproportionately large impact on vegetation patterns across the landscape (Moritz 1997; Strauss and others 1989), so it is important that the simulation period is long enough to allow sufficient opportunity for these rare events to occur. The fire return interval influences the simulation length appropriate for capturing fire and vegetation characteristics, and thus the appropriate simulation length varies across landscapes. Our selection of the total simulation period was largely informed by the number of samples needed for departure analysis. Holsinger and others (Ch. 11) found that a minimum of 200 independent observations from LANDSUMv4 were required to develop a time series reasonable for quantifying historical landscape conditions for departure calculations. Based on this criterion, we calculated simulation periods of 4,500 years and 10,500 years (each including a 500-year initialization period) for Zone 16 and Zone 19, respectively.

Fire ignition and fire spread parameters—In LANDSUMv4, wildland fire is modeled in three steps: ignition, spread, and effects. Fire effects are determined stochastically by the probabilities defined in the vegetation pathways. Fire ignition uses a three-parameter Weibull hazard function (Johnson and Gutsell 1994; Johnson and Van Wagner 1985) based on the fire probabilities in the vegetation pathways, a shape parameter, and a years-until-reburn parameter to adjust the probability in the pathways to account for fuel build-up. The fire probabilities from the vegetation pathways reflect point estimates of fire return interval and describe the probability that a fire will burn a point on the landscape. The probability is adjusted using the relationship of average fire size (ignition average fire size parameter) to the pixel area (90 m^2) and patch size to pixel area to scale point-level fire probabilities to stand-level ignition probabilities. The ignition probability is also adjusted for yearly weather variations based on a fire weather parameter that establishes the number of dry, normal, and wet fire years in a decade (for a thorough discussion of the equations and parameters used LANDSUMv4 fire simulations, see Keane and others 2002a and Keane and others 2006). The fire spread algorithm calculates a fire size from a heavy-tailed exponential distribution that is defined by a shape and a scale parameter (Keane and others 2002a; Keane and others 2006). Fire is then spread cell-to-cell based on the modified equations of Rothermel (1991) and wind and slope vectors until it reaches the calculated fire size or an unburnable boundary. In this section, we will discuss the ignition average fire size parameter, the spread scale parameter, and the ignition fire weather parameter.

Both the ignition average fire size parameter and the spread scale parameter are related to average fire size. The spread scale parameter influences the average fire size simulated by LANDSUMv4 by controlling the distribution from which fire sizes are drawn. As the scale parameter increases, the simulated average fire size also increases (fig. 4). The ignition fire size parameter should approximate the estimated average fire size for the landscape and is used in scaling fire probabilities to ignition probabilities. As the ignition fire size parameter increases, the number of fires (number of ignitions) decreases (fig. 4). Estimating both of these parameters correctly requires information about historical fire sizes; however, reliable data on historical average fire sizes are difficult to obtain. We calculated an average fire size from the National Integrated Fire Management Interagency Database (NIFMID; USDA Forest Service 1993) for each mapping zone. Although this database records recent fires only and is therefore likely a poor representation of historical fire sizes, it was the only source available for estimating fire size across the entire United States. We used the NIFMID estimate as a starting point for the ignition average fire size and the spread scale parameter estimates. Together, ignition and spread will determine the mean fire return interval over the simulation. In an attempt to refine these parameters, we tried various combinations of the ignition average fire size and spread scale parameters within a test area and evaluated the mean fire return interval. The vegetation pathways define fire probabilities based on estimates of historical fire frequencies from literature review and fire history studies (Long and others, Ch. 9). We averaged these probabilities and treated these mean probabilities

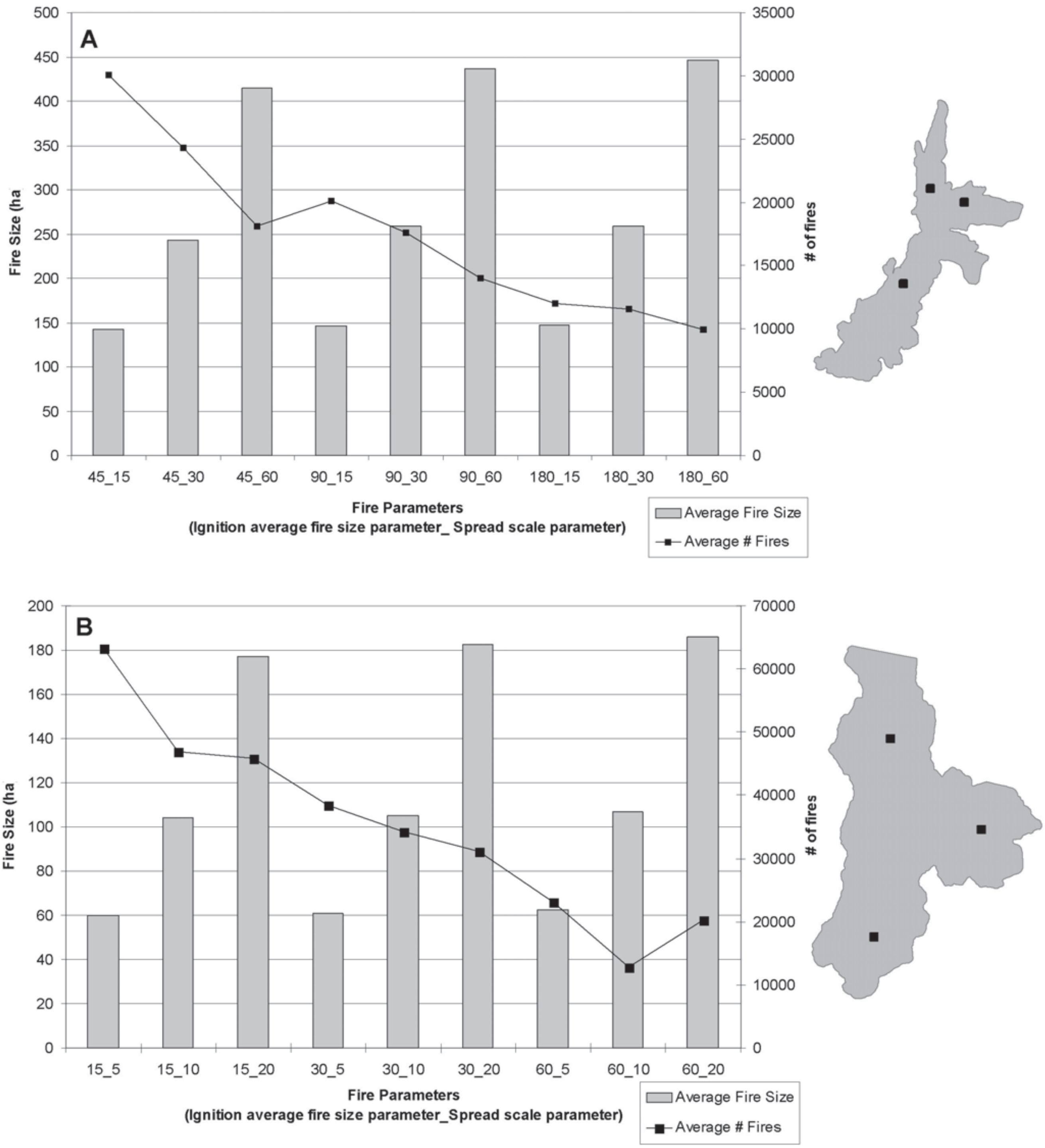

Figure 4—Average fire size and average number of fires as a function of fire size parameter pairs (ignition fire size parameter and spread scale parameter) for three test landscapes in a) Zone 16 and b) Zone 19. The average fire size and the number of fires were calculated for each landscape and then averaged for a single parameter pair.

as the expected fire occurrence and the inverse of these probabilities as the expected mean fire return interval. Fire occurrence in LANDSUMv4 is based, in part, on the probabilities of fire in the succession pathways, so we operated under the assumption that the MFRI modeled by LANDSUMv4 should be reasonably close (within 25 percent) to the expected MFRI calculated from the vegetation pathways. LANDSUMv4 calculates and reports a simulated MFRI and an expected MFRI (calculated from the pathway-defined fire probabilities) for the entire simulation landscape. For Zone 16, we found that an ignition average fire size parameter that was three times the spread scale parameter resulted in simulated MFRIs for the simulation landscape that were similar to the expected MFRI as calculated by LANDSUMv4. We set the spread scale parameter to the 30-ha NIFMID estimate and the ignition average fire size parameter to 90 ha for Zone 16.

After simulating the entire zone, the MFRI for many PVTs in Zone 16 were much longer than expected (see the *Results* section below for details). We therefore modified our methods for setting the ignition average fire size and spread scale parameters for Zone 19. We started with an average fire size estimate of 30 ha from the NIFMID database. We then varied the two fire size distribution parameters and ran simulations for each parameter pair on three test landscapes of varying topography and vegetation (fig. 5). We calculated the simulated mean fire return interval for each PVT and calculated a similarity value (expected MFRI divided by simulated MFRI) to compare the simulated MFRI and expected MFRI for each PVT (fig. 5b). For the Zone 19 simulations, we selected 30 ha for the ignition average fire size parameter based on the 30 ha NIFMID estimate and 15 ha for the spread scale parameter.

The ignition fire weather multiplier does not affect the long-term fire probabilities, but rather affects the year-to-year probability of fire occurrence. To estimate the weather parameter (the number of dry, normal, and wet years in a decade), we used reconstructions of the Palmer Drought Severity Index (PDSI; Palmer 1965) from various sources. PDSI is an index of soil moisture based on precipitation, temperature, and available water content (AWC) of the soil. The index varies roughly between -6.0 and +6.0, with positive numbers representing wetter conditions and negative numbers drier conditions. For Zone 16, we relied on the Northeastern Utah Palmer Drought Severity Index Reconstruction, which is based on tree ring chronologies in and around the Uinta Basin (Gray and others 2003), to estimate historical climate conditions from 1405 to 2000 A.D. We assumed that wet years were those with a PDSI greater than 1.0, normal years were those with a PDSI between –1.99 and 0.99, and severe drought years were those with a PDSI of less than –1.99. Accordingly, we estimated the number of dry, normal, and wet years over the course of a decade as 3, 5, and 2, respectively. For Zone 19, we extracted data from the Alternative Method USA Summer PDSI Reconstruction (Zhang and others 2004). This data set is based on tree ring chronologies from 1700 to 1894 and instrumental data from 1895 to 1978. Using the same breaks for wet, normal, and dry years as described above, we estimated the number of dry, normal, and wet years as 1, 6, and 3, respectively, for Zone 19.

Model Output

Although there are many maps and tabular files output from LANDSUM, we produced only two types of data for the LANDFIRE Prototype: (1) vegetation chronosequence data and 2) fire regime maps. The time series data that define reference conditions for vegetation are summarized in a tabular file that summarizes the area (m^2) within each reporting unit that is occupied by each PVT-succession class combination for each reporting year. Holsinger and others (Ch. 11) used these data to calculate FRCC and departure values for each reporting unit. While there are many important characteristics of fire regimes, we mapped and evaluated only fire frequency and fire severity values. Other characteristics such as fire size and pattern can be evaluated using output from LANDSUMv4 but, because of limited computer resources, we chose not to create these files for the entire mapping zone. The fire frequency and fire severity maps were processed to create the final LANDFIRE Prototype fire regime map products.

