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RESEARCH ARTICLE

Determining landscape extent for succession and disturbance simulation modeling

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Abstract Dividing regions into manageable landscape units presents special problems in landscape ecology and land management. Ideally, a landscape should be large enough to capture a broad range of vegetation, environmental and disturbance dynamics, but small enough to be useful for focused management objectives. The purpose of this study was to determine the optimal landscape size to summarize ecological processes for two large land areas in the southwestern United States. We used a vegetation and disturbance dynamics model, LANDSUMv4, to simulate a set of nine scenarios involving systematically varied topography, map resolution, and model parameterizations of fire size and fire frequency. Spatial input data were supplied by the LANDscape FIRE Management Planning System (LANDFIRE) prototype project, an effort that will provide comprehensive and scientifically credible mid-scale data to support the National Fire Plan. We analyzed output from 2,000 year simulations to determine the thresholds of landscape condition based on the variability of burned area and dominant vegetation coverage. Results show that optimal landscape extent using burned area variability is approximately 100 km^2 depending on topography, map resolution, and model parameterization. Variability of dominant vegetation area is generally higher and the optimal landscape sizes are larger in comparison to those features determined from burned area. Using the LANDFIRE project as a case study, we determined landscape size and map resolution for a large mapping project, and showed that optimal landscape size depends upon geographical, ecological, and management context.

Keywords Scale · Fire · Simulation modeling · Forest succession · Vegetation and disturbance dynamics

Introduction

As interpretation of ecological processes and patterns ultimately depends upon the scale of analysis, the areal extent and spatial grain with which we observe and quantify ecological systems and conditions is of critical importance to landscape scale ecological studies (Allen and Starr

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1982; Wiens 1989). However, many studies fail to identify appropriate landscape scale characteristics for their projects. Others, out of necessity, define the spatial extent and resolution of their project by the extent and grain of available data and then evaluate ecosystem characteristics within that spatial domain (Mayer and Cameron 2003). Consideration of landscape scale is imperative for ecological and land management issues (Bailey et al. 1994; Bourgeron and Jensen 1994; Tang and Gustafson 1997; White et al. 2000). Indeed, many landscape ecological studies have emphasized this matter and focused on identification of landscape extents and spatial grains that accurately characterize ecological patterns or conditions using various methodologies including semivariance analysis (Meisel and Turner 1998), attractor reconstruction (Habeeb et al. 2005), similarity indices (Baker 1989) and range of variability (Wimberly et al. 2000).

Studies that address issues of landscape extent tend to ask questions that are essential to landscape ecology, such as: ‘How big is a landscape?’ or ‘How large must an area be to function as a landscape?’ (Forman and Godron 1986). This depends on the landscape characteristic under evaluation and the specific objective of the analysis. For example a bark beetle’s (*Coleoptera Scolytidae*) landscape might be intermediate in size (3 km^2) because callow adults fly about 1 km after emergence, whereas a much larger landscape might be needed (10^2 or 10^3 km^2) to study fire patterns (Turner et al. 1995). However, what if characteristics for defining a landscape were many and broad (e.g., vegetation composition and structure) and the context of evaluation vastly complex (e.g., determining the historical range and variability of all vegetation communities)? Specifically, what would be the appropriate area to evaluate changes in fire regime, vegetation composition, and stand structure in a regional context? It is difficult to determine an appropriate landscape extent or ‘‘footprint’’ for summarizing spatial attributes because interactions between fire, vegetation succession, and biophysical settings are complex and occur over several spatio-temporal scales (Baker 1989). For example, Wimberely et al. (2000) found that variation in landscape attributes increased with decreasing landscape extent. Clearly, landscape extent and map resolution must be selected so that they reflect the scale of the pattern forming processes of interest (Fortin and Dale 2005).

The LANDFIRE project is charged with the mapping of fire regime condition class (FRCC) across the entire US (Rollins et al. 2006; www.landfire.gov). FRCC is a three category ordinal index that describes how far the current landscape composition has departed from the range and variation of historical conditions (Hann 2004) (see http://www.frcc.gov for complete details). However, the value of FRCC is strongly scale dependent because it is greatly influenced by the spatial extent and resolution of the data that describes the ecological characteristics of the area under evaluation. For example, the variability of fire and vegetation area over time is often large for relatively small evaluation areas (Li 2002). Conversely, if a fire management treatment area comprised only a small portion of a large evaluation area, then results of the treatment might be undetectable. The LANDFIRE project needed to determine a landscape extent that would be small enough to detect subtle changes brought about by land management, but large enough to reflect the characteristic variability of important ecological processes such as fire, succession, and biophysical environment in the appropriate spatial context.

The challenge, then, was to identify an optimal landscape size and an appropriate data grain with which to summarize spatio-temporal dynamics of important ecosystem characteristics such that effects of management treatments and fires could be determined in a context that was both meaningful ecologically and applicable to land management planning. This study used simulation modeling to explore the influence of landscape extent and data resolution on the spatio-temporal dynamics of important ecosystem characteristics, such as fire size and vegetation succession class. The primary objective was to determine optimal landscape extent for summarizing ranges of historical ecosystem conditions used in the computation of representative FRCC estimates over the large regions mapped in the LANDFIRE project. This study also evaluated the influence of simulation parameters and model initialization on the selection of the characteristic landscape extent.

We initiated this study when the LANDFIRE prototype project (Rollins et al. 2006) found that to compute and map FRCC from the simulated range of historical variation in landscape composition across large regional domains, it was necessary to first define the size of the FRCC mapping unit (Pratt et al. 2006). The variability of simulated output was the metric that we used to find the appropriate extent (spatial domain) and resolution (pixel size) for describing simulated time series of historical landscape composition. We define the "optimal" landscape extent as the smallest spatial extent that minimizes the influence of artificial variance due to landscape size.

