

# Climate change effects on historical range and variability of two large landscapes in western Montana, USA

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## Abstract

Quantifying the historical range and variability of landscape composition and structure using simulation modeling is becoming an important means of assessing current landscape condition and prioritizing landscapes for ecosystem restoration. However, most simulated time series are generated using static climate conditions which fail to account for the predicted major changes in future climate. This paper presents a simulation study that generates reference landscape compositions for all combinations of three climate scenarios (warm-wet, hot-dry, and current) and three fire regime scenarios (half historical, historical, and double historical fire frequencies) to determine if future climate change has an effect on landscape dynamics. We applied the spatially explicit, state-and-transition, landscape fire succession model LANDSUM to two large landscapes in west-central Montana, USA. LANDSUM was parameterized and initialized using spatial data generated from the LANDFIRE prototype project. Biophysical settings, critical spatial inputs to LANDSUM, were empirically modeled across the landscape using environmental gradients created from historical and modeled future climate daily weather data summaries. Successional pathways and disturbance probabilities were assigned to these biophysical settings based on existing field data and extensive literature reviews. To assess the impact of changes in climate and fire regime, we compared simulated area burned and landscape composition over time among the different simulation scenario combinations using response variables of Sorenson's index (a global measure of similarity) and area occupied by the dominant vegetation class (simple indicator of change in landscape composition). Results show that simulated time series using future predicted climate scenarios are significantly different from the simulated historical time series and any changes in the fire regime tend to create more dissimilar and more variable simulated time series. Our study results indicate that historical time series should be used in conjunction with simulated future time series as references for managing landscapes. Published by Elsevier B.V.

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## 1. Introduction

The concept of historical range and variability (HRV) of landscape composition and structure is becoming an important reference for assessing current landscape condition and prioritizing areas for ecosystem restoration treatments (Landres et al., 1999; Nonaka and Spies, 2005; Rollins et al., 2006). A quantification of the area covered by vegetation types or affected by disturbance agents in the past can serve as reference for comparing current and future landscapes under various management alternatives (Wimberly, 2002). However, historical time series may represent a small slice of time with unique climate and disturbance regimes, and this slice may be an inadequate reference for guiding the management of future

landscapes that are experiencing rapid climate change. Predicted climate warming due partly to increased carbon dioxide from the burning of fossil fuels can rapidly alter vegetation, disturbance processes, and climate regimes (Stocks et al., 1998; Flannigan et al., 2005; IPCC, 2007) and land managers need to be able to account for this future change in reference time series to effectively prioritize, design, and implement sustainable landscape level restoration treatments. In this paper, “reference” is used to identify a baseline landscape time series against which today's landscapes are compared.

Empirical estimations of historical conditions for landscapes dominated by wildland fire are rare because of the lack of comprehensive historical spatial data over large regions and the limited temporal span of most historical studies and data (Egan and Howell, 2001; Beckage et al., 2005). A viable alternative is simulation modeling where spatially limited historical field studies are used to parameterize and initialize spatially explicit

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landscape models or the studies are used to validate and test model results (Boychuk et al., 1997; Keane et al., 2002b; Wimberly, 2002). These spatial simulation models, often called landscape fire succession models (LFSM; Keane et al., 2004), are quite diverse and unique, and most are specific to a singular disturbance, unique geographic area, or particular ecosystem. Many LFSMs, particularly those used in resource management, employ a state-and-transition modeling approach for simulating vegetation development and often use a simplistic fire spread model to simulate wildland fire spatial dynamics. Few LFSMs explicitly simulate the effects of climate on both fire and vegetation dynamics, especially those models that use state-and-transition modeling. Because climate is rarely static and all indications are that the world's climate will change in the coming decades (IPCC, 2007), it is essential that simulated reference time series account for changes in the landscape processes under future climate conditions and resultant altered fire regimes to effectively prioritize, design, and implement current landscape level restoration treatments.