Fire regime maps—LANDSUMv4 outputs four different fire regime maps — three severity maps and one frequency map — which we then processed to create the final LANDFIRE Prototype fire regime maps. Fire effects in LANDSUMv4 are defined as one of three severity types: non-lethal surface, mixed-severity, and stand-replacing fires. LANDFIRE produces maps for each of these severity types that display the percentage of fires of the given severity type experienced by a particular pixel. Fire severity is calculated as the total number of fires of the given severity type divided by the total number of fires experienced by that cell times 100. Values for each map range from 0 - 100 and, for any cell, the sum of the three maps should equal 100. The fire frequency map simply reports the fire return

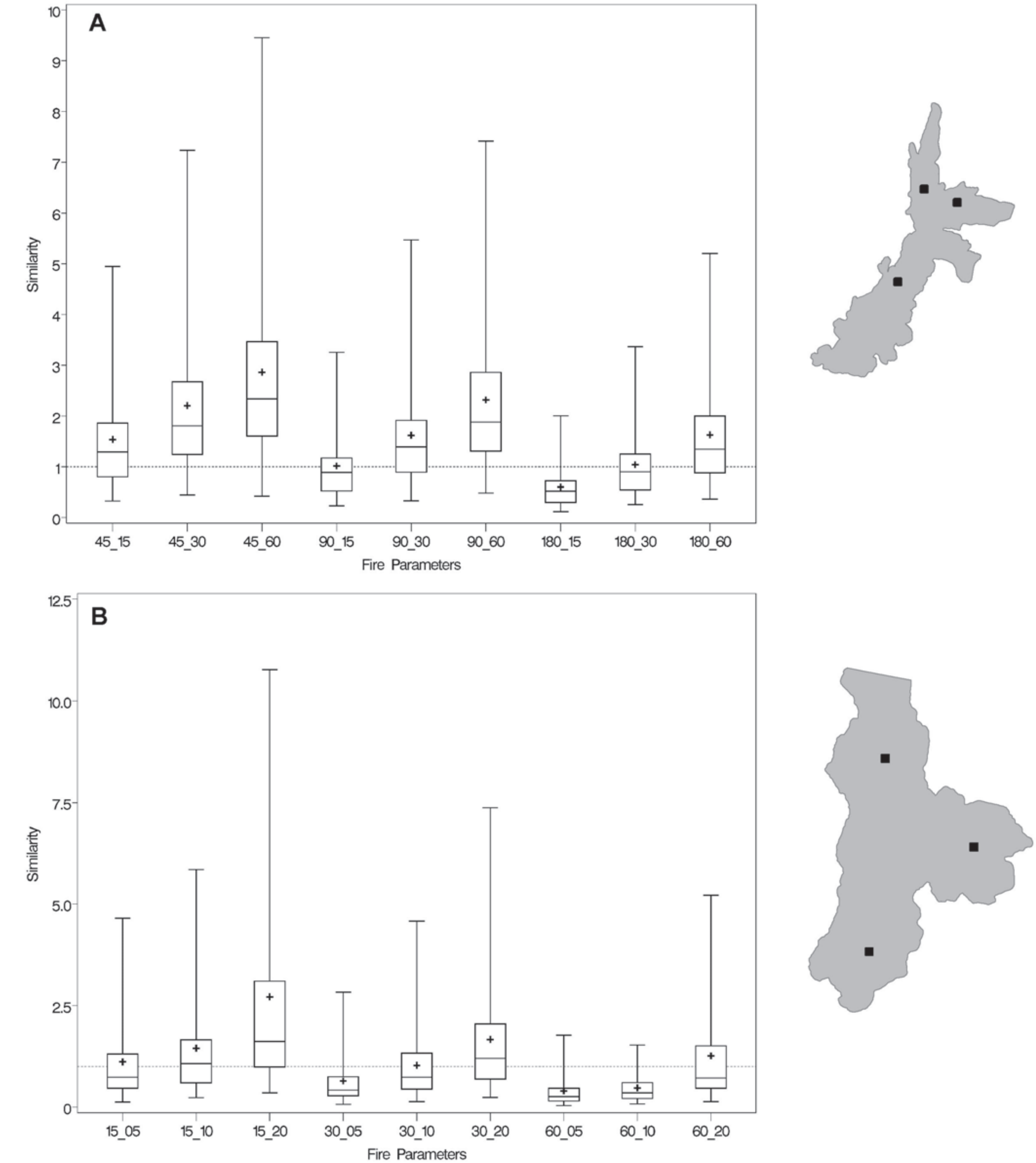

Figure 5—Box and whisker plots for the similarity index calculated for each of the nine fire parameter pairs (ignition fire size parameter and spread scale parameter) for three test landscapes in a) Zone 16 and b) Zone 19. The similarity index is a measure of the similarity between the simulated mean fire return intervals and the mean fire return intervals based on the fire probabilities set in the vegetation pathways. A similarity value of 1 indicates that the two MFRIs are the same. A similarity above 1 indicates that the simulated MFRI is shorter than the scenario MFRI, and a similarity less than 1 indicates that the simulated MFRI is longer than the scenario MFRI.

interval (in years) and is calculated as the total number of simulation years divided by the total number of fires occurring in that cell.

When the fire frequency maps from the individual simulations were tiled together to create a composite map for the entire zone, the resulting map contained a heavy imprint from the individual simulation landscapes (fig. 6a). We used the simulation buffer areas to smooth the edges between adjacent simulation landscapes and reduce the imprint to create a seamless map for the zone. The buffer area for one simulation landscape overlapped the context area of the adjacent simulation landscape (fig. 3). As noted above, these buffer regions tended to yield underestimations of fire frequencies. However, since fires tend to burn primarily in the direction of the prevailing winds (WSW in our simulation areas), buffer areas along the north and east edges still had many fires burning in from the context area; thus, fire was usually realistically simulated in these areas. We clipped the south and west buffer areas off of each context area and left the north and east buffer areas intact. We then used the *mosaic* command in ARC/INFO to overlay the individual simulation landscapes and smooth the overlapping areas (fig. 6b). Although this process led us to change some pixel values from their original simulated value, values were changed only in areas where fires tended to be underestimated by the model (along the western and southern borders of the context area). Following the smoothing process for Zone 16, 26 percent of the pixel values on the map changed from the simulated values and the mean change for all pixels was three fires.

Results

Fire Regime Maps

Fire frequency—Figure 7 shows the mean fire return interval (MFRI) in years for both mapping zones. The MFRIs for Zone 16 were relatively short: 58 percent of the zone had a fire return interval of 35 years or less, 94 percent of the zone had a fire return interval of 100 years or less, and fire return intervals of more than 100 years occurred in less than 0.5 percent of the zone. Six percent of the zone never burned during the 4,500-year simulation period. The MFRIs in Zone 19 tended to be longer: 31 percent of the zone had a fire return interval of 35 years or less, 93 percent had fire return intervals of 100 years or less, and nearly 5 percent of the zone had fire return intervals between 100 and 200 years. Less than 3 percent of the zone was unburned during the 10,500-year simulation period. In both zones, most of the pixels that did not burn (99 percent) belonged to PVTs that were defined as unburnable in the model (water, rock, snow/ice, agriculture, and urban for Zone 16 and water, rock, and snow/ice for Zone 19). There were a few vegetated areas with the potential to burn that never burned; these pixels were imbedded in a matrix of unburnable pixels, thereby preventing fires from spreading to those pixels.

To get a sense of how well the model simulated fire for different vegetation types, we compared the expected MFRI calculated from the fire probabilities in the vegetation pathways to the simulated MFRIs averaged for each PVT (tables 1 and 2). As noted previously, the simulation of fire in LANDSUMv4 is based in part on the fire probabilities in the vegetation pathways. Fire spread, however, operates independent of these probabilities. Furthermore, adjacency of PVTs with different fire probabilities may cause the simulated MFRI to be different from the expected MFRI in some PVTs. We determined, however, that when averaged by PVT across the zone, the simulated MFRI should be within 25 percent of the expected MFRI for most PVTs. Two-thirds of the PVTs in Zone 16 had more than a 30-percent difference between the simulated MFRI and the expected MFRI (table 1). Many of these PVTs represented only a small portion of the zone, but together, these 20 PVTs represented over 70 percent of Zone 16. In all but three of these PVTs, the simulated MFRI was shorter than the expected MFRI. For example, the Spruce Fir / Spruce Fir PVT had an MFRI in the pathways of 53 years, whereas the MFRI simulated by LANDSUMv4 for this PVT was 32 years. For some PVTs, however, the simulated MFRI was fairly close to the expected MFRI (see Pinyon Juniper / Mountain Big Sagebrush / South, Douglas-fir / Douglas-fir, and Grand Fir – White Fir in table 1). In Zone 19, the simulated MFRIs corresponded somewhat better to the expected MFRIs (table 2). Just over 50 percent of the PVTs in Zone 19 had more than a 30-percent difference between the simulated MFRI and the expected MFRI; however, these PVTs comprised only 38 percent of Zone 19. Again, the simulated MFRIs tended to be shorter than the expected MFRIs for these PVTs (see Spruce-Fir / Timberline in table 2, for example), yet six PVTs did have a simulated MFRI that was longer than the pathway MFRI (see Douglas-fir / Ponderosa Pine / Douglas-fir in table 2, for example).

Fire severity—The model produced three fire severity maps, one for each severity type (stand-replacing, mixed-severity, and non-lethal surface fires). Each map displayed the percentage of total fires that were of a particular severity (see *Model Output* in the *Methods* section for

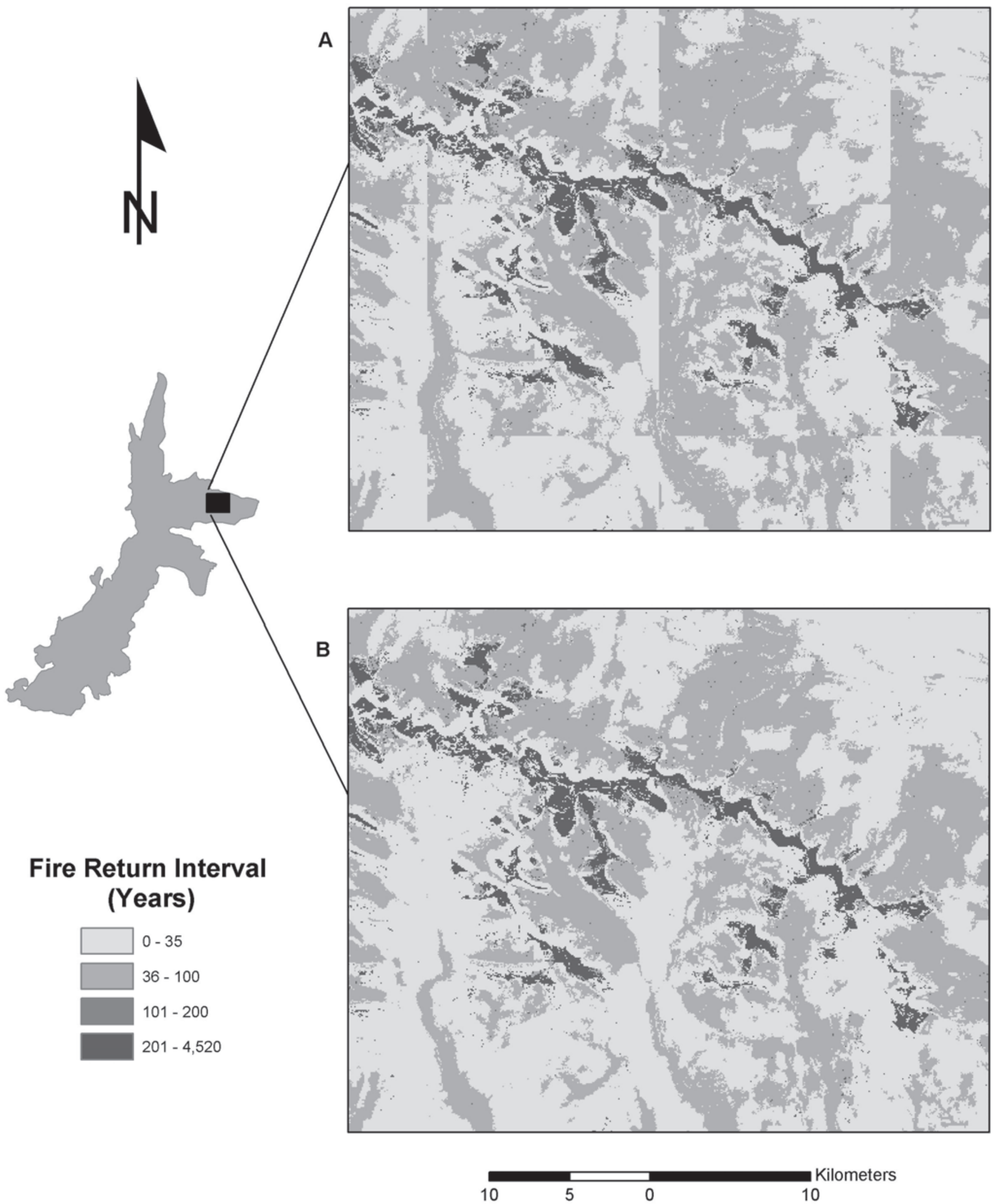

Figure 6—Fire frequency maps for two adjacent simulation landscapes in Zone 16 that were processed by a) removing all 3-km buffer areas and merging the context areas and b) removing only the south and west 3-km buffer areas and mosaicking the context areas and overlapping buffers.