Background

The FRCC is an approximation of the departure of current conditions from a simulated range of historical conditions. The concept of historical range of variability (HRV) serves as the foundation to represent historical conditions in all FRCC calculations (Landres et al. 1999; Swetnam et al. 1999; Keane et al. 2002a). In this study, HRV is defined as the quantification of temporal and spatial fluctuations of ecological processes and characteristics prior to European settlement (1900). The central assumption is that the quantification of HRV can serve as an ecologically meaningful reference for computing the departure (i.e. direction and magnitude of changes) of current landscape structure and compositions from historical trends. To use HRV in an operational context, it was necessary to select an historical time span that best reflects the range of conditions to use as reference for the management of future landscapes; an assumption that may be overly simplistic because of documented climate change, exotic introductions, and human land use (Hessburg et al. 1999, 2000). For this study, we limited the temporal context of HRV to the time span from circa 1600 AD to 1900 AD as this period provides the historical data (fire scar chronologies) necessary to quantify simulation parameters.

HRV can be described from many ecological characteristics, and in this study, we selected landscape composition (percent abundance) as the primary evaluation criteria. We describe landscape composition as the area occupied by the combination of the Potential Vegetation Type (PVT) and succession class map units. A PVT identifies a distinct biophysical setting that supports a unique and stable plant community in the absence of disturbance under a constant climate regime (Daubenmire 1966; Pfister and Arno 1980). The succession class is represented by a combination of cover type (named for the dominant plant species based on canopy cover) and structural stage (defined by canopy cover and height stratifications). Structural stages represent linear progressions of stand development based on the classification of O'Hara et al. (1996) where low cover and height represent early successional stages and high cover and height represent late successional stages.

LANDSUMv4

The LANDscape SUccession Model (LANDSUMv4) was used to generate the simulated HRV statistics. It is a C++ program wherein vegetation development is simulated as a deterministic process and disturbances are modeled as stochastic, spatially explicit processes (Keane et al. 1997). LANDSUMv4, the fourth major revision of the original LANDSUM, was developed to simulate the historical landscape dynamics which quantify the historical range and variation of landscape characteristics used to calculate the FRCC (Keane et al. 1996, 2002b). The model uses a spatial state-and-transition succession approach where fire growth is simulated with a cell percolation module. The first LANDSUM was created by modifying the CRBSUM model (Keane et al. 1996), implemented at a 1 km pixel scale, to simulate succession at a polygon level (1–100 ha) (Keane et al. 1997). A spatially explicit fire spread algorithm was included (LANDSUM version 2.0) to explore the limitations and implications of using a simulation approach to describe landscape dynamics (Keane et al. 2002b). A simplistic climate driver was then implemented to create LANDSUM version 3.0 (Cary et al. 2006). The LANDSUMv4 version contains extensive refinements to the fire spread and successional development algorithms (e.g., improved ignition simulation, climate driver, and multiple effects pathways for a single disturbance) and options for generating historical time series information for LANDFIRE (e.g., fire atlas layers, a list of all fires and an output format compatible with statistical software) (Keane et al. 2006).

LANDSUMv4 simulates succession within a polygon (adjacent similar pixels) using the multiple pathway fire succession modeling approach presented by Kessell and Fischer (1981) and based on the seminal works of Noble and Slatyer (1977), and Davis et al. (1980). This approach assumes all pathways of successional development will eventually converge to a stable or quasi-climax plant community (PVT) (Fig. 1). There is a single set of successional pathways for each PVT present on a given landscape (Arno et al. 1985). Successional development within a polygon is simulated as a change in successional class (cover type-structural stage doublet) at an annual time step. The length of time a polygon remains in a succession class (transition time-years) is an input parameter that is held constant throughout the simulation. Disturbances disrupt succession and can delay or advance the time spent in a succession class, or cause an abrupt change to another succession class. Occurrences of human-caused and natural disturbances are stochastically modeled from input probabilities based on historical frequencies. All disturbances are simulated at a polygon level, except for wildland fire, which is spread across the landscape at a pixel level using a spatial cell automata. Fire is spread cell-to-cell based on vectors of slope (derived from an input digital elevation model, DEM) and wind (average speed and direction are input parameters) until it reaches a stochastically determined fire size calculated from an exponential function of fire size parameterized from average fire size inputs (Keane et al. 2002a). For full documentation of all LANDSUMv4 algorithms, along with model sensitivity and behavior analyses, see http://www.fs.fed.us/rm/pubs/rmrs_gtr171.pdf.

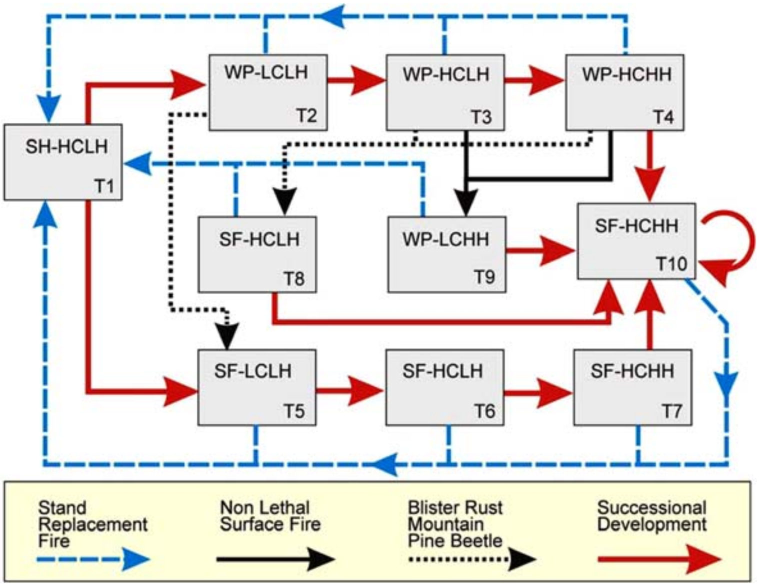

Fig. 1 A simplistic succession pathway in LANDSUMv4 where cover type and structural stage categories are linked along pathways of successional development based on shade tolerance. The terminal cover type (SF) is the Potential Vegetation Type (PVT) category because it represents the most shade tolerant tree species. Cover type names are as follows: mountain shrub (SH), whitebark pine (WP), subalpine fir (SF). Structural stage names are defined as: low cover low height (LCLH) early succession stage, high cover low height mid-seral stage (HCLH), high cover high height late succession stage (HCHH), low cover high height (LCHH) disturbance maintained late succession stage. T1-11 identify unique succession classes