This paper presents a simulation study that explores the effect of changing climates and altered fire regimes across two large landscapes in west-central Montana of the western United States. We used the landscape fire succession model LANDSUM to simulate landscape dynamics under the climate and fire scenarios (Keane et al., 2006). LANDSUM was parameterized and initialized using spatial data generated from the LANDFIRE prototype project (Rollins et al., 2006). The LANDFIRE prototype project developed methods and databases for a national mapping effort that integrates the sciences of remote sensing, biophysical modeling, and landscape simulation to produce nationally consistent and comprehensive maps of historical fire regimes, Fire Regime Condition Class (FRCC), and fuel characteristics for fire management ([www.landfire.gov](http://www.landfire.gov)). Climate change effects were simulated in this study using a statistical modeling approach that created alternative maps of biophysical settings from environmental gradients that were modified to create three climate scenarios—current, warm-moist, and hot-dry. Simulated time series of burned area and vegetation type coverage for over 2000 years were compared across each simulation scenario to describe the effect that climate might have on reference conditions. Because effects of climate change on fire regime may be non-linear (Cary and Banks, 1999; Flannigan et al., 2005), we also investigated these climate effects under three different fire regimes using three nested landscape analysis area sizes. While this approach may be simplistic when compared to other more mechanistic climate change simulation efforts (Bachelet et al., 2001; Thornton et al., 2002), we believe that this process can be used for many management-oriented state-and-transition spatial models to integrate climate change into management planning at a level that is appropriate and understandable to managers.

## 2. Methods

This study used the LANDSUM model, parameterized from the LANDFIRE prototype effort (Long et al., 2006), to generate

a simulated time series of landscape composition for all combinations of three climate and three fire regime scenarios (total of nine scenarios). The three climate scenarios were represented by three different LANDSUM input maps of potential vegetation mapped using statistical modeling where species distribution was modeled from plot data and environmental gradients. The environmental gradients were simulated using spatial climate data that was modified to produce the three climate scenarios. The fire regime scenarios were created by doubling and halving input fire frequency LANDSUM parameters quantified from published studies.

To investigate the effect of topography, analysis scale, and vegetation diversity on these scenarios, we performed the nine simulations (3 climate  $\times$  3 fire regime) on two large landscapes in western Montana, USA within mapping Zone 19 of the LANDFIRE prototype project area (Fig. 2) (see Rollins and Frame, 2006 for more detailed information). The two landscapes are within the same ecoregion but have distinctly different topography, vegetation and geography—one is flat and one is mountainous. They were selected to evaluate if estimated climate change effects vary by topography. Each landscape was also stratified into three nested landscapes of progressively smaller extents. We summarized our results by these sizes to evaluate the effect of scale on study results (Karau and Keane, 2007).

### 2.1. The LANDSUM model

LANDSUM (LANDscape SUccession Model) is a simplistic LFSM (Keane et al., 2004) that deterministically simulates vegetation development at the polygon-level using state-and-transition pathway models and stochastically simulates fire ignition, spread and effects at a landscape level using cell automata approaches. It has been used to explore the advantages and disadvantages of using simulation to generate historical time series of landscape characteristics (Keane et al., 2002a,b, 2003) and to explore the effects of alternative management treatments implemented across landscapes (Keane et al., 1997; Cary et al., 2006). A version of LANDSUM is currently being used to generate HRV time series for the conterminous United States in the LANDFIRE project (Rollins et al., 2006). While LANDSUM is one of the most basic LFSMs, its design is similar to many spatial models used in land management. The LANDSUM program is described in detail in Keane et al. (2006) so only a brief summary of the program is presented here.