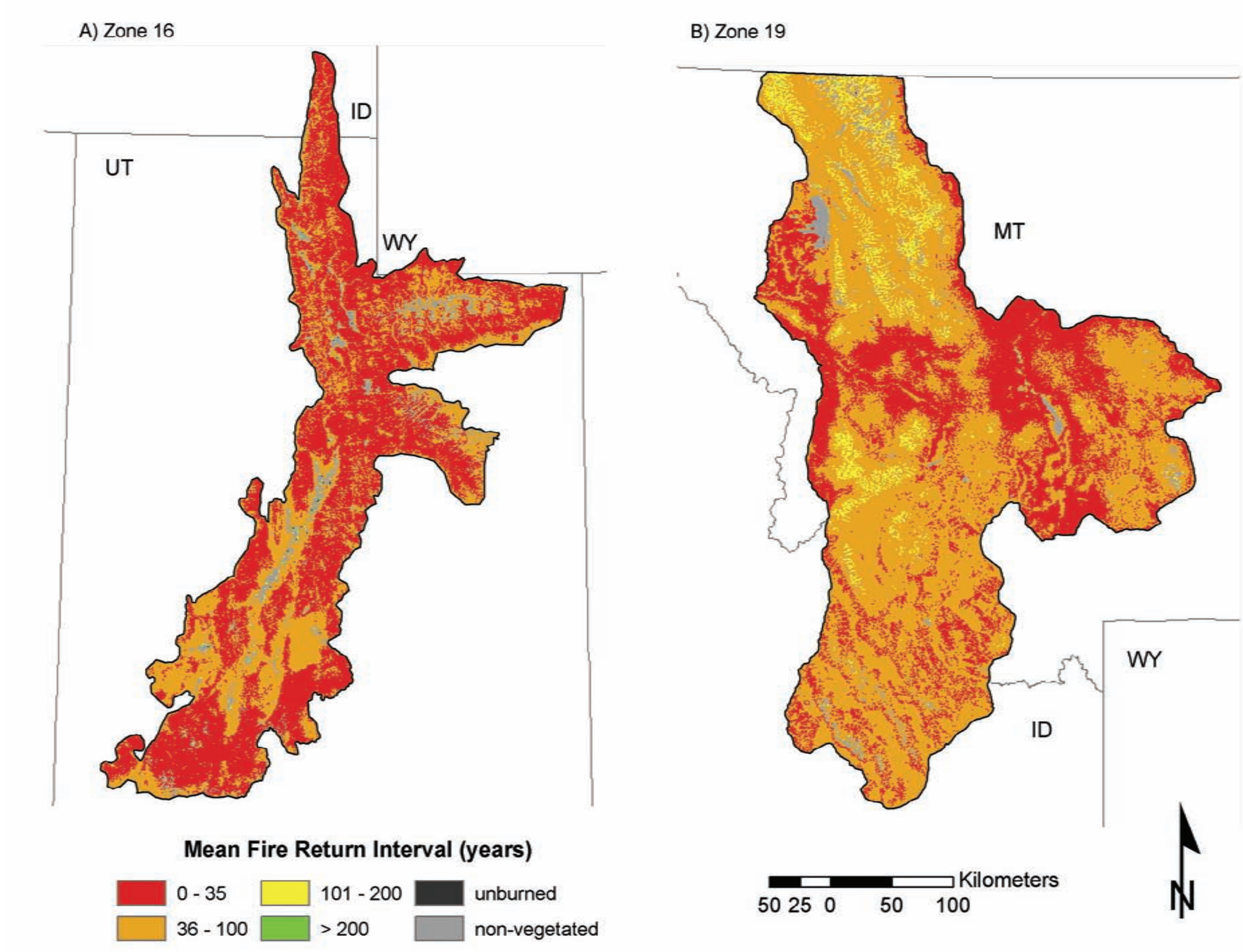

Figure 7—Mean fire return interval (MFRI) in years for a) Zone 16 and b) Zone 19. MFRI was calculated for each pixel as the total simulation time divided by the total number of fires that occurred within the pixel during the simulation period. Non-vegetated pixels are those areas with no natural vegetation, such as water or rock, and therefore cannot burn. Unburned pixels are vegetated pixels that never burned during the simulation period.

Table 1—Mean fire return interval (MFRI) values summarized for each PVT in Zone 16. MFRIs are reported as "Pathway MFRI" (the mean of the fire probabilities for all succession classes in a PVT weighted by the percent area of the PVT occupied by each succession class in 200 reporting years), "Classified MFRI" (percent of the PVT in each of the five MFRI classes used by Schmidt and others 2002 after the 4500-year simulation), and "Raw MFRI" (mean MFRI for the PVT after the 4,500-year simulation). The percent of Zone 16 that each PVT occupies is also given.

PVT		Pathway MFRI (yrs)	Raw simulated MFRI (yrs)		Classified simulated MFRI (% of PVT)				
Name	**% of zone**	**Mean**	**Mean**	**Std. dev.**	**0**	**1-35 yrs**	**36-100 yrs**	**101-200 yrs**	**200+ yrs**
Alpine	0.33	244	71	290	0.6	39.6	55.8	2.3	1.6
Aspen	2.07	63	33	28	0.0	78.4	21.6	0.0	0.0
Blackbrush	0.36	200	65	142	0.2	9.1	88.7	1.6	0.4
Cool Herbaceous	0.14	25	47	153	0.2	54.6	43.9	0.8	0.5
Douglas-fir / Douglas-fir	3.17	29	32	17	0.0	80.5	19.5	0.0	0.0
Douglas-fir / Lodgepole Pine	0.19	41	33	4	0.0	79.8	20.2	0.0	0.0
Douglas-fir / Timberline Pine	0.47	44	31	29	0.0	89.4	10.6	0.0	0.0
Dwarf Sagebrush	4.48	97	46	73	0.0	23.7	75.9	0.2	0.1
Grand Fir – White fir	7.02	36	31	12	0.0	90.3	9.7	0.0	0.0
Grand Fir – White Fir / Maple	2.61	34	42	133	0.1	57.7	41.2	0.6	0.3
Lodgepole Pine	0.81	60	33	4	0.0	71.6	28.4	0.0	0.0
Mountain Big Sagebrush	8.67	20	32	44	0.0	83.1	16.8	0.1	0.1
Pinyon – Juniper / Gambel Oak	1.44	41	39	112	0.1	65.8	33.4	0.5	0.3
Pinyon – Juniper / Mountain Big Sagebrush / North	1.16	24	34	42	0.0	78.4	21.3	0.2	0.0
Pinyon – Juniper / Mountain Big Sagebrush / South	5.22	30	33	19	0.0	79.3	20.6	0.0	0.0
Pinyon – Juniper / Mountain Mahogany	1.06	58	34	38	0.0	73.7	26.2	0.1	0.0
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / North	2.43	66	48	53	0.0	4.9	94.6	0.4	0.1
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	16.47	56	39	34	0.0	36.3	63.5	0.1	0.0
Ponderosa Pine	2.48	15	29	19	0.9	93.4	5.7	0.0	0.0
Riparian Hardwood	2.11	72	37	66	0.1	55.4	44.4	0.1	0.1
Riparian Shrub	1.00	64	72	316	1.1	41.8	54.0	1.5	1.5
Salt Desert Shrub	2.13	119	69	197	0.2	2.6	94.5	1.7	1.0
Spruce – Fir / Blue Spruce	1.15	41	32	34	0.0	84.0	15.9	0.0	0.0
Spruce – Fir / Blue Spruce / Lodgepole Pine	0.54	43	34	13	0.0	68.2	31.8	0.0	0.0
Spruce – Fir / Spruce – Fir	7.97	53	32	24	0.0	86.2	13.7	0.0	0.0
Spruce – Fir / Spruce – Fir / Lodgepole Pine	13.25	53	34	12	0.0	72.0	27.9	0.0	0.0
Timberline Pine	0.03	186	32	30	0.0	86.6	13.3	0.0	0.0
Warm Herbaceous	0.73	40	45	151	0.1	56.2	42.6	0.6	0.4
Wetland Herbaceous	0.27	183	48	186	0.3	57.8	40.5	0.6	0.7
Wyoming – Basin Big Sagebrush	4.45	81	54	177	0.2	27.1	70.8	1.2	0.7

Table 2—Mean fire return interval (MFRI) values summarized for each PVT in Zone 19. MFRIs are reported as "Pathway MFRI" (the mean of the fire probabilities for all succession classes in a PVT weighted by the percent area of the PVT occupied by each succession class in 200 reporting years), "Classified MFRI" (percent of the PVT in each of the five MFRI classes used by Schmidt and others 2002 after the 4500-year simulation), and "Raw MFRI" (mean MFRI for the PVT after the 10,500-year simulation). The percent of Zone 19 that each PVT occupies is also given.

PVT		Pathway MFRI (yrs)	Raw simulated MFRI (yrs)		Classified simulated MFRI (% of PVT)				
Name	% of zone	Mean	Mean	Std. dev.	0	1-35 yrs	36-100 yrs	101-200 yrs	200+ yrs
Alpine	0.03	245	39	15	0.00	50.56	48.69	0.74	0.02
Bluebunch Wheatgrass	9.46	26	32	27	0.00	77.27	22.70	0.02	0.01
Bluebunch Wheatgrass / Conifer	0.26	26	33	68	0.01	74.07	25.75	0.14	0.04
Douglas-fir / Douglas-fir	10.52	52	39	13	0.00	42.05	57.66	0.29	0.00
Douglas-fir / Lodgepole Pine	4.19	53	45	15	0.00	24.65	74.71	0.64	0.01
Douglas-fir / Ponderosa Pine/ Douglas Fir	3.03	20	32	7	0.00	72.00	28.00	0.00	0.00
Douglas-fir / Timberline Pine	1.11	48	39	16	0.00	45.79	53.92	0.29	0.01
Douglas-fir / Ponderosa Pine/ Western Larch/	2.43	21	32	14	0.00	77.27	22.49	0.21	0.03
Dry Shrub	1.28	29	40	108	0.01	58.50	40.35	1.04	0.09
Dry Shrub / Conifer	0.21	26	61	169	0.04	19.73	73.14	6.82	0.27
Dwarf Sagebrush Complex / Conifer	0.00	67	36	7	0.00	61.32	38.68	0.00	0.00
Dwarf Sagebrush Complex	0.26	32	40	6	0.00	18.81	81.15	0.04	0.00
Fescue Grasslands	2.02	25	36	36	0.00	60.90	38.84	0.23	0.02
Fescue Grasslands / Conifer	0.46	34	42	29	0.00	36.68	62.18	1.09	0.05
Grand Fir - White Fir	0.82	55	55	37	0.00	12.51	83.79	3.07	0.63
Lodgepole Pine	3.65	85	53	18	0.00	9.62	88.76	1.62	0.01
Mountain Mahogany	0.28	32	37	21	0.00	46.31	53.67	0.02	0.00
Mountain Big Sagebrush Complex/Conifer	0.76	33	41	40	0.00	33.68	65.95	0.36	0.01
Mountain Big Sagebrush Complex	5.20	34	37	14	0.00	48.06	51.91	0.03	0.00
Ponderosa Pine	1.14	13	28	10	0.00	89.55	10.37	0.06	0.02
Riparian Hardwood	1.43	122	46	64	0.00	26.99	71.61	1.26	0.14
Riparian Shrub	0.92	62	48	107	0.02	21.08	77.94	0.87	0.10
Rocky Mountain Juniper	0.12	31	36	32	0.00	52.28	47.69	0.03	0.01
Spruce - Fir / Montane / Douglas-fir	4.01	97	50	23	0.00	17.74	80.29	1.96	0.01
Spruce - Fir / Subalpine	6.69	209	81	48	0.00	2.50	73.28	23.86	0.36
Spruce – Fir / Timberline	8.88	261	81	86	0.01	2.02	77.41	20.43	0.13
Spruce - Fir / Montane/ Western Larch	8.21	73	66	28	0.00	7.50	82.51	9.91	0.09
Threetip Sagebrush / Conifer	0.02	31	38	9	0.00	42.44	57.54	0.01	0.00
Threetip Sagebrush	0.54	32	36	6	0.00	53.15	46.85	0.01	0.00
Timberline Pine / Limber Pine	0.13	211	40	98	0.02	48.08	51.31	0.52	0.07
Timberline Pine / Whitebark Pine	0.44	368	70	250	0.08	6.85	88.65	4.05	0.36
Western Redcedar	0.55	107	65	25	0.00	6.41	86.67	6.68	0.24
Wetland Herbaceous	1.32	180	52	101	0.02	20.84	76.97	1.98	0.20
Wyoming – Basin Big Sagebrush Complex / Conifer	0.50	54	39	32	0.00	41.49	58.31	0.17	0.03
Wyoming – Basin Big Sagebrush Complex	16.72	54	42	28	0.00	19.23	80.70	0.06	0.01