Methods

Study areas

We implemented this study on two large landscapes (each approximately 75 × 75 km^2) chosen from within mapping Zone 16 of the LANDFIRE prototype project area (Fig. 2) (see Rollins et al. 2006 for more detailed information). Mapping zones were developed by the Earth Observation and Science (EROS) Data Center (http://www.nationalmap.gov). They are broad biophysical land units represented by similar surface landforms, land cover conditions, and natural resources; there are 66 in the continental U.S. The 'mountainous' landscape is situated in north central Utah's Uinta Mountains and the 'flat' landscape encompasses the town of Manti in the south central part of the state. These landscapes were selected to represent two large regions that differ in geography, topography, and ecology, but still lie within the same mapping zone.

The mountainous landscape is dominated by temperate coniferous forests of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) at lower elevations and lodgepole pine (*P. contorta*), subalpine fir (*Abies lasiocarpa*), and spruce (*Picea* spp.) at higher elevations. A spruce-fir cover type makes up just over 25% of the mountainous landscape, while other dominant cover types are: lodgepole pine (19%), aspen-birch (16%), and mountain big sagebrush (*Artemesia Tridentata vaseyana*) (12%). The following cover types each occupy between 1% and 5% of the mountainous landscape: Douglas-fir, pinyon-juniper, Wyoming Basin big sagebrush (*A. t.*

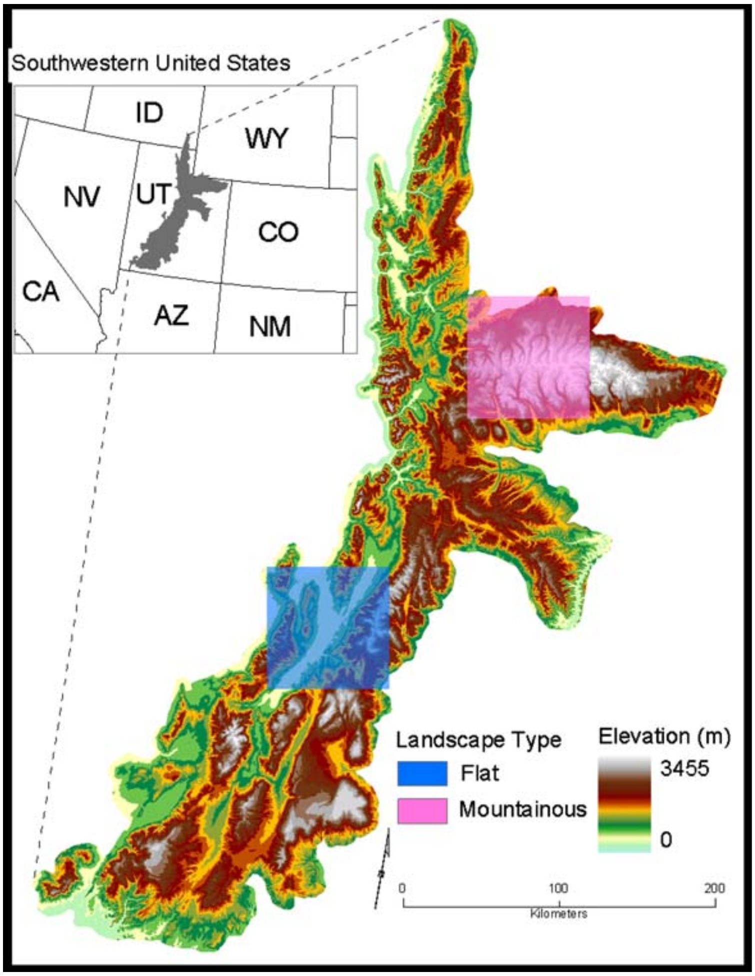

Fig. 2 The two simulation landscapes, flat and mountainous, shown within mapping Zone 16 of the LANDFIRE prototype project

wyomingensis), dwarf sagebrush (*A. t. scopulorum*), mountain deciduous shrub, riparian shrub, cool-season perennial grasslands, and open water. Barren and alpine environments on the ridges and high peaks of the Uintas cover about 9% of total mountainous landscape area. Though the mountainous landscape terrain primarily features steep topography, it includes areas that are hilly, undulating and flat.

The flat landscape is primarily comprised of cover types that tend to occur at low elevation in flat to rolling terrain; pinyon or pinyon-juniper covers over 30% of the landscape and each of the following cover types occupy between 5% and 10%: salt desert shrub, mountain deciduous shrub, Wyoming basin big sagebrush complex and agriculture. Mountain big sage, dwarf sage, rabbitbrush (*Chrysothamnus nauseosus*), perennial grasslands, urban, barren and open water cover types each occupy between 1% and 5% of the flat landscape. Because Utah topography is so diverse and the simulated landscape so large (over 5,500 km^2), it was impossible to center the nested landscape box on an area that was entirely flat. Consequently, grand fir (*A. grandis*), spruce-fir and aspen (*Populus tremuloides*) vegetation types, situated in small areas of foothills and mountains, cover between 5% and 10% of the flat landscape's total extent.