LANDSUM simulates succession within a polygon using the multiple pathway succession modeling approach presented by Kessell and Fischer (1981) and based on the work of Noble and Slatyer (1977), Cattellino et al. (1979), and Davis et al. (1980). This approach assumes all pathways of successional development will eventually converge to a stable or climax plant community called a Potential Vegetation Type (PVT) (Fig. 1). A PVT identifies a distinct biophysical setting that supports a unique and stable climax plant community under a constant climate regime (Daubenmire, 1966; Pfister and Arno, 1980). In LANDSUM, a PVT can have multiple climax plant

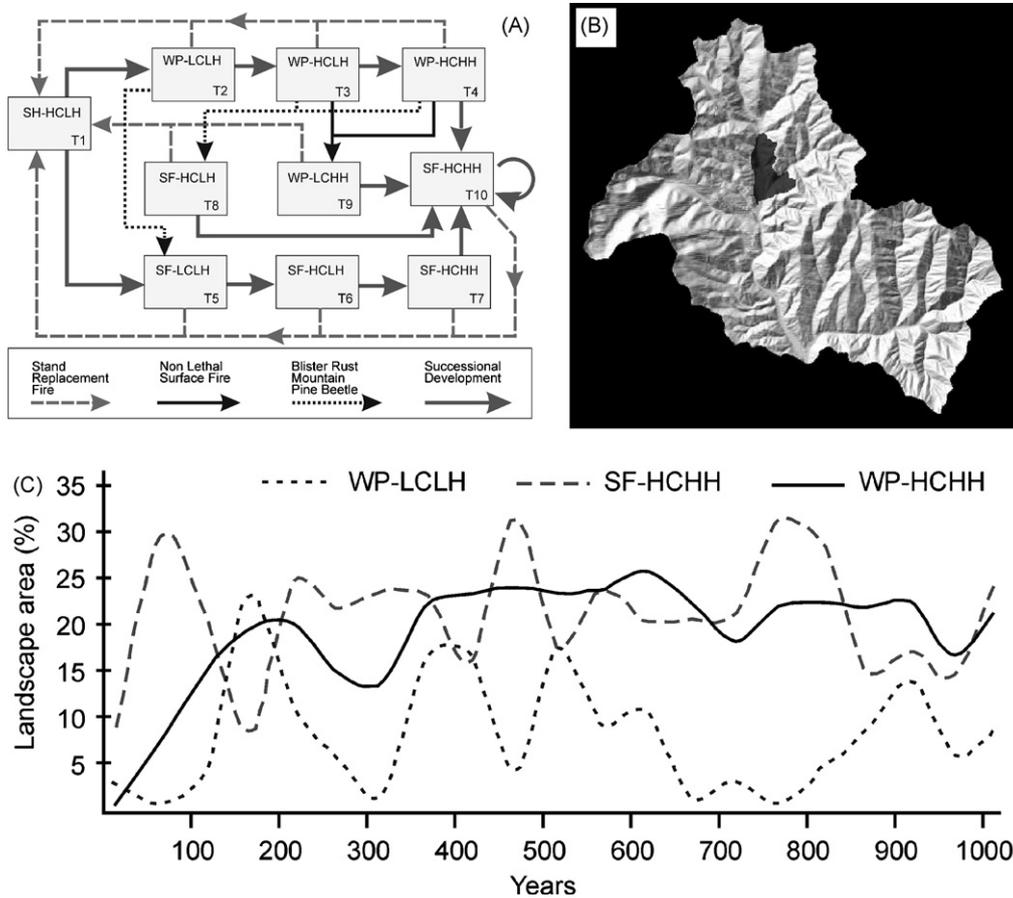


Fig. 1. The critical components of the LANDSUM model. (A) An example of a successional pathway for a high elevation spruce-fir Potential Vegetation Type (PVT) with cover type names: SH, mountain shrub; WP, whitebark pine; SF, subalpine fir and structural stage names: LCLH, low cover low height early succession stage; HCLH, high cover low height mid-seral stage; HCHH, high cover high height late succession stage; LCHH, low cover high height disturbance maintained late succession stage. Labels T1–11 identify unique successional classes. Fire, beetles, and blister rust disturbance pathways are also shown, (B) the simulation of fire spread and effects, and (C) an example of simulation spatial output.

species indicators to account for broad trends in successional dynamics. There is a single set of successional pathways for each PVT mapped on the simulation landscape (Steele, 1984; Arno et al., 1985) (Fig. 1). Each pathway is composed of a sequence of plant communities called successional classes that are linked along gradients of vegetation development. Each successional class is represented by a cover type (dominant species) and a structural stage (cover and height).