a more detailed explanation). The three severity maps for each zone are shown in figure 8. Both zones were dominated by stand-replacing fires. The mean percentage of stand-replacing fires was 69.8 percent in Zone 16 and 72.5 percent in Zone 19. The mean percentage of non-lethal surface fires was 17.1 percent and 14.5 percent, and that of mixed-severity fires was 6.5 percent and 12.2 percent for zones 16 and 19, respectively. We also examined severity in relation to PVT (tables 3 and 4). In Zone 16, most of the forest PVTs had roughly equal amounts of stand-replacing and non-lethal surface fires, with very few (15 percent or less) mixed-severity fires. A few forest PVTs had almost exclusively stand-replacing fires. Mixed-severity fires were more common in Zone 19, where several PVTs had a mean greater than 20 percent. Timberline pine PVTs had almost exclusively stand-replacing fires, with mean probabilities from 78 percent to 97 percent. In both zones, almost all of the rangeland types had predominantly stand-replacing fires (80 to 100 percent). In Zone 19, only the Riparian Shrub PVT had less than 99 percent stand-replacing fires. Zone 16 shrub and herbaceous PVTs were slightly more diverse in terms of fire severity. In Zone 16, a few PVTs were equally divided between having stand-replacing and non-lethal surface fires and one PVT almost equally divided between stand-replacing and mixed-severity fires. There was fairly close correspondence between the mean percentages for simulated fires and the mean percentages calculated from the pathway probabilities for both zones.

Historical Vegetation Reference Conditions

The simulated historical reference conditions for vegetation were summarized as the area occupied by each succession class in each PVT for every reporting unit across each reporting year. There were 200 reporting years in a simulation with up to 33 succession classes (with an average of 13) per PVT and as many as 26 PVTs (with an average of 11) per reporting unit for Zone 16. For demonstration purposes, figures 9 and 10 show a sample of this data set for the top six succession classes for one forest (Lodgepole Pine) and one rangeland (Mountain Big Sagebrush) PVT in a single simulation landscape (20,000 ha). These figures illustrate the large range of vegetation conditions experienced over the simulation period. In the Mountain Big Sagebrush PVT, for example, Low Cover, Low Height Cool Season Perennial Grass occupied anywhere from zero to almost 90 percent of the PVT for this landscape throughout the 4,000 years of simulation. Other succession classes had less amplitude. Low Cover, Low Height Dry Deciduous Shrub occupied only between zero and 10 percent of the landscape. In general, the Mountain Big Sagebrush PVT appeared to be dominated alternately by Mountain Big Sagebrush and Cool Season Perennial Grass succession classes, with other shrub types at lower levels throughout the simulation. The Lodgepole Pine PVT was generally dominated by Aspen-Birch succession classes, with Lodgepole Pine succession classes dominating for short periods and generally at moderate levels.

Discussion

Limitations of the Simulation Approach for Describing Historical Conditions

Estimating fire parameters—One of the main difficulties in realistically simulating historical fire regimes lies in the estimation of model parameters. Fire history studies remain the primary source for estimating fire probabilities in modeling efforts, particularly fire return interval. However, the data collected in fire history studies pose problems of scale and analysis. First, many fire history studies are conducted in small areas within highly complex landscapes. Topographical features and their orientation, coupled with predominant wind patterns, can influence fire history within a small study area. Second, in a fire history chronology, there are often years in which only a single scar exists and years where nearly every tree in the area is scarred. To be considered in the calculation of mean fire return interval for the study area, a fire year is often determined by a threshold number of trees that show evidence of fires (for example, a "fire year" is one where 10 percent or more of the trees in the area are scarred). The number of fire years incorporated into the calculation of mean fire return interval is highly sensitive to this threshold. Furthermore, if a tree shows no scar, it is difficult to determine whether this is because the tree was not in the area burned by the fire or because the fuel located directly around the tree was insufficient to generate the intensity required to create a scar. Thus, the computed fire return interval is dependent upon not only the number of trees used to identify a fire year, but also upon the number of fire-scarred trees sampled within the study area. To complicate matters further, fire scars are point measures of fire history and do not integrate the complex spatial interactions of fire spread over a study area or landscape. Finally, fire history studies are spatially limited to several key ecosystems (mostly forest) of the United States and document fire events over

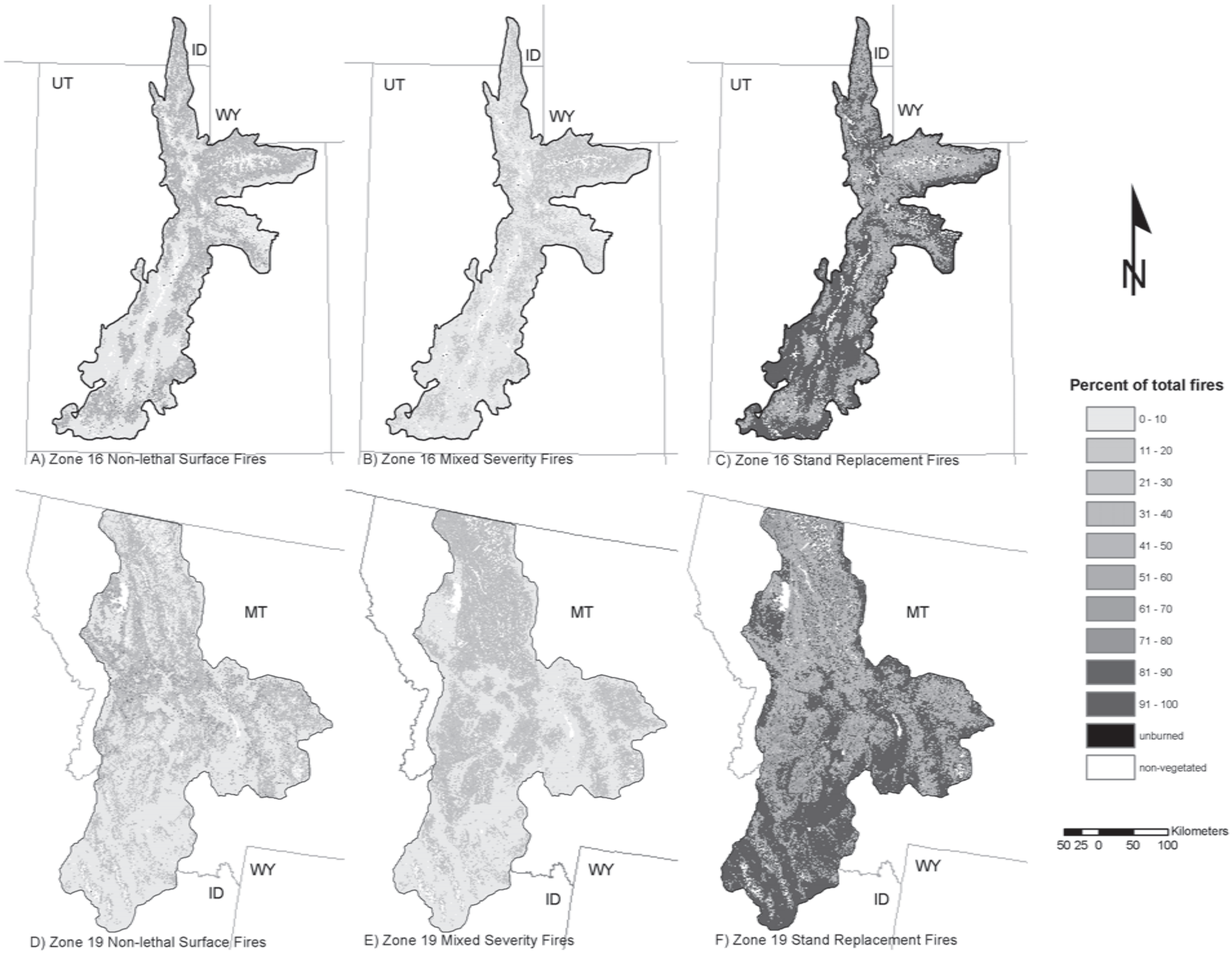

Figure 8—Percentage of simulated fires that were a) stand-replacing, b) mixed-severity, and c) non-lethal surface fires in Zone 16 and d) stand-replacing, e) mixed-severity, and f) non-lethal surface fires in Zone 19. Non-vegetated pixels are those areas with no natural vegetation, such as water or rock, and therefore cannot burn. Unburned pixels are vegetated pixels that never burned during the simulation period.

Table 3—Mean percentage of stand-replacing fire (SRF), mixed-severity fire (MSF), and non-lethal surface fire (NLSF) for each potential vegetation type (PVT) for Zone 16 calculated from the simulated fire severity maps (SIM MEAN) and the vegetation pathways (PATH MEAN). For each severity type, the simulated mean was calculated by taking the mean of the percentage value reported on the severity map for each pixel across each PVT. The pathway mean is the mean of the probabilities for the severity type for each succession class in each PVT weighted by the percent area of the PVT occupied by each succession class over all 200 reporting intervals.

	SRF		MSF		NLSF	
PVT NAME	PATH MEAN	SIM MEAN	PATH MEAN	SIM MEAN	PATH MEAN	SIM MEAN
Alpine	88.0	99.4	0.0	0.0	0.0	0.0
Aspen	61.1	57.4	0.0	0.0	38.9	41.7
Blackbrush	100.0	99.8	0.0	0.0	0.0	0.0
Cool Herbaceous	100.0	99.8	0.0	0.0	0.0	0.0
Douglas-fir / Douglas-fir	42.2	39.3	10.8	11.3	47.0	47.9
Douglas-fir / Lodgepole Pine	47.0	43.8	15.9	16.0	37.2	38.7
Douglas-fir / Timberline Pine	60.2	59.6	4.0	4.0	35.8	34.9
Dwarf Sagebrush	100.0	100.0	0.0	0.0	0.0	0.0
Grand Fir – White fir	40.6	36.8	13.1	13.5	46.3	48.2
Grand Fir – White Fir / Maple	93.5	91.0	6.5	7.9	0.0	0.0
Lodgepole Pine	60.7	56.8	10.7	12.6	28.6	29.2
Mountain Big Sagebrush	100.0	100.0	0.0	0.0	0.0	0.0
Pinyon – Juniper / Gambel Oak	98.2	97.4	1.8	1.7	0.0	0.0
Pinyon – Juniper / Mountain Big Sagebrush / North	86.5	83.7	13.5	15.4	0.0	0.0
Pinyon – Juniper / Mountain Big Sagebrush / South	97.2	95.9	2.8	3.2	0.0	0.0
Pinyon – Juniper / Mountain Mahogany	99.6	99.2	0.4	0.4	0.0	0.0
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / North	98.5	97.5	1.5	1.8	0.0	0.0
Pinyon – Juniper / Wyoming – Basin Big Sagebrush / South	96.1	95.7	3.9	3.4	0.0	0.0
Ponderosa Pine	37.4	37.4	5.0	4.6	57.6	56.6
Riparian Hardwood	63.7	59.4	2.1	1.6	34.3	37.6
Riparian Shrub	68.5	56.5	31.5	41.7	0.0	0.0
Salt Desert Shrub	100.0	99.8	0.0	0.0	0.0	0.0
Spruce – Fir / Blue Spruce	41.4	37.5	14.2	15.3	44.4	45.8
Spruce – Fir / Blue Spruce / Lodgepole Pine	42.0	38.1	12.4	13.7	45.5	46.8
Spruce – Fir / Spruce – Fir	54.4	48.5	11.0	13.1	34.7	36.9
Spruce – Fir / Spruce – Fir / Lodgepole Pine	52.4	46.8	12.6	14.6	35.0	37.1
Timberline Pine	97.8	97.8	0.3	0.1	1.9	1.6
Warm Herbaceous	100.0	99.9	0.0	0.0	0.0	0.0
Wetland Herbaceous	100.0	99.7	0.0	0.0	0.0	0.0
Wyoming – Basin Big Sagebrush	100.0	99.8	0.0	0.0	0.0	0.0

a very short time period of approximately three to five centuries. The lack of fire history data for large areas of the United States and the limited temporal depth of evidence of past fires are perhaps the largest obstacles to simulating historical conditions across the nation.