Model initialization and parameterization

The LANDSUMv4 input data layers required for this study were developed by the LANDFIRE prototype project. The DEM layer was taken from the National Elevation Dataset (http://www.nationalmap.gov). Creation of the input PVT map (Fig. 3) involved a supervised classification of an extensive field plot database and spatial modeling of over 50 biophysical data layers (Frescino et al. 2006). The cover type and structural stage layers for current conditions were developed from an integration of Landsat 7 ETM satellite imagery with the 50 biophysical layers

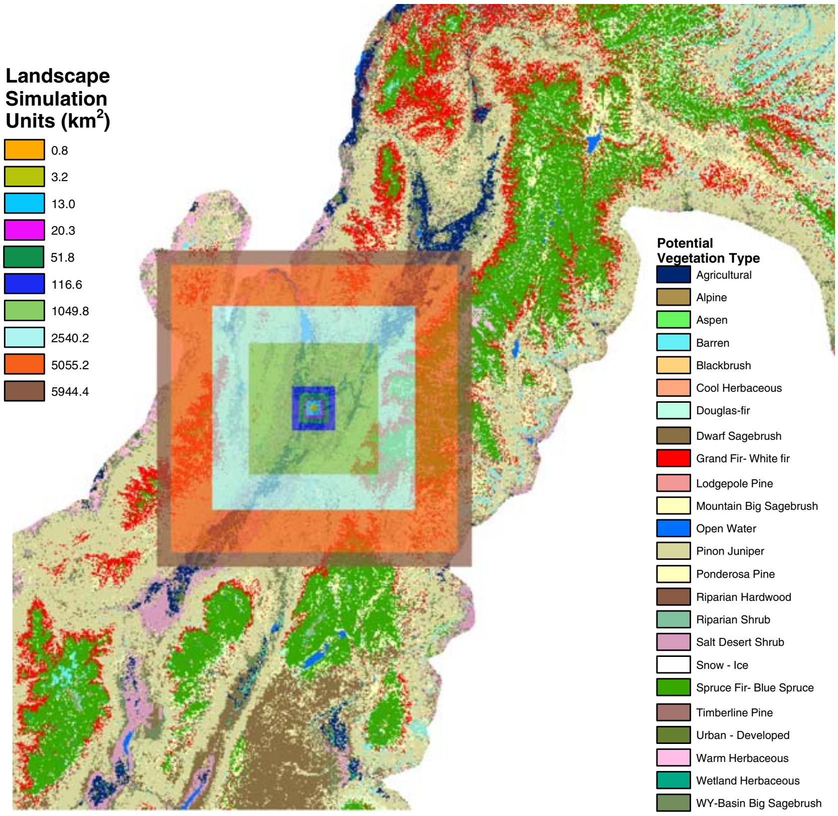

Fig. 3 The nested set of simulation reporting units centered on the flat landscape and draped on the LANDFIRE Zone 16 Prototype Potential Vegetation Type map. The same set of nine nested landscape sizes was used for the mountainous landscape

(Zhu et al. 2006). All input layers were developed at 30 m spatial resolution for the entire mapping zone (Fig. 2). Considering that previous studies evaluated LANDSUMv4 behavior and sensitivity and found that the initial landscape had no effect on simulated conditions after 300–500 years of simulation (Keane et al. 2002b, 2006; Pratt et al. 2006), we created initial conditions for the succession class map in the LANDSUMv4 simulations by assigning the most dominant succession class for each PVT across the landscape.

The LANDSUMv4 model was parameterized using the fire and succession information compiled by the LANDFIRE team for Zone 16 (summarized in Table 1, but see Long et al. 2006 for details). As mentioned, LANDSUMv4 was parameterized for LANDFIRE to simulate historical conditions representative of the 1600–1900 AD time span. Succession transition times were taken from extensive literature searches and stand development data, historical fire frequencies from fire history studies conducted within the general mapping zone, and fire size distributions from data compiled by Schmidt et al. (2002) which incorporates the National Interagency Fire Management Integrated Database (NIFMID) database and local fire records.

Simulation scenarios

The simulation design comprised nine nested reporting units selected to represent a range of landscape extents from very small (approximately 1 km^2) to very large (over 5,000 km^2), each sized to allow cells from four map resolutions to fit perfectly within box boundaries (Fig. 3). Around the largest landscape reporting unit we added a 3 km wide buffer to minimize edge effects and ensure that fires burn realistically into the largest landscape (Keane et al. 2001; Pratt et al. 2006). Simulated burned area and dominant vegetation area results were output from LANDSUMv4 for each of the reporting unit landscapes across the 2000 year simulation interval.

We included four levels of landscape resolution in our study design to investigate the effect of spatial grain on optimal landscape extent. We aggregated the original 30 m resolution landscapes by assigning the mean elevation value and modal PVT value to the three coarser resolution grids (90, 300 and 900 m per side). When the landscape size is 0.81 km^2 and landscape resolution is 900 m, only one pixel defines the entire reporting area.

Because disturbance frequencies and size distributions ultimately influence landscape composition over time (Turner et al. 1993), we varied

Table 1 Summary of key parameters used for the two simulation areas in the LANDSUMv4 simulations for the three most common potential vegetation types (PVT)

Most common PVT	Average fire probability	Average transition time (years)	Number of successional classes*	Initial successional class*
Mountainous landscape (33 PVTs)				
Spruce fir	0.00755	31	40	Spruce-fir HCHH
Mountain big sagebrush	0.04850	17	10	Mountain big sagebrush complex HCLH
Riparian shrub	0.00875	9	4	Riparian shrub HCHH
Flat landscape (31 PVTs)				
Wyoming-basin big sagebrush	0.01257	45	11	Wyoming-basin big sagebrush complex LCLH
Pinyon-junipe/Wyoming-basin big sagebrush	0.01396	32	20	Juniper LCLH
Pinyon-juniper/mountain big sagebrush	0.02587	28	18	Juniper LCLH

For full documentation of model parameters, see Long et al. (2006)

* Successional Class is represented by a combination of cover type and structural stage combination. Here, structural stage is abbreviated using a combination of four letters: C = Cover (%), H = height (m), L = low, H = high. For example, HCLH = High Cover Low Height

LANDSUMv4 fire parameters to quantify the effect of disturbance on the optimal landscape size, again using the burned area and vegetation composition time series. Two LANDSUMv4 parameters describe fire dynamics in any simulation: average fire size and fire ignition probability. We chose three levels of average fire size (0.01, 0.30 and 10.0 km^2) to represent a range of sizes for regions across the United States. The historical fire ignition probabilities quantified by the LANDFIRE prototype project represented the reference or historical fire probability set and they are quantified for every PVT-succession class combination input by the user. We then created another set of fire probabilities that were half the historical parameters (Table 1) and a third set that was double the historical parameters. We expected higher variance for simulations that had larger fires or more frequent fires because more area would be burned each simulation year.