Successional development within a polygon is simulated at an annual time step where the polygon’s successional class will change if the length of time spent in the current successional class (transition time) exceeds a user-defined maximum residence time that is held constant throughout the simulation. Disturbances can disrupt succession by delaying or advancing the time spent in a successional class, or they can cause an abrupt change to another successional class (see the disturbance pathways in Fig. 1A). Occurrences of human-caused and natural disturbances are stochastically modeled from probabilities based on historical frequencies that are input to LANDSUM by PVT and successional class. All disturbances specified by the user in the input file are simulated at a polygon-level, except for wildland fire, which is simulated as a spatial cell-to-cell spread process across the landscape.

The spatial simulation of fire in LANDSUMv4 is represented by three phases: ignition, spread, and effects. Ignition is stochastically simulated from the fire probabilities that are input into the model by PVT and successional class. These input probabilities are adjusted for scale to account for the size of the polygon and the fire size distribution. Fire is spread from the ignition point to cells across the landscape using directional vectors of wind (input to model) and slope (derived from an input DEM layer) (Fig. 1B). Fire spread is limited by stochastically calculating a maximum fire size (ha) for each fire from a fire size distribution that is selected and parameterized in the input files for the program. The effect of the fire on the burned polygon is again stochastically determined from probabilities of each fire severity type specified in the input file by PVT and successional class. The program cycles through all polygons in the burned area and slices all burned polygons into sections that are burned and sections that are unburned. The unburned polygons retain all characteristics of the original polygon prior to the fire. Burned polygons are assigned new successional classes, stand ages, and year since fire attributes using parameters specified in another input file. Each year, the program summarizes the area (m<sup>2</sup>) in each PVT-successional class for the landscape and the burned

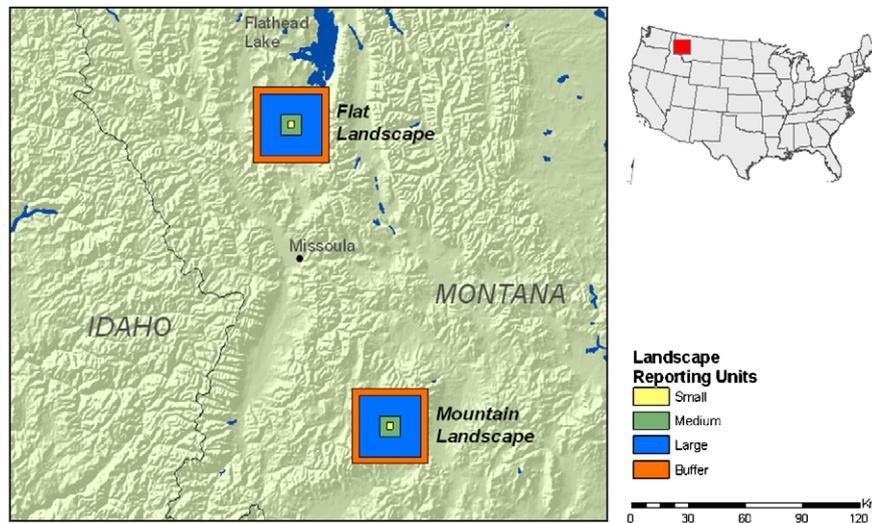


Fig. 2. The two simulation landscapes used in this study (flat = FL, mountainous = MT) shown with the three nested landscape reporting sizes (small = 10 km<sup>2</sup>, medium = 100 km<sup>2</sup>, and large = 1000 km<sup>2</sup>) and the simulation buffer that is 3 km wide.

area by fire severity type and prints this information to an output file that we used in our statistical analysis (Fig. 1C).