The fire size parameters required by LANDSUMv4 are even more difficult to estimate because sound historical data do not exist at broad scales. While fire scars or pollen records can be used to reconstruct historical fire frequencies, they cannot be used to reconstruct historical fire perimeters or fire sizes. Atlases of fires over time have been compiled for some areas, but the temporal scale is relatively short (Rollins and others 2001). Fire size data from recent decades are available for most of the nation, but these data reflect fire size distributions during an era where fire suppression was common, and thus these fire sizes may not be representative of historical conditions. Moreover, NIFMID data – the only source for nationwide fire data – further compound this problem by including double reports of fires and excluding reports of small fires. Further complicating the attempt to compare historical fire size estimates with fire sizes simulated by LANDSUMv4 is the fact that the model does not simulate small fires. Due to the spatial scale of input data and model efficiency, no fires smaller than 1 ha are simulated. This exclusion removes a portion of the

Table 4—Mean percentage of stand-replacing fire (SRF), mixed-severity fire (MSF), and non-lethal surface fire (NLSF) for each potential vegetation type (PVT) for Zone 19 calculated from the simulated fire severity maps (SIM MEAN) and the vegetation pathways (PATH MEAN). For each severity type, the simulated mean was calculated by taking the mean of the percentage value reported on the severity map for each pixel across each PVT. The pathway mean is the mean of the probabilities for the severity type for each succession class in each PVT weighted by the percent area of the PVT occupied by each succession class over all 200 reporting intervals.

	SRF		MSF		NLSF	
PVT NAME	PATH MEAN	SIM MEAN	PATH MEAN	SIM MEAN	PATH MEAN	SIM MEAN
Alpine	86.9	100.0	0.0	0.0	0.0	0.0
Bluebunch Wheatgrass	100.0	100.0	0.0	0.0	0.0	0.0
Bluebunch Wheatgrass / Conifer	100.0	99.9	0.0	0.0	0.0	0.0
Douglas-fir / Douglas-fir	32.0	46.4	24.2	24.5	28.3	27.6
Douglas-fir / Lodgepole Pine	33.0	45.7	20.7	21.5	32.4	31.3
Douglas-fir / Ponderosa Pine/ Douglas Fir	21.4	29.2	7.1	7.0	64.6	62.4
Douglas-fir / Timberline Pine	71.3	84.1	3.1	2.9	12.2	11.5
Douglas-fir / Ponderosa Pine/ Western Larch	26.1	34.8	7.2	7.2	58.5	56.6
Dry Shrub	100.0	100.0	0.0	0.0	0.0	0.0
Dry Shrub / Conifer	99.2	98.6	0.8	0.7	0.0	0.0
Dwarf Sagebrush Complex / Conifer	100.0	99.9	0.0	0.0	0.0	0.0
Dwarf Sagebrush Complex	100.0	100.0	0.0	0.0	0.0	0.0
Fescue Grasslands	100.0	100.0	0.0	0.0	0.0	0.0
Fescue Grasslands / Conifer	100.0	99.9	0.0	0.0	0.0	0.0
Grand Fir - White Fir	26.6	34.2	23.1	25.4	38.5	38.9
Lodgepole Pine	37.2	62.2	24.0	25.4	12.0	10.9
Mountain Mahogany	99.7	99.3	0.3	0.1	0.0	0.0
Mountain Big Sagebrush Complex/Conifer	84.8	99.0	0.5	0.3	0.0	0.0
Mountain Big Sagebrush Complex	100.0	100.0	0.0	0.0	0.0	0.0
Ponderosa Pine	28.8	33.4	6.7	6.6	59.7	58.6
Riparian Hardwood	47.1	50.0	0.0	0.0	45.7	49.0
Riparian Shrub	66.5	60.7	33.5	38.3	0.0	0.0
Rocky Mountain Juniper	99.4	98.9	0.6	0.4	0.0	0.0
Spruce – Fir / Montane/ Douglas-fir	37.3	53.8	24.1	24.6	20.7	20.1
Spruce – Fir / Subalpine	47.1	67.7	22.1	24.7	7.3	6.1
Spruce – Fir / Timberline Pine	59.0	78.3	13.0	14.1	7.0	6.1
Spruce – Fir / Montane/ Western Larch	31.1	38.9	27.4	29.0	31.7	30.7
Threetip Sagebrush / Conifer	99.6	99.3	0.4	0.2	0.0	0.0
Threetip Sagebrush	100.0	100.0	0.0	0.0	0.0	0.0
Timberline Pine / Limber Pine	82.3	97.1	0.7	0.5	1.9	1.6
Timberline Pine / Whitebark Pine	71.8	94.3	2.6	2.5	2.4	2.0
Western Redcedar	34.3	44.2	25.3	28.5	25.7	25.8
Wetland Herbaceous	100.0	100.0	0.0	0.0	0.0	0.0
Wyoming – Basin Big Sagebrush Complex/Conifer	100.0	99.8	0.0	0.0	0.0	0.0
Wyoming – Basin Big Sagebrush Complex	100.0	100.0	0.0	0.0	0.0	0.0

left end (small fires) of the fire size distribution curve, which is where the largest numbers of fires occur. This effectively increases the simulated mean fire size.

Even though the fire probabilities are estimates only and have inherent problems, we can assume that the simulated MFRIs approach the fire frequencies in the vegetation pathways that were used to parameterize the model (if the model is functioning properly). There are several possible reasons for the differences between the expected MFRIs and the simulated MFRIs, including 1) the role of the pathway fire probabilities in ignition and spread, 2) the spread of fire from PVTs with different fire probabilities, and 3) incorrect model parameterization.

First, the fire probabilities in the pathways represent the likelihood that a point on the landscape will burn given a particular PVT/succession class combination. These probabilities consider both ignition and spread. In LANDSUMv4, ignition and spread are simulated separately, and the fire probabilities influence only fire

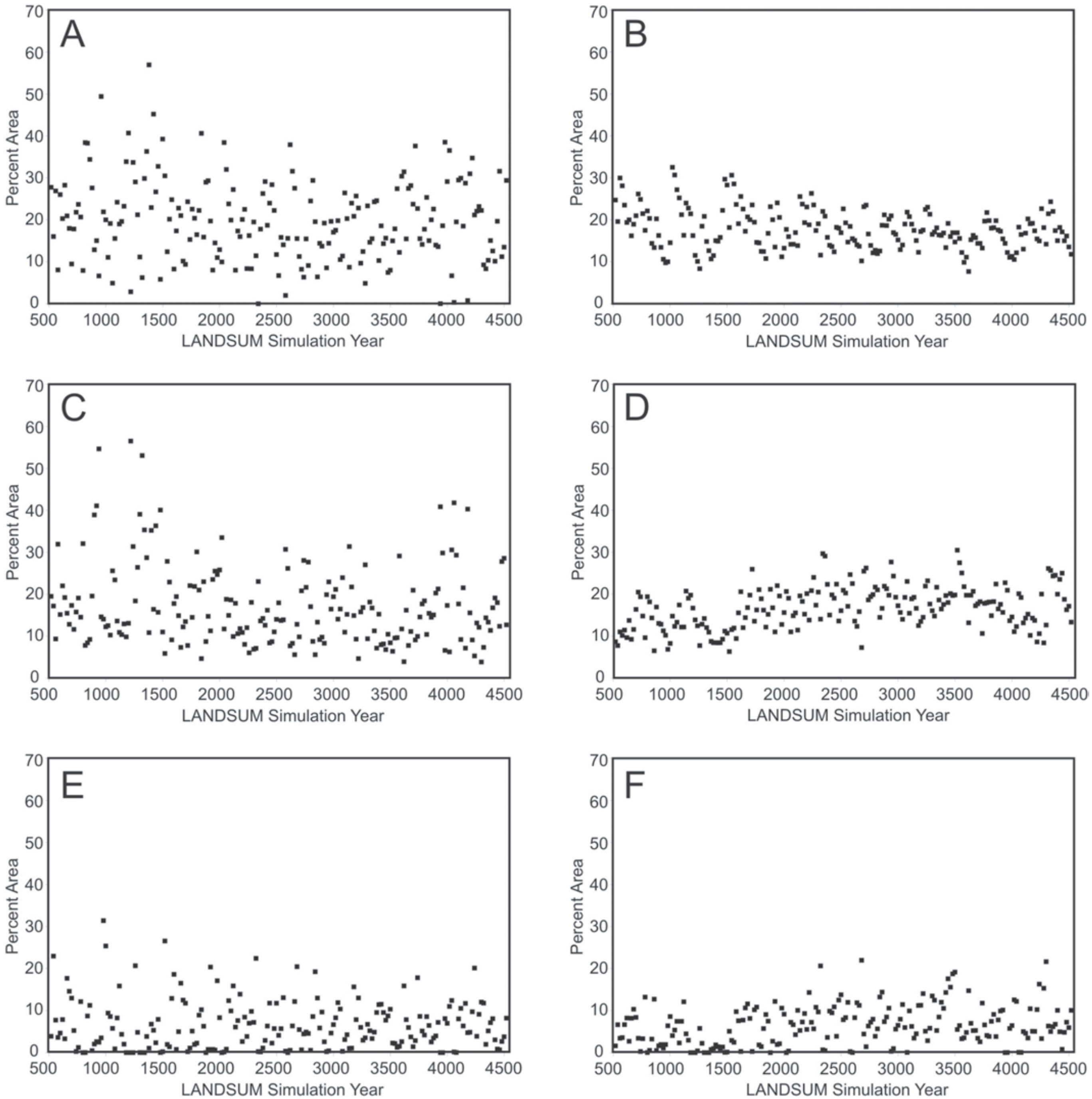

Figure 9—Percent area occupied for each of the top six succession classes in the Lodepole Pine PVT by reporting year for Zone 16. Succession classes shown are a) Aspen - Birch Low Cover, Low Height Forest; b) Aspen - Birch High Cover, Low Height Forest; c) Lodgepole Pine Low Cover, High Height Forest; d) Aspen - Birch Low Cover, High Height Forest; e) Aspen - Birch High Cover, High Height Forest; and f) Lodgepole Pine High Cover, High Height Forest.