We ran the LANDSUMv4 landscape fire succession model for each of the 72 factor permutations of topography (flat and mountainous), spatial grain (pixel sizes: 30, 90, 300 and 900 m per side), average fire size (0.01, 0.3, and 10.0 km^2), and ignition probability (half historical, historical, and double historical). LANDSUMv4 will only simulate a fire in a pixel if the fire size is greater than half the size of the pixel, so no output was generated for the factor combination 900 m resolution, 0.81 km^2 reporting unit, and 0.01 km^2 average fire. Results were summarized for nine landscape extents: 0.81, 3.2, 13.00, 20.30, 51.80, 116.60, 1,049.80, 2,540.20, and 5,055.30 km^2. A 3 km buffer surrounds the largest extent and brings the total area of the simulation landscape to 5,944.4 km^2 (Fig. 3).

To minimize the effect of initial conditions, we ran the model for a 500 year spin-up period before printing the first year of output, then burned area and dominant PVT-succession class area were output for each landscape size (nine reporting units) every 20 years thereafter for a total of 2,000 years. This yielded 100 data points per factor combination. Our choice of the 2,000 year simulation length and 20 year reporting interval allowed us to obtain enough data points to avoid temporal autocorrelation while minimizing lengthy simulation times (Keane et al. 2002b; Pratt et al. 2006). Exceptionally long model simulation times for the 30 m input layers precluded study replication (the 30 m resolution simulation sets each ran for over 1 month, 90 m resolution sets ran for approximately one week, and the 300 and 900 m resolution less than 1 day).

We used two diagnostic variables to determine optimal landscape extent from the set of reporting units: (1) $\ln(\sigma^2_{\mathrm{ba}})$, representing the natural log of variation throughout the simulation interval of the percent of each reporting unit area burned by fire and (2) $\ln(\sigma^2_{\mathrm{vg}})$, representing the natural log of variation of the percent of each reporting unit area occupied by the PVT-succession class combination that is present on all of the nested landscape reporting units; Wyoming Basin Big Sage (High Cover, Low Height) for the flat landscape, and Spruce-Fir (Low Cover, High Height) for the mountainous. The notation $\ln(\sigma^2)$ refers to both $\ln(\sigma^2_{\mathrm{ba}})$ and $\ln(\sigma^2_{\mathrm{vg}})$.

We chose to look at the variation of these factors because quantification of historical range and variation is important for landscape scale fire regime studies. We reasoned that until the landscape size is large enough that there is no longer a change in variance of the response variable (variance reaches a plateau when plotted against increasing reporting unit size), measurement accuracy will be compromised because values will be influenced by variation due to the size of the landscape rather than due only to natural fluctuations in the factor of interest.

To graphically summarize relative differences in variance between fire size, fire frequency and landscape resolution permutations, we plotted variance for all factor combinations through the range of landscape extents (Figs. 4, 5). Because there was a large range in raw variance values, we used a natural log transformation to mathematically compress the range of the data so that variance curves could be shown on the same charts. Also for display purposes, we truncated the curves to show only the first six landscape sizes, as the lines were generally flat through the largest landscape extents and the optimal landscape size was always under 500 km^2.

To determine optimal landscape size, $\ln(\sigma^2_{\mathrm{ba}})$ and $\ln(\sigma^2_{\mathrm{vg}})$, were evaluated across the range of