## 2.2. Study areas

Two areas were simulated in this study. The mountain landscape is located in the Anaconda and Flint Creek Mountain ranges, northeast of Anaconda, Montana (Fig. 2). The topography is highly dissected with over 1500 m of relief. The vegetation at the upper elevations is dominated by spruce-fir forests that are comprised of lodgepole pine (*Pinus contorta*) and whitebark pine (*Pinus albicaulis*) in early stages of succession with subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) dominating in the later stages of stand development (Table 1). Mid elevations areas are primarily Douglas-fir (*Pseudotsuga menziesii*) forests with

some seral lodgepole pine stands, while the lowest elevations are grasslands and sagebrush grasslands. Rainfall ranges from over 1500 mm at the high elevations (over 2500 m above MSL) to under 250 mm at the lowest elevations (around 1200 m). Average slope is over 35% and aspects are well distributed across all directions. Climate is mostly dry, maritime with weather systems coming mostly from the west but there is a heavy continental influence (Arno, 1979).

The flat landscape is in the southern Flathead Valley, south of Flathead Lake near Ronan, Montana USA (Fig. 2). This flat landscape averages less than 10% slope and is mostly mesic bunchgrass grasslands and sagebrush shrublands in the valley bottoms with ponderosa pine (*Pinus ponderosa*)/Douglas-fir forests common as elevation increases in the Mission Mountains towards the eastern edge of this landscape. The top of the Mission Mountains is mostly spruce-fir forests

Table 1  
Composition of Potential Vegetation Types (PVT) and existing cover types for the flat and mountainous landscapes in percent of total area within the largest landscape

Mountain landscape	Percent of area	Flat landscape	Percent of area
<b>PVT</b>		<b>PVT</b>	
Subalpine spruce-fir	25.5	Bluebunch Wheatgrass	20.0
Montane spruce-fir	23.1	Douglas-fir/Ponderosa pine	17.1
Douglas-fir/Douglas-fir	16.9	Riparian Hardwood	16.5
Douglas-fir/lodgepole pine	7.9	Wyoming Basin Big Sagebrush	15.8
Lodgepole pine	7.3	Subalpine spruce-fir	8.9
Mountain Big Sagebrush	5.8	Montane spruce-fir	8.2
Whitebark pine	3.8	Douglas-fir/Douglas-fir	3.6
<b>Existing cover type</b>		<b>Existing cover type</b>	
Spruce-fir	41.8	Native bunchgrass graminoid	28.2
Douglas-fir	22.4	Wyoming Basin Big Sagebrush	22.4
Lodgepole pine	14.0	Douglas-fir	15.6
Native bunchgrass graminoid	9.0	Wetland herbaceous	11.9
Wyoming Basin Big Sagebrush	5.1	Spruce-fir	6.6
Timberline forest	3.2	Ponderosa pine	4.4
		Riparian Hardwood	3.1

Only types that occur above 3% are shown for simplicity. These types were classified for the LANDFIRE prototype project and are described in detail in Long et al. (2006) and Rollins and Frame (2006).

Table 2  
The four factors used in this simulation study

Factors	Scenarios	Abbreviation	Description	Source
Climate	Historical/current	CC	Eighteen years of daily weather represents current and historical climate conditions	Thornton et al. (1997)
	Warm, wet	C2	A warmer (+2 °C), wetter (125%) spring and summer, near normal fall-winter (+1 °C, 99% precipitation)	Mote et al. (2005), Salathe et al. (in press)
	Hot, dry	C6	A hotter (6 °C), drier (90%) spring-summer, warmer (3–4 °C), drier (90%) fall-winter	Mote et al. (2005), Salathe et al. (in press)
Fire regime	Historical normal	HN	Fire probabilities parameterized from many fire history studies	Long et al. (2006)
	Half historical	HH	Multiplied all FR-HI probabilities by 0.5	Karau and Keane (2007)
	Double historical	HD	Multiplied all FR-HI probabilities by 2.0	Karau and Keane (2007)
Landscape reporting size	10 km <sup>-2</sup>	Small	Small landscape used for project level assessment	This study
	100 km <sup>-2</sup>	Medium	Larger landscape used in landscape assessments	This study
	1000 km <sup>-2</sup>	Large	A large, regional landscape	This study
Landscape complexity	Flat	FL	Anaconda/Flint Creek Mountain Range	Rollins and Frame (2006)
	Mountainous	MT	Southern Flathead Valley	Rollins and Frame (2006)