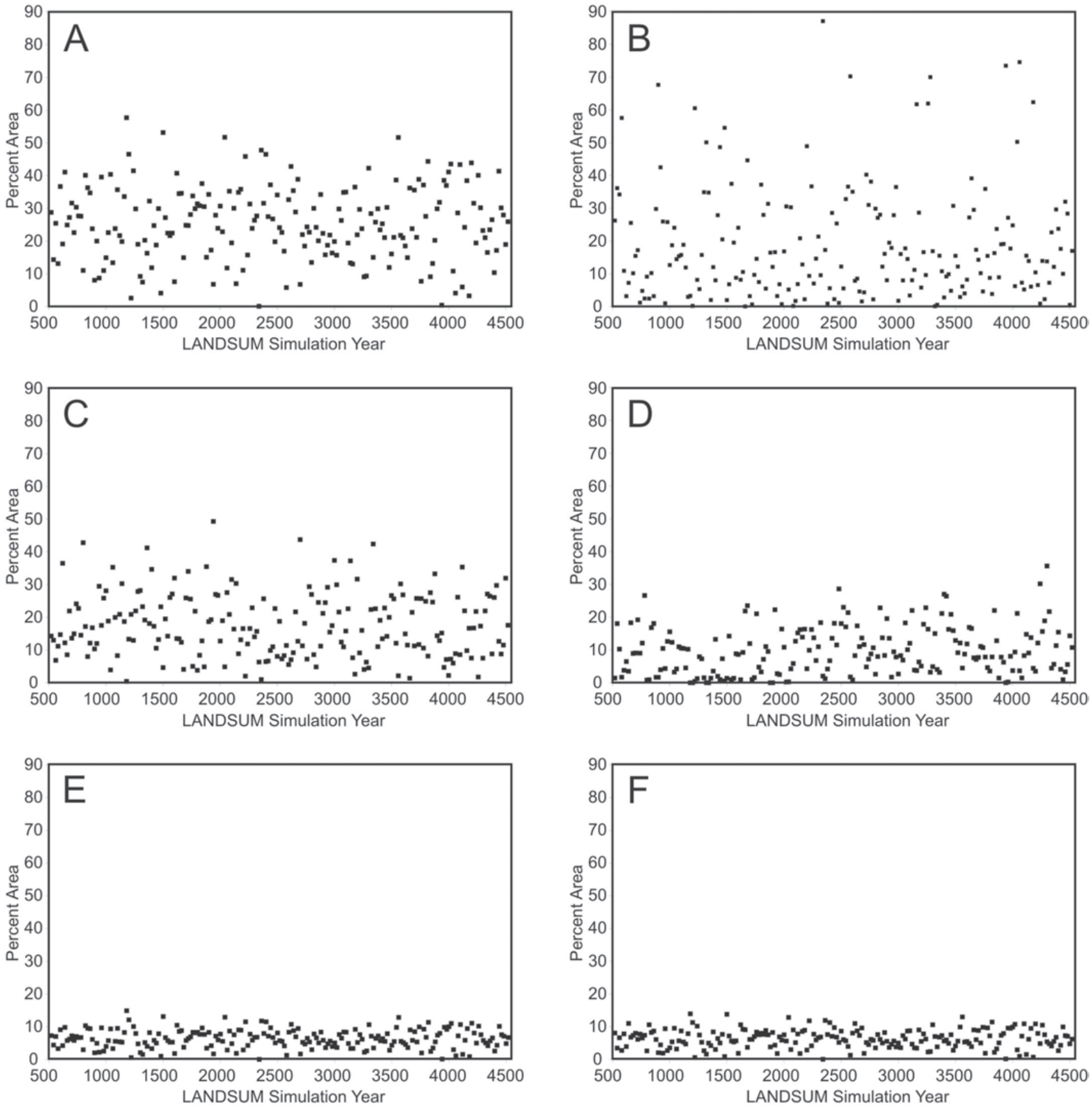

Figure 10—Percent area occupied for each of the top six succession classes in the Mountain Big Sagebrush PVT by reporting year for Zone 16. Succession classes shown are a) Mountain Big Sagebrush Low Cover, Low Height Shrubland; b) Cool Season Grasses Low Cover, Low Height Herbaceous; c) Cool Season Grasses High Cover, Low Height Herbaceous; d) Mountain Big Sagebrush High Cover, Low Height Shrubland; e) Mountain Deciduous Shrub Low Cover, High Height Shrubland; and f) Dry Deciduous Shrub High Cover, Low Height Shrubland.

ignition. Once ignited, fire spread is controlled by wind and slope and can spread equally to all PVTs. Neither vegetation nor associated fire probabilities (estimated from the literature and fire history studies) influence where a fire burns. A PVT with a low fire probability could therefore have many pixels that burn as a result of fire spread, which could cause the simulated MFRI to be quite different than the expected MFRI.

The effect of spatial adjacency on the simulated MFRIs is also related to how fire spread is modeled in LANDSUMv4. Because fire can spread to any adjacent pixel that is burnable, areas adjacent to those with high fire probabilities will tend to burn more often than expected based on the fire probabilities in the pathways. In addition, topography influences fire spread in that areas upslope will burn more often than areas downslope. If MFRI were determined only by fire probabilities for each PVT, we would expect the map in figure 11b to look very similar to the map in 11a. In figure 11a, there are areas with high fire probabilities at the southern end of many of the drainages. In figure 11b, this high fire probability continues up most of the drainage as a result of fire spread, causing shorter MFRIs than expected in vegetation with lower fire probabilities. The fact that so much of the area in figure 11b has shorter MFRIs than expected suggests that fire spread is overwhelming the underlying fire probabilities. This supposition is supported by the observation that the mean fire size simulated by LANDUSMv4 in our test areas using the model parameters for both Zone 16 and Zone 19 was considerably larger than the NIFMID estimate (fig. 4).

In addition, incorrect estimations of the parameters that control fire ignition and fire spread could result in shorter than expected MFRIs. The fact that the simulated MFRIs were shorter than the pathway MFRIs for most PVTs in Zone 16 and many PVTs in Zone 19, combined with the fact that the average fire size was so much larger than any estimates we have for this area, indicates that the fire parameters we used resulted in too much fire on the simulation landscape. Although the fire parameters used in Zone 19 resulted in general correspondence between the simulated MFRIs and the expected MFRIs in our test landscapes, the average simulated fire sizes for these landscapes using these parameters were still much larger than the NIFMID estimate (fig. 4). The spread scale parameter will likely have a stronger influence on the overall fire frequencies because far more pixels will burn as a result of fire spread than fire ignitions. When the simulated fire sizes are too large, the spread of fire and the effect of PVT adjacency may have a disproportionate influence on simulated MFRIs. Keane and others (2003) found that an error of 20 percent in estimating the spread scale parameter could result in an error of more than 50 percent in the fire return interval. The average fire size for all the test simulations in both zones varied with the spread scale parameter (fig. 4). The relationship of the spread scale parameter to the simulated average fire size is directly related to the shape parameter for the maximum fire size equation of the fire spread algorithm (3.0 for LANDFIRE simulations). We did not examine the effect of the shape parameter on the simulated average fire size or on the correspondence of simulated and pathway MFRIs. Although our test simulations were informative, more research is needed as to the effect of these crucial parameters and how they can best be estimated for a particular landscape.

Scale and complexity in fire simulation—Even if sound historical data for estimating fire parameters were abundant, differences between simulated fire regimes and actual historical fire regimes are to be expected. Fire, like many natural processes, is complex. Any attempt to model it is a simplified abstraction of the actual process. Fire operates at many different spatial and temporal scales. Its occurrence is influenced by many factors, such as vegetation, weather, wind, topography, and climate, 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 execute for large landscapes and over long simulation periods. Fire simulation in LANDSUMv4 incorporates mainly large-scale processes. The weather parameters in the model function at a yearly time-step and are generalized for the entire zone. Wind speed and direction are also parameterized for the entire zone and then varied by time–step; they are not varied locally for each fire event (Keane and others 2006). The model does not incorporate daily or localized weather information. Fire ignition is tied only to vegetation in terms of succession class changes, which operate at a coarser grain than fuel build up, and ignition probabilities are constant within a succession class. The most important limitation of the LANDSUMv4 model is absence of the close linkage between fuel, weather, and topography when determining fire effects and pattern (Keane and others 2006). Fire is spread solely on the basis of wind and topography. 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. Integrating fine-scale processes of weather or fuel into the model would make the model computationally intensive and

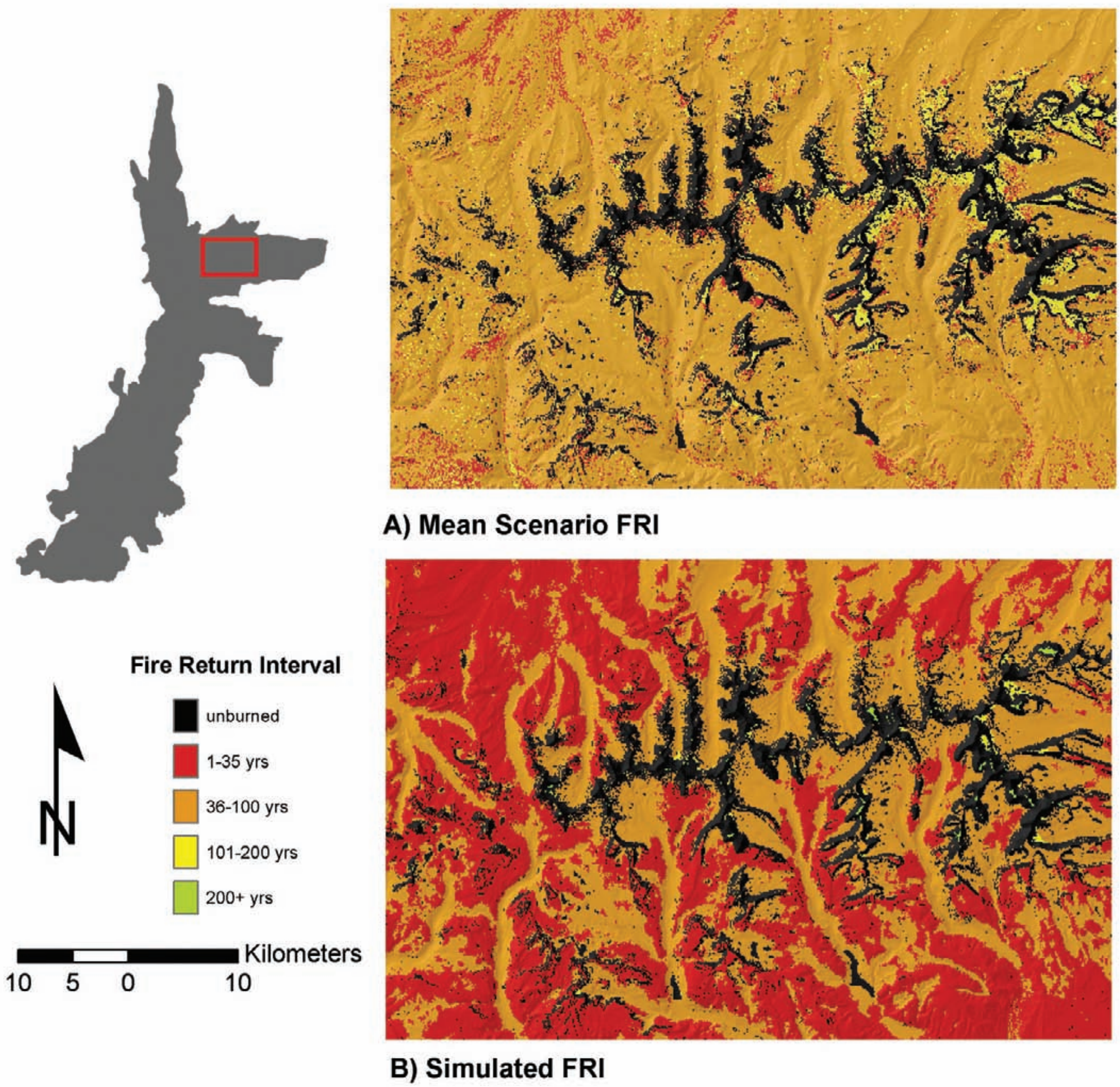

Figure 11—Comparison of mean fire return intervals a) calculated from the probabilities in the vegetation pathways and mapped to the potential vegetation type and b) simulated by LANDSUMv4 during the 4,500-year simulation period for Zone 16. Fire was much more frequent in fire regime maps derived from the spatial simulation of fire in LANDSUMv4 than in maps based solely on the aspatial fire regime information contained in the vegetation pathways.

would dramatically increase the complexity and length of the model executions. Furthermore, estimating even the most generalized fire parameters is difficult, as discussed above. Parameterizing the model for fine-scale processes would be even more difficult, and the problems inherent in estimating these values for historical conditions (on which we have limited data) would result in limited returns for considerable time and effort. It is important to understand that the fire regime results from the model are general and not intended to be applied at the pixel level or yearly time-step at which the model operates.

Fire spread and the simulation landscape—As noted above, we had to simulate each of the mapping zones as a series of smaller simulation landscapes for more efficient processing of the model. One of the problems in defining simulation landscapes lies in the fact that the simulation landscape edges create artificial boundaries that fires cannot traverse. In actual landscapes, water, rock, and topography create real boundaries and influence fire spread, but our simulation landscapes did not follow natural boundaries and sometimes even divided areas of homogeneous vegetation or topography through which fire would naturally spread. This problem is obvious if the simulation landscape is not large enough relative to the size of the larger fires as more fires will tend to run into the arbitrary boundaries of the simulation landscape, and fire will thus not be realistically simulated. Knight (1987) recommends the simulation area be 5 to 10 times the size of the largest fire, whereas Baker (1992) suggests 50 to 100 times the average fire size. Based on estimates of average fire size from NIFIMID, the simulation landscape for both zones should be about 3000 ha. However, using maximum fire size estimates from NIFMID, the simulation landscape should be about 35,000 ha for Zone 16 and 100,000 ha for Zone 19.