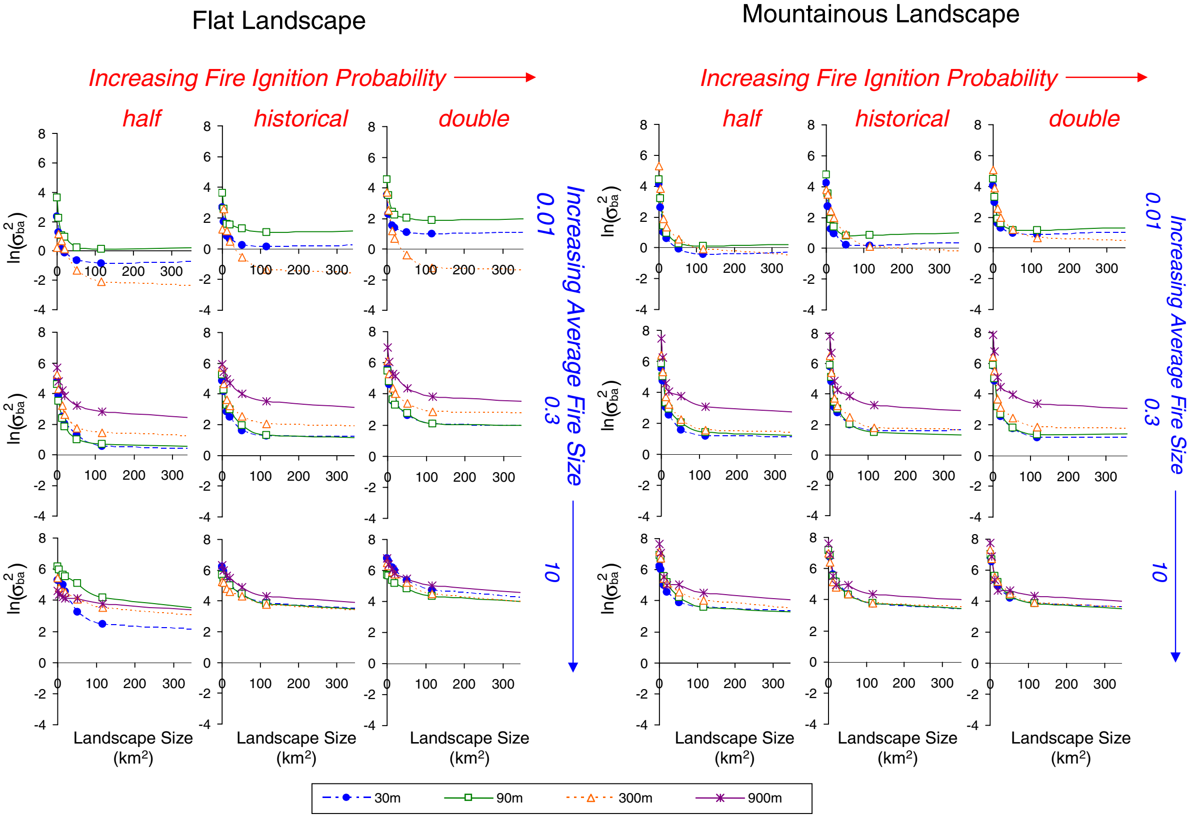

Fig. 4 $\ln(\sigma^2_{\mathrm{ba}})$ versus landscape size for the flat and mountainous landscapes. The three fire ignition probabilities (half, historical and double) are arranged in columns and the three average fire sizes (0.01, 0.3, and 10 km^2) in rows. As the curves remain quite flat for the largest landscapes, the x-axes are truncated to show only the first six landscapes

landscape sizes to locate the landscape reporting unit where the $\ln(\sigma^2)$ approaches an asymptote. We assumed that this point identified the landscape size where the variability of simulated diagnostic variables is least affected by the size of the reporting unit, so choosing a reporting unit of this size (or larger) to summarize simulated fire regime variables will minimize artificial variance. The curve fitting method that we used, a third order polynomial interpolation, consistently produced the best fit through our $\ln(\sigma^2)$-landscape size points. For a consistent and repeatable measurement, and to account for slight deviations from the general shape trend in a few of the curves, we defined the asymptote as the point where the slope of the interpolated curve first exceeds 0.005 percent^2 km^{-2} (a 0.5% or 0.29° angle). The corresponding x-axis value was then taken as the optimal landscape extent.

Results

The majority of the $\ln(\sigma^2)$-landscape size curves had a shape defined by very large $\ln(\sigma^2)$ values for small landscapes (~0–50 km^2), steep drops in $\ln(\sigma^2)$ in the intermediate landscape extents (~50–200 km^2), and a plateau after extents larger than approximately 200 km^2. There were slight deviations from this trend in a few of the curves due to greater variety of PVT-succession class combinations at large landscape sizes. Note that there are no results for the 0.01 km^2 average fire size in the 900 m resolution case, as the model

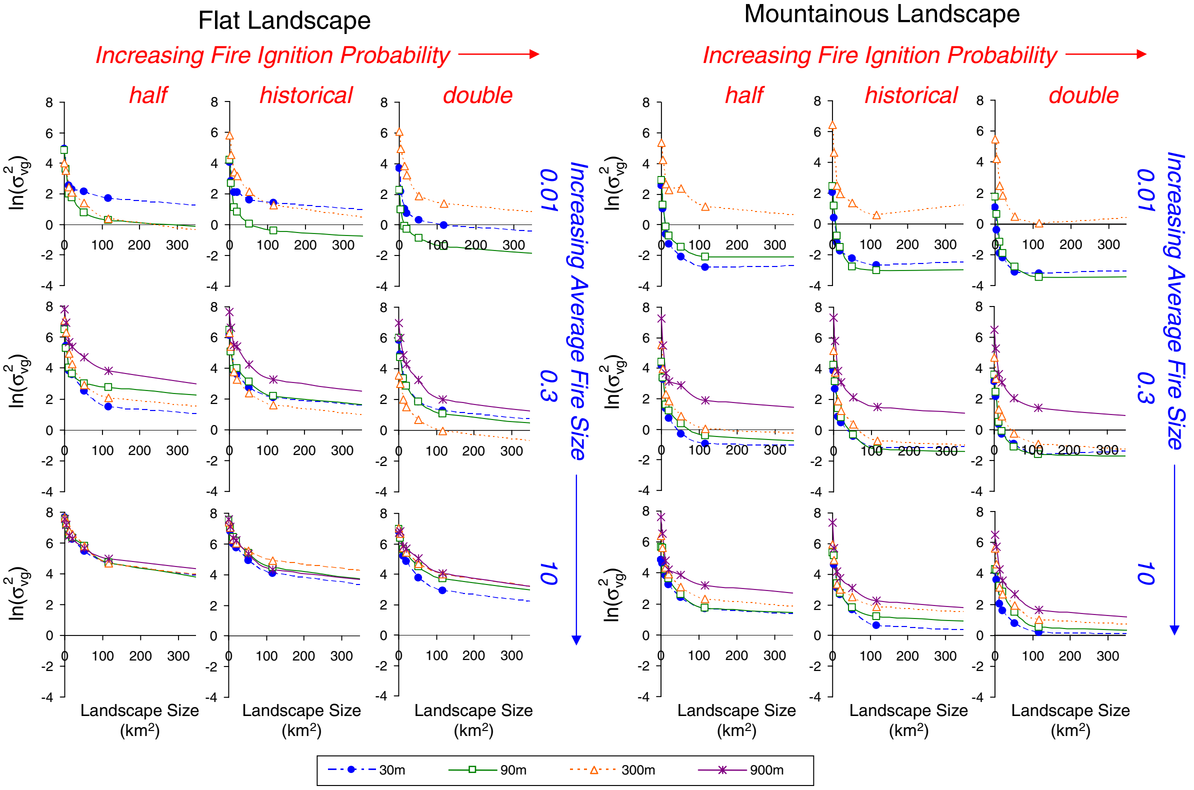

Fig. 5 $\ln(\sigma^2_{\mathrm{vg}})$ versus landscape size for the flat and mountainous landscape. The three fire ignition probabilities (half, historical and double) are arranged in columns and the three average fire sizes (0.01, 0.3, and 10 km^2) in rows. As the curves remain quite flat for the largest landscapes, the *x*-axes are truncated to show only the first seven landscapes

only ignites a fire in a pixel if the fire size is greater than half of the pixel size.