Each factor was represented by a set of scenarios that totalled 54 combinations where only the climate and fire regime scenarios were evaluated using a full factorial ANOVA analysis. The source identifies the origin of the data used for that scenario.

composed primarily of lodgepole pine and subalpine fir. Elevations are around 970 m above MSL in the Flathead Valley with the Mission Mountains rising over 2700 m of mostly westerly facing slopes. Precipitation is around 250 mm in the valley and rises over 2000 mm at the top of the Mission Mountains (Arno, 1979).

### 2.3. Simulation design

Two factors were formally investigated in this simulation study using a full factorial nested design (Table 2). The first factor was *climate* represented by three scenarios—current climate (CC), warm-moist (C2), and hot-dry (C6) (details are in Table 3). Climate scenarios, in this study, were represented in the model by three different PVT input maps created from environmental gradients calculated from daily climate streams that were modified to create the three climate scenarios. The current climate was quantified by the spatially explicit weather DAYMET database ([www.daymet.org](http://www.daymet.org)) that consists of 18 years (1980–1997) of daily weather described by five variables – minimum and maximum temperature (°C), vapor pressure deficit (MPa), precipitation (m), and solar radiation

Table 3  
The two climate change scenarios used in this study created by Mote et al. (2005)

Season	Temperature min (°C)		Temperature max (°C)		Precipitation factor	
	C2	C6	C2	C6	C2	C6
Winter	+1.8	+2.5	+1.8	+2.5	0.99	1.11
Spring	+1.0	+3.0	+1.0	+3.0	1.27	1.02
Summer	+2.0	+6.7	+2.0	+6.7	1.24	0.66
Autumn	+1.6	+4.6	+1.6	+4.6	1.05	0.93

The temperature values are added to the raw DAYMET daily data while the precipitation factor is multiplied by the daily rainfall values in DAYMET. The C2 scenario is considered warm and moist while the C6 scenario is hot and dry.

(W m<sup>-2</sup>) – for the entire conterminous United States at 1 km resolution. It was created by Thornton et al. (1997) by extrapolating weather data from over 1500 weather stations across a 1 km grid using mechanistically derived lapse rates and a Gaussian kernel extrapolation approach (Running and Thornton, 1996; Thornton et al., 1997, 2000). We made the assumption that the current climate represented by the DAYMET data also represents the historical climate under which data for succession pathways and fire frequency parameters were measured and synthesized. The two other climate scenarios were created by modifying the DAYMET daily weather data to create two PVT maps (these methods discussed in Section 2.4).

The second factor was *fire regime* represented by three scenarios—historical (HN), half historical (HH), and double historical (HD) (Table 2). The historical fire regime was parameterized using a synthesis from the various fire history studies conducted in and around the study area (Long et al., 2006). Historical fire frequencies and fire sizes were mostly quantified from fire scar age data collected from tree cross-sections taken from living, dead, and downed trees (Arno, 1980; Barrett et al., 1991; Morgan et al., 1996). These data were summarized by PVT and succession classes by Long et al. (2006) and used as model inputs. The half historical and double historical scenarios were created by multiplying all input fire probabilities by 0.5 and 2.0, respectively. These fire regime scenarios were created to explore the effect of changing fire regimes that could occur independently of the climate change scenarios described above.