Another problem arose from the fact that areas near the edge of the simulation landscape have a limited number of surrounding pixels from which a fire can spread. This problem was exacerbated by wind direction. A single wind direction (60 degrees, randomly varied ±45 degrees) was used for the entire simulation and, because fire is spread by wind and slope, all fires tended to spread from the west-southwest to the east-northeast. As a result, pixels near the south and west edges had the lowest probability of burning, while those near the north and east edges had the highest probability of burning.

As noted above, a 3-km buffer area was placed around each 20,000 ha context area to create the simulation landscape and to decrease the edge effect in the context area or the area from which the reference conditions are defined (fig. 3). If the buffer area is large enough, the position of pixels within the landscape relative to the edge will not influence the chance of burning, and fire frequency will be determined by the input fire probabilities and topography. Areas that were simulated twice, once as part of the buffer and once as part of the context area, proved useful for examining the function of the buffers. Fire probabilities and topography were constant between the two runs, but the position of the pixels relative to the landscape edges changed (fig. 12). Fire should be realistically simulated in the eastern buffer region because most fires burned from the direction of the southwest. If the buffer is large enough, fire should also be realistically simulated in the context area as the buffer should provide an adequate source for fires to spread from the west. If the buffer width is adequate, therefore, the fire frequency in the eastern buffer region should not be substantially different from the fire frequency for this same region when it is part of the context area. However, as shown in figure 12, there still tended to be differences –sometimes by 20 or more fires – between these two areas. This indicates that the 3-km buffer may not be large enough to eliminate the edge effect. We are conducting a more detailed analysis of model behavior with respect to the sizes of the context and buffer areas, which will be used to inform future decisions regarding the simulation landscape.

Selecting simulation time parameters—Another challenge lies in the selection of simulation time parameters that result in efficient model execution over mapping zones while allowing sufficient initialization periods to reduce significant trends in the vegetation. We allowed for a 500-year initialization period before actually collecting data from the model for each mapping zone. In evaluating the vegetation chronosequences for both zones, we found that some succession classes in some PVTs continued to have noticeable trends beyond this 500-year period (fig. 13). Some succession classes had distinct upward trends over thousands of years, others trended downward, and yet other succession classes varied around a mean, as expected. Use of an initialization time that is long enough to allow all succession classes to reach equilibrium is not logistically possible because it would extend total simulation times beyond a reasonable length. Assigning the dominant succession class from the current conditions to each PVT for the initial landscape may have increased the time required to reach equilibrium for some PVTs. In addition, the complexity of the vegetation pathway may also impact initialization time as pathways with more succession classes may take longer to reach equilibrium. More research is being conducted to study the effect of

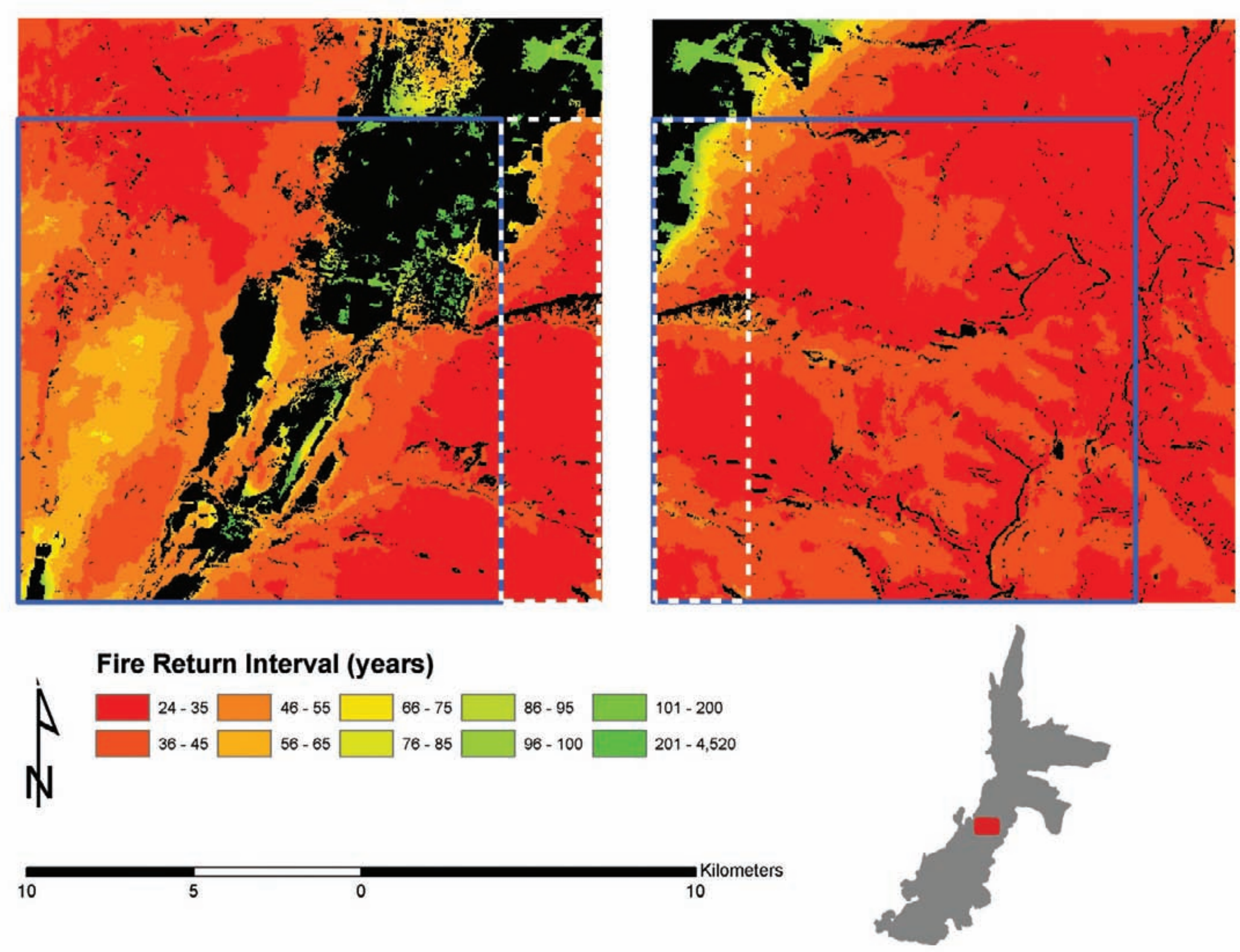

Figure 12—Mean fire return intervals for two adjacent context areas and their north and east buffer areas. The area inside the dashed rectangle is simulated in both landscapes and then smoothed using the mosaic command in ArcInfo. Differences in fire return intervals in the area simulated twice are due to the difference in the amount of the simulation landscape to the south and west from which fires can immigrate.

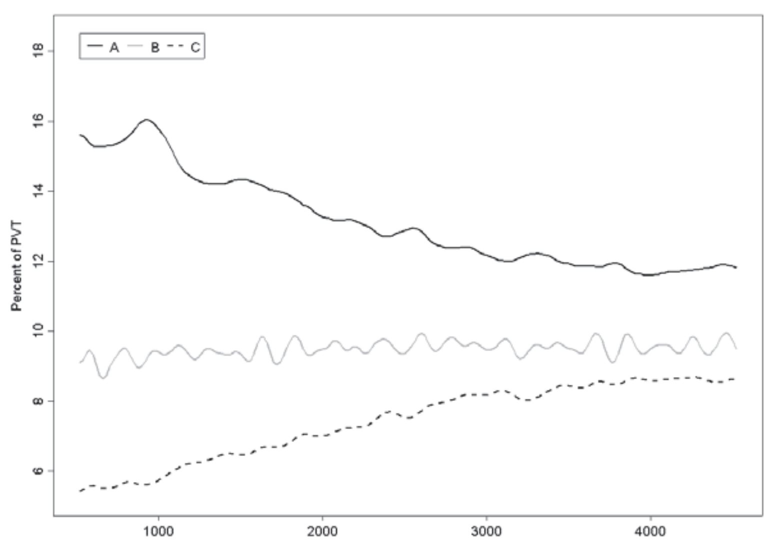

Figure 13—Succession class time series data smoothed using a 20-year lag for succession classes in the Spruce – Fir / Spruce – Fir PVT in Zone 16. Succession classes shown are A) Aspen - Birch High Cover, Low Height Forest; B) Aspen - Birch High Cover, High Height Forest; and C) Douglas-fir High Cover, High Height Forest.

autocorrelation and succession class trends on LANDSUMv4 output and the subsequent departure and FRCC calculations. These results will be used to mitigate the effects of these issues in LANDFIRE National.

Benefits of the Simulation Approach for Describing Historical Conditions

Although simulation models in general and the LANDSUMv4 model in particular have limitations, simulation modeling is still a useful, and perhaps the most viable, approach for generating historical reference conditions of vegetation and fire regimes across the entire nation. While data on actual historical conditions are limited, simulation modeling can estimate the reference conditions efficiently and in a consistent manner across the United States. Simulated historical reference conditions are not intended to replace actual historical data where they exist, but they can provide information where it is currently lacking.

In addition to effectively increasing the spatial extent of empirically derived historical reference conditions, simulation modeling can increase the temporal depth. Although the fire and climate data used to parameterize LANDSUMv4 are taken from historical databases and represent a narrow time frame, data can be simulated for much longer time spans (Keane and others 2003; Keane and others 2002b). It may seem problematic to simulate fire and landscape dynamics over millennial simulation periods while holding climate and fire regimes constant. This would be true if the objective of LANDSUMv4 modeling was to replicate historical fire events. However, the primary purpose of LANDSUMv4 modeling efforts is to document the historical variability of vegetation conditions and fire regimes across landscapes. This documentation of the entire range and variation of landscape conditions and processes serves the important purpose of allowing current conditions to be compared against a realistic and comprehensive reference database. Wherever possible, the modeling effort uses the results of fire history studies to parameterize the models, even though these represent a small duration of time. We selected the last three to five centuries as our reference time span because it is an era for which fire history data are available and is likely the most climatically similar to the present and near future. However, the fire events that actually occurred during this time frame represent only one unique sequence of fire occurrences, and the timing of these events created the unique landscapes observed today. This sampled fire history represents only one record of events. If these events had occurred according to a different timetable or in different locations, an entirely new set of landscape conditions may have resulted. It follows then that documentation of landscape conditions derived solely from historical records would tend to underestimate the variability of conditions that a particular landscape could have experienced and will experience in the future. We therefore attempted to quantify the entire range of conditions by simulating the static historical fire regime for thousands of years. We assume that 3,000 to 5,000 years is a long enough span from which to approximate all the conditions this historical landscape would have experienced. We determined that this is the best way to estimate historical reference conditions because it allows future landscapes to have variable fire ignitions and fire patterns. Despite its limitations, LANDSUMv4 creates the ability to generate a consistent and comprehensive set of data from which to estimate historical reference conditions across the entire nation.

Recommendations for National Implementation

Simulation Landscape Size and Shape

Much of the LANDSUMv4 modeling effort for the LANDFIRE Prototype involved balancing the need for realistic simulations of fire and vegetation dynamics with the often conflicting goal of computational and logistical efficiency, and balancing these two goals will present an even greater challenge as methods are applied for national implementation. We have found that larger simulation landscapes are logistically simpler and produce better simulation results overall, but there is likely some specific landscape size at which the model becomes inefficient and overall processing time to complete a zone increases dramatically. The 20,000 ha landscapes used in the prototype simulations were likely too small, given the expected size of large fires for these regions. We recommend that simulation landscapes larger than 20,000 ha be used for national implementation. Larger landscapes may result in more realistic simulations by reducing the impact of the edge effect and increasing the simulation landscape size relative to the size of the larger fires. At the same time, such landscapes may decrease processing time by reducing areas of overlap and simplifying the logistics involved in a large number of model executions. Tests on 100,000-ha landscapes for Zone 19 demonstrated that these landscapes are, given our current computing resources, too large to run the model efficiently with landscape and pathway complexities similar to those of the prototype effort. Simplified pathways and an improved computing platform could alleviate this problem and allow the simulation of sufficiently large landscapes.