The relationship of $\ln({\sigma_{\mathrm{ba}}}^2)$ to landscape size is similar for both topographic types (flat and mountainous) across all landscape resolutions (Fig. 4) with the coarsest resolutions displaying the highest values. This relationship is also apparent for $\ln(\sigma^2_{\mathrm{vg}})$, through the range of landscape sizes (Fig. 5). For both flat and mountainous landscapes, the 900 m resolution simulation exhibited the highest $\ln(\sigma^2)$ and the highest optimal landscape sizes. Interestingly, there is very little difference between the 30, 90, and 300 m pixel resolution simulation $\ln(\sigma^2)$ curves for both burned area and vegetation class and for a number of landscape sizes and landscape types. The 30 and 90 m curves are particularly similar, while the coarser resolution curves (300 m) and especially the 900 m curves displayed notably higher magnitudes of $\ln(\sigma^2)$ (Figs. 4, 5).

LANDSUMv4 simulations with LANDFIRE historical fire regime parameterizations at 30 m resolution (simulation design used by the LANDFIRE project) produced $\ln(\sigma^2_{\mathrm{ba}})$ results that appear to approach an asymptote when the landscape reporting area is between 80 km^2 and 100 km^2 for both the flat and mountainous landscape types (Fig. 4). Indeed the specific optimal landscape for these simulation sets were 84 km^2 for the flat and 90 km^2 mountainous topographic types (Table 2). The $\ln(\sigma^2_{\mathrm{vg}})$ curve flattened further along the landscape size axis (Fig. 5) and the optimal landscape sizes were 106 and 112 km^2 for the flat and mountainous landscapes respectively (Table 3).

Table 2 Optimal landscape sizes (km^2) for various combinations of simulation scenarios—average fire size, fire frequency adjustments, terrain type, and resolution—using $\ln(\sigma^2_{\mathrm{ba}})$ as the diagnostic variable

Fire size (km^2)	Fire frequency	Resolution			
		30 m	90 m	300 m	900 m
Mountainous landscape					
0.01	Half	84	51	108	*
	Historical	50	47	108	*
	Double	46	47	100	*
0.30	Half	87	103	104	111
	Historical	90	99	105	108
	Double	100	103	101	106
10.0	Half	74	104	106	114
	Historical	106	102	106	113
	Double	84	95	103	106
Flat landscape					
0.01	Half	56	51	107	*
	Historical	49	78	107	*
	Double	47	36	107	*
0.30	Half	107	73	72	81
	Historical	84	104	97	98
	Double	100	105	101	99
10.0	Half	108	116	111	108
	Historical	96	108	108	107
	Double	109	106	113	92

* There are no results for the 0.01 km^2 average fire size and the 900 m resolution simulation combination

Table 3 Optimal landscape sizes (km^2) for various combinations of simulation scenarios—average fire size, fire frequency adjustments, terrain type, and resolution—using $\ln({\sigma_{\mathrm{vg}}}^2)$ as the diagnostic variable

Fire size (km^2)	Fire frequency	Resolution			
		30 m	90 m	300 m	900 m
Mountainous landscape					
0.01	Half	103	102	158	*
	Historical	95	63	107	*
	Double	51	103	88	*
0.30	Half	110	109	110	115
	Historical	112	108	112	107
	Double	106	93	106	108
10.0	Half	109	110	112	113
	Historical	111	104	109	112
	Double	102	108	111	113
Flat landscape					
0.01	Half	107	91	191	*
	Historical	62	89	193	*
	Double	72	102	91	*
0.30	Half	113	63	112	244
	Historical	106	135	115	188
	Double	107	113	114	206
10.0	Half	208	176	204	113
	Historical	158	179	113	116
	Double	138	344	179	276

* There are no results for the 0.01 km^2 average fire size and the 900 m resolution simulation combination

Mountainous landscapes generally had lower $\ln(\sigma^2)$ curves for both burned area and vegetation class diagnostic variables. For the dominant vegetation class diagnostic variable, and especially at the highest average fire size, mountainous landscape $\ln(\sigma^2)$ curves tended to flatten sooner than those of flat landscapes, however this effect was not evident in the $\ln(\sigma^2_{\mathrm{ba}})$ results. With few exceptions, the $\ln(\sigma^2_{\mathrm{vg}})$ curves showed larger optimal landscape sizes less than the $\ln(\sigma^2_{\mathrm{ba}})$ curves.