We also evaluated the effect of *landscape reporting size* on HRV time series statistics as climate and fire changed by nesting smaller landscapes within a larger core simulation landscape and summarizing results by each nested landscape. We used three landscape reporting sizes for this factor – approximately 10, 100, and 1000 km<sup>2</sup> – called small, medium, and large, respectively (Fig. 2; Table 2). We increased the core

simulation area by adding a 3-km wide buffer around the edge to more realistically simulate fire disturbances by allowing fires to ignite and spread from the buffer into the large landscape reporting area (Fig. 2) (Pratt et al., 2006). Simulation results were summarized by area occupied by each nested landscape. And, as mentioned, we also evaluated the influence of *landscape complexity* on climate and fire by performing the nine climate–fire scenarios on two study areas—mountainous and flat (Table 1).

We simulated each scenario for three factors (climate, fire regime, landscape complexity;  $3 \times 3 \times 2 = 18$  combinations) for the largest reporting area (large) for 2500 years using the LANDSUM model. The simulation landscape was initialized using the most dominant vegetation type in each PVT-succession pathway following methods presented in Pratt et al. (2006). We ran the model for 500 years and then output the simulated landscape composition (area by PVT-succession class) and burned area statistics every 20 years for the next 2000 years to obtain 100 observations total. Previous studies have established that a reporting interval of 20 years is sufficient to eliminate most concerns of temporal autocorrelation (Keane et al., 2002b). Other important simulation inputs for our LANDSUM simulations included: (1) 1:3:6 weather year ratios (one severe year to every 6 normal years to 3 dry years) (Keane et al., 2006), (2) average wind speed of  $5 \text{ m s}^{-1}$ , (3) average wind direction of  $60^\circ$  azimuth, (4) succession and fire input parameters taken from many sources (Long et al., 2006; Pratt et al., 2006; Karau and Keane, 2007), and (5) average fire size of 30 ha (Pratt et al., 2006).

#### 2.4. Developing potential vegetation maps

We implemented a two-step procedure for developing the three PVT maps that represent the three climate scenarios (CC, C2, and C6). The first step involved simulating a set of environmental gradient layers, and, in the second step, we used those gradient layers, in combination with field-based plot data, to predict PVTs across the analysis area using classification and regression tree analysis for each of the three climate scenarios. Most environmental gradient layers were created using the WXFIRE program, a biophysical simulation model, that integrates DAYMET climate data with topographic spatial data (elevation, aspect, slope), soils data, leaf area index, and ecophysiological site data to compute climatic and biophysical gradients (Keane and Holsinger, 2006). WXFIRE was used to scale the coarse 1 km DAYMET data to 30 m resolution in complex topography and then to summarize the scaled DAYMET daily weather to annual averages for a diverse set of environmental descriptors. The WXFIRE model generates 38 spatially explicit maps of climate and ecosystem variables (see Keane and Holsinger, 2006, for a full list).

The WXFIRE program was then modified for this project to adjust the input DAYMET weather spatial data to create the C2 and C6 climate scenarios (Table 3). The WXFIRE climate change module altered daily weather sequences from prescribed seasonal inputs to create possible climate change scenarios by simply adjusting (adding or multiplying) the five

daily weather DAYMET values by the values stratified by four seasons in Table 3. The two climate change scenarios were developed by Mote et al. (2005) to bracket the possible changes in climate for the Pacific Northwest USA (Salathe et al., in press). The first climate change scenario, called the *warm, moist scenario* (C2 for  $2^\circ\text{C}$  increase in summer temperature), represented a consensus of output from six Global Climate Models for a future doubled carbon dioxide atmosphere. The *dry, hot scenario* (C6 for a  $6^\circ\text{C}$  increase in temperature) represents a possible worse case scenario also derived from these six models (Table 3). The final output from the WXFIRE simulations was three sets of environmental gradients (Table 4) to represent the three climate conditions (CC, C2, and C6).