Square simulation landscapes worked well, reducing overlap and simplifying processing. While square landscapes create unnatural landscape edges and fire breaks, the use of buffers mitigates this effect. Although the 3-km buffer we used did help to reduce the edge effect, this buffer may be too small; however, a larger buffer will increase overall processing time as the area of overlap increases (leading to more areas of the landscape that will be simulated twice). Overall, we recommend continuing with square simulation landscapes and using a 5-km buffer to better allow for simulation of fire spread without substantially impacting the total processing time.

Simulation time is another important aspect of the simulation design that impacts the balance between efficiency and realism. The 10,000-year simulations used for Zone 19 appear sufficiently long although the 500-year initialization period may not be adequate for some systems. We recommend simulations of 10,000 years and recommend increasing the initialization period beyond 500 years to the extent possible given computing limitations. In addition, we recommend assigning the historically dominant succession class (rather than the current dominant class) to each PVT for the initial landscape in an attempt to reduce the time required to reach equilibrium.

Determining Model Parameters

In addition to the LANDFIRE Prototype research, past sensitivity analyses indicate that there are several parameters of particular importance to the simulation results that must be accurately quantified for the LANDFIRE National. The ignition average fire size parameter – especially the spread scale parameter – strongly influences fire frequencies and, in-turn, vegetation dynamics. As discussed above, the historical data available for estimating these parameters are limited. A consistent methodology is required for setting these parameters to achieve appropriate fire frequencies. We recommend more research be conducted on the role of the spread shape parameter in these relationships. The NIFMID database contains only information on recent fires, and therefore the fire size estimates based on these data have been affected by fire suppression. Taking this limitation into consideration, we nevertheless recommend starting with the NIFMID estimate as a target average fire size because it represents the only source of recorded data on fire size for the entire United States. Vegetation modelers and ecologists who develop the succession pathway models for LANDSUMv4 present another source of information for estimating historical fire sizes and fire regime parameters. These individuals are presumably familiar with local ecosystems and offer estimates of fire sizes based on their extensive experience in addition to a literature review conducted when developing the pathways. These estimates could be used in combination with the NIFMID information to establish a target average fire size. Until further research is completed, we recommend executing the model over several test landscapes and varying both parameters until the average simulated fire size approaches the estimated average fire size for the zone and the fire frequencies simulated for each PVT approach the probabilities set in the pathways.

Error-checking

Another key to efficient and accurate simulations lies in the development of a consistent methodology for testing the pathways and parameters established for a mapping zone to check for errors and problems before the entire zone is simulated. We found two main sources for problems related to LANDSUMv4 executions: inconsistencies or errors in the input data and problems or "bugs" in the code. LANDSUMv4's extensive error-checking routine scans the input data for inconsistencies between the various input files, which can cause problems during simulation. However, there are problems with the input data that the error-checking routine does not recognize as inconsistencies but may still lead to unexpected results. In addition, although the LANDSUMv4 model underwent an extensive de-bugging process, it is always possible that some new, unique circumstance will arise in a new mapping zone that will cause unexpected results. We recommend performing a thorough quality assurance and quality control (QA/QC) process for the pathways once they are developed by the vegetation modelers. Once the pathways have passed this QA/QC, three to five landscapes – distributed throughout the mapping zone and containing a variety of topography and PVTs – should be simulated. Vegetation and fire regime information should be summarized for these test simulations and given to the vegetation modelers (or other experts) to check for any unexpected results. If there are any suspicious results, further analysis should be performed to determine the source of the unexpected results before proceeding with simulations for the full zone. Results from the test landscapes do not always reveal problems that can develop when the entire zone is simulated. Because simulating an entire zone may take six weeks or more, we recommend developing a systematic way to periodically check the output from the individual simulation landscapes within the zone as they are completed.

Further Study

Finally, although the LANDSUMv4 model has been tested (Keane and others 2002a; Keane and others 2003) this testing was conducted with earlier model versions, on smaller landscapes, and using parameters different from those being used in LANDFIRE. And while the prototype effort has contributed much information concerning the parameterization of the model for the national implementation of LANDFIRE, it has also raised many questions. Extensive testing and revision of the LANDSUMv4 model has begun, focusing on the application of the model for LANDFIRE purposes and examining the effects and interactions of several simulation parameters, including simulation time, context and buffer sizes, and fire size parameters. Separate studies are also planned to evaluate issues of scale in summarizing the data and the effect of autocorrelation and trends in the vegetation output of LANDSUMv4 on the computation of departure and FRCC. It is our recommendation that the national implementation of LANDFIRE incorporate, to the extent possible, the information from these studies as it becomes available. Furthermore, the model and the key parameters should be tested as they are applied to different regions of the country.

Conclusion

The methods outlined in this chapter were successful in producing estimates of historical reference conditions for vegetation and fire regimes in a manner that can be applied consistently across the nation. While the methodology used for simulating reference conditions for the LANDFIRE Prototype was generally sound, we recommend that more research be conducted to facilitate a more thorough understanding of the effect of various parameters on model behavior. Furthermore, we propose that development of consistent methods for setting appropriate values for key parameters, particularly the fire spread parameters, before proceeding with national implementation be a top priority. Finally, it is extremely important to consider the assumptions and limitations of the simulation approach and LANDSUMv4 when applying the results of the model. When the strengths and limitations are carefully considered, the use of simulation modeling, and LANDSUMv4 in particular, appears to be an effective and feasible way to generate estimates of historical reference conditions for vegetation composition and structure and wildland fire regimes for large landscapes on a national scale.

For further project information, please visit the LANDFIRE website at www.landfire.gov.

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Appendix 10-A—Vegetation and Disturbance Dynamics Database

The Vegetation and Disturbance Dynamics Database (VADDD) is structured to store all vegetation and disturbance dynamics information used as input to LANDSUMv4. VADDD served as the primary reference for the codes and labels for all map unit classifications developed in LANDFIRE, including PVT, cover type, and structural stage. In addition, this database was designed to efficiently check for errors in the succession and disturbance information prior to input into simulation modeling and to provide a standardized set of LANDSUMv4 parameters for subsequent applications of the model in different settings.

The database is composed of two general components. The first set of tables is primarily for reference only and serves as lookup tables for the PVT, cover type, structural stage, succession class, and disturbance codes used in the modeling process. The second set of tables is used for creating the LANDSUMv4 inputs and describes succession and disturbance dynamics for each succession class, including subsequent effects and the probability of those effects occurring. The "VEGDEV" table contains important vegetation development information about every succession class by PVT, including successional development parameters and descriptors that quantify the pathways of successional development without disturbance. The "DISTURB_PARM" table quantifies the consequences of disturbance for a PVT/succession class combination and the "SCENARIO_PARM" table contains data regarding the probabilities of a particular disturbance occurring in a PVT/succession class combination.

App. 10-A: Table 1—Field names and descriptions for the potential vegetation type table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region ID number
PVTUnique	PVT ID number
PVTLABEL	Unique header to use as labels on graphs and tables
PVTNAME	Unique name to use for report writing and data file building
PVTDESC	Brief description of this type

App. 10-A: Table 2—Field names and descriptions for the cover type table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
COVTYPE	Unique cover type ID number
CTLABEL	Unique header to use as labels on graphs and tables
CTNAME	Unique name to use for report writing and data file building
CTDESC	Brief description of this type

App. 10-A: Table 3—Field names and descriptions for the structural stage table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
SSTAGE	Unique structural stage ID information
SSLABEL	Unique header to use as labels on graphs and tables
SSNAME	Unique name to use for report writing and data file building
SSDESC	Brief description of this type

App. 10-A: Table 4— Field names and descriptions for the succession class table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
SCLASS	Unique succession class ID number
COVTYPE	Unique cover type ID number
SSTAGE	Unique structural stage ID information
SCLABEL	Unique header to use as labels on graphs and tables
SCNAME	Unique name to use for report writing
SCDESC	Brief description of this type

App. 10-A: Table 5—Field names and descriptions for the disturbance type table in VADDD.

Field name	Field description
PROJECT	Project code
REGION	Region code
DISTURB	Unique disturbance type ID number
DISTLABEL	Unique header to use as labels on graphs and tables
DISTNAME	Unique name to use for report writing and data file building
DISTDESC	Brief description of this type

App. 10-A: Table 6—Field names and descriptions for the vegetation development (VEGDEV) table in VADDD.

Field name	Field description
PROJECT	Project ID number
REGION	ID number for geographical region
PVT	PVT ID number
SCLASS	Unique succession class ID number
BYEAR	Beginning year of this succession class
EYEAR	Ending year of this succession class
NEXT_SCLASS	Next succession class this class goes to once AGE > EYEAR
PROB	Probability that this transition will occur

App. 10-A: Table 7—Field names and descriptions for the disturbance parameter (DISTURB_PARM) table in VADDD.

Field name	Field description
PROJECT	Project ID number
REGION	ID number for geographical region
PVT	Unique PVT ID for this disturbance information
SCLASS	Unique succession class ID for this disturbance information
DIST	Unique ID number of disturbance or management action in question
GOTO_SCLASS	Ensuing structural stage resulting from this disturbance
PROB	Probability of this disturbance transition
NEXT_AGE	Successional age to set resultant succession class after this disturbance
AGE_INC	Number of years to add/subtract from pixel age

App. 10-A: Table 8—Field names and descriptions for the scenario parameter (SCENERIO_PARM) table in VADDD.

Field name	Field description
PROJECT	A unique ID naming the project application of these data
REGION	A unique ID naming a geographic management region to apply data
SCENARIO	The ID code of the scenario
PVT	Unique PVT ID for this disturbance information
SCLASS	Unique succession class ID for this disturbance information
DIST	Unique ID number of disturbance or management action in question
PROB	Probability of occurrence for this disturbance

Appendix 10-B

Values for LANDSUMv4 model parameters used in the Zone 16 and Zone 19 simulations and the information source used for estimating the parameters. In the source column, "Preliminary Testing" refers to parameters estimated from simulations done on several test landscapes (see *Methods* section for more information) and "LANDFIRE" refers to model execution parameters set to meet the needs of the LANDFIRE Project.

Parameter	Description	Zone 16	Zone 19	Source
Simulation time	Number of years to simulate	4520	10500	Preliminary Testing
Age initialization	Controls how age is assigned to initial stands (0 - use age in stand info., 1 - random, 2 - midpoint of stage, 3 - entered beg. age in PVT)	1	1	Keane and others 2002a
Reporting interval	Interval (yrs) to print results to output maps and tabular files	20	50	Preliminary Testing, Keane and others 2002a
Initialization time	Year to start recording output results to maps and tabular files	520	550	Preliminary Testing, Keane and others 2002a
Disturbance exclusion	Specifies which disturbance to exclude (0 - include all dist., 1 - exclude all dist., 2 - exclude all but fire)	0	0	LANDFIRE
Random number scheme	0 = different every time, 1 = repeatable random	0	0	LANDFIRE
Random number generator	0 = system, 1 = Ran1, 2 = Ran2	0	0	Keane and others 2006
Fire spread model	Model of spatial spread simulation (1 - cell automata, 2 - cookie-cut shapes, 3 - cell spread percolation)	3	3	Keane and others 2002a
Fire weather multiplier	Number of years that a dry, normal and wet year occurs in a decade (must sum to 10)	3/5/2	1/6/3	Palmer Drought Severity Index Reconstructions
Average fire size - ignition	Average fire size (ha) for ignition equation	90	30	NIFMID, Preliminary Testing
Wind simulation	Mode of wind simulation: 0 - same wind speed/dir. every year, 1 - vary by year, 2 - vary by fire, 3 - vary by time-step, 4 - vary by cell)	3	3	LANDFIRE
Wind speed	Average wind speed in meters per second	5	5	Expert Opinion
Wind direction	Average wind direction for a fire event (azimuths true north)	60	60	Expert Opinion
Fire ignition equation	Equation for computing probability of ignition (1 - Weibull)	1	1	Keane and others 2002a
Years since burn	Years since burn parameter for the ignition equation	3	3	Keane and others 2002a
Shape parameter - ignition	Shape parameter for the ignition equation	2	2	Keane and others 2002a
Fire size equation	Equation for computing fire size (1 - Pareto, 2 - lognormal, 3 - exponential, 4 - uniform, 5 - normal, 6 - extreme, 7 - negative exponential, 8 - logistic, 9 – let burn	7	7	Keane and others)2002a
Fire size distribution magnitude	Magnitude parameter for the fire size equation	30	10	NIFMID, preliminary testing
Fire size distribution shape	Shape parameter for the fire size equation	3	3	Keane and others 2002a