When ignition probability and average fire size were greater, we generally found that $\ln(\sigma^2)$ was higher (Figs. 4, 5), and optimal landscape sizes larger (Tables 2, 3) than when simulated fire activity was lower. To visualize this result, consider the following example: in Fig. 4, if the row of graphs associated with the 0.3 km^2 average fire size is considered (fire size is held constant), the curves of $\ln(\sigma^2_{\mathrm{ba}})$ shift from lower to higher $\ln(\sigma^2_{\mathrm{ba}})$ along the progression of columns from the half to the historical and finally to the double fire ignition probabilities. Similarly, with ignition probability held constant at historical probabilities, the 0.01 km^2 average fire size simulations showed the lowest $\ln({\sigma_{\mathrm{ba}}}^2)$ patterns, the 0.3 km^2 average fire size $\ln(\sigma^2_{\mathrm{ba}})$ patterns were intermediate, and the 10 km^2 average fire size showed the highest $\ln(\sigma^2_{\mathrm{ba}})$ patterns throughout the range of landscape extents. Large average fire sizes tended to minimize the differences between resolutions and in some cases, the $\ln(\sigma^2_{\mathrm{ba}})$ increases with higher fire frequency probabilities, though the fire frequency effect is less pronounced than that of fire size.The highest $\ln({\sigma_{\mathrm{ba}}}^2)$ throughout the range of fire sizes and landscape scales occur for the double fire frequency simulations. However in the mountainous landscape, ignition probabilities do not seem to influence $\ln(\sigma^2_{\mathrm{ba}})$ patterns through the range of landscape extents.

Discussion

If we were dividing LANDFIRE mapping Zone 16 into a grid for reporting historical fire and vegetation dynamics to ultimately compute

FRCC, based on our results, we would select a summary unit size between 50 km^2 and 120 km^2 (Figs. 4, 5; Tables 2, 3). The optimal landscape extent would likely be larger if changes in vegetation composition were important and smaller if fire regimes, represented here by the nine fire size-frequency scenarios, were emphasized in the analysis. The landscape reporting unit sizes can be smaller for mountainous areas or for regions that are topographically complex, but must be larger when the region is flat and when fires can become large. Mountainous landscapes tend to have lower $\ln(\sigma^2)$ than flat landscapes, especially at fine resolutions and when vegetation is emphasized; coarse resolutions may be appropriate when fires are large in mountainous landscapes (Figs. 4, 5).

Simulation results from the 30 and 90 m resolution landscapes were very similar in magnitude and pattern of $\ln(\sigma^2)$ for all simulation scenarios, indicating that simulations using 90 m or even 300 m resolution landscapes may have comparable quality to 30 m resolution. If coarser resolutions are viable for large area applications such as LANDFIRE, simulation and processing time would be accelerated, with potentially small losses in information content. This result is fortuitous for cases where fine-grained data are unavailable, but most importantly, coarse-grained landscapes allow efficient simulation of larger areas and longer time spans, allowing generation of statistically stronger estimates of historical ranges and variation of landscape characteristics.

There are a number of reasons why $\ln(\sigma^2_{\mathrm{ba}})$ differed from $\ln(\sigma^2_{\mathrm{vg}})$. First, the magnitude of burned area for each output reporting interval was often less than the simulated dominant vegetation class extent. Also, vegetation class will change as a result of fire *and* successional development, causing great diversity in vegetation class area across output reporting intervals. Moreover, a change in one vegetation class will always result in a change in one or more other classes, thus increasing $\ln(\sigma^2_{\mathrm{vg}})$.

The LANDSUMv4 fire spread algorithm had a great influence on the effects of resolution and fire regime on variability and optimal landscape size. Since fires will not ignite unless the computed fire size is greater than half the pixel size, coarser resolutions have few small fires because many of the simulated fire starts have sizes much less than half the pixel size (0.4 km^2 for the 900 m resolution). This explains why $\ln(\sigma^2_{\mathrm{ba}})$ was the same across all resolutions when average fire sizes are large, and why $\ln(\sigma^2_{\mathrm{ba}})$ was high for burned area simulations with coarse resolutions and small average fire size (Figs. 4, 5). Additionally, this model condition explains why coarse resolution $\ln(\sigma^2)$ tends to stay high even at very large landscape reporting units. The high values in $\ln(\sigma^2_{\mathrm{vg}})$ for mountainous terrain using coarse resolutions is partially a result of the fire start algorithm, but may also be a function of the greater diversity of PVT-succession class combinations in the mountainous landscape coupled with a more complex successional development pathway.

While our findings confirm our understanding of fire regimes and how disturbance scales with analysis extent (Shugart and West 1981; Baker 1989; Wimberly et al. 2000), they also provide landscape modelers additional insight into the effect of landscape extent and spatial grain on modeled results when determination of optimal extent is sought. However, extrapolation of results from this preliminary study to other large regional scale modeling projects should be carefully considered since our results have shown that optimal landscape size varies with topography, fire regime, and spatial resolution. While LANDSUMv4 appears to have similar behavior when formally compared with other landscape simulation models (Cary et al. 2006), there are certainly differences in model structure and design that may influence optimal landscape size. For example, Wimberly et al. (2000) suggested that an area no smaller than 300,000 ha is required to appropriately manage age-class distributions based on historical variability in the Oregon Coast range. This result is two orders of magnitude higher than our findings.

Optimal landscape size may be dependent on many other factors not addressed in this paper, including (1) the choice of simulation model; (2) the underlying simulated ecosystems being; (3) the biophysical setting of the simulated region (climate, topography, soils); (4) the inherent fire regime including severity; (5) the parameterization and initialization of the model; and (6) the specific process under investigation. Therefore, it is reasonable to assume that optimal landscape size is probably quite variable across the entire US thereby making it difficult to divide the country into a fixed grid of LANDFIRE FRCC reporting units. Ideally, the grid should be variable and sized to reflect the factors used in our simulation experiment. It would be worthwhile in future research to identify additional factors dictating optimal landscape extent for the major biomes of the United States and to replicate this experiment with different models, parameterizations, and underlying input landscapes.

Landscape simulation models like LANDSUMV4 are valuable tools for exploring historical fire regimes as they allow analysis of spatial ecological and disturbance data throughout a long time series. Because this type of modeling can characterize spatio-temporal vegetation and disturbance dynamics for myriad research and management applications, it plays an important role in landscape ecology. Using a national scale mapping project (LANDFIRE) as a case study, we have demonstrated that the appropriate choice of input landscape extent is a critical element to consider if landscape modelers aim to uphold the informational quality of their efforts.

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