We developed PVT maps for each climate scenario and landscape (FL, MT), using methods similar to those described by Frescino and Rollins (2006) for the LANDFIRE prototype project. We began our process by obtaining georeferenced plot datasets built by the LANDFIRE prototype project where each plot was assigned a PVT from measured species cover data (Caratti, 2006). Using WXFIRE, we computed the above-mentioned climate and ecosystem gradient variables for each plot for the current climate scenario (CC) and then created a statistical model that predicted current PVT from simulated variables (i.e., environmental gradients) using regression tree analysis (De'ath, 2002). A previous analysis revealed the important variables to include in our empirical model (Holsinger et al., 2006). We used the program See5 version 2.02 (Rulequest Research, 2006) to produce three classification trees for (1) forest vs. non-forest PVT types, (2) forest PVT only, and (3) non-forest PVTs only, using a number of See5 features such

Table 4

The list of simulated environmental variables produced by WXFIRE program used in classification and regression tree analyses to produce the three Potential Vegetation Type (PVT) maps

Variable	Description	Units
TMAX	Maximum daily temperature	$^\circ\text{C}$
TMIN	Minimum daily temperature	$^\circ\text{C}$
TAVE	Average daily temperature	$^\circ\text{C}$
TDAY	Daytime daily temperature	$^\circ\text{C}$
TNITE	Nighttime daily temperature	$^\circ\text{C}$
PPT	Precipitation	cm
RH	Relative humidity	%
SRAD	Solar radiation flux	$\text{kW m}^{-2} \text{day}^{-1}$
DSS	Days since last snow	Days
DSR	Days since last rain	Days
PET	Potential evapotranspiration	$\text{kg H}_2\text{O year}^{-1}$
G	Leaf conductance to sensible heat	$\text{m s}^{-1}$
SWF	Soil water fraction	Proportion
VWC	Volumetric water content	Proportion
SNOW	Snowfall	$\text{kg H}_2\text{O m}^{-2} \text{day}^{-1}$
EVAP	Evaporation	$\text{kg H}_2\text{O m}^{-2} \text{day}^{-1}$
TRANS	Soil water transpiration	$\text{kg H}_2\text{O m}^{-2} \text{day}^{-1}$
W10M	NFDRS—10 h wood moisture content	%
KBDI	Keetch-Byram drought index	Index
ASPECT	Aspect	Degrees azimuth
LAI	Leaf area index	$\text{m}^2 \text{m}^{-2}$
SDEPTH	Soil depth	cm
SLOPE	Slope	%

as pruning, boosting, and winnowing attributes. See5 constructs classification trees by pruning back highly complex trees to more simplified ones through merging classes, thereby minimizing classification error and improving model efficiency (Breiman et al., 1984). We chose to prune the initial tree by 25%, and constrained the degree to which the initial tree fits the data by allowing a minimum of two training cases to follow at least two of the branches in a decision tree. We also used See5's boosting feature (10 boosting trials) where multiple trees are built in an iterative process and each tree 'learns' from the misclassification errors to improve model accuracy. See5's most relevant output, for our procedure, were a 'tree' file describing classification breaks across environmental gradients and a file describing the environmental variables chosen for the model (Table 4).

We then mapped the See5 regression tree models across the landscapes using the Mapsee5 program version 0.4 developed by Ward (2005). This program used the classification trees, in conjunction with gradient spatial layers, to predict PVTs across our mountain and flat landscapes. We ran Mapsee5 for each PVT model (PVT type, forest PVT, non-forest PVT) and produced our final PVT maps, for each landscape, by merging the forest and non-forest PVT layers by their predicted PVT type. To predict PVT for the potential future scenarios of C2 and C6 climates, we used the same classification tree developed from current climate conditions and applied it in Mapsee5 using the set of environmental gradients predicted for C2 and C6 climate scenarios by WXFIRE. Ultimately, we created six PVT maps, for each climate condition (CC, C2, and C6) and for each landscape (mountain and flat).

### 2.5. Statistical analysis

Three response variables were used in our analysis: (1) area burned, (2) area of dominant succession class, and (3) Sorenson's index of departure. The simulated area burned was summed over each 20-year period because it is a more stable measure than the area burned in any single year, which is quite variable (Cary et al., 2006). The dominant succession class varies by landscape reporting size because as the area gets larger, different patterns of vegetation arise. We decided to use the dominant succession class for the largest landscape reporting size from the historical baseline scenario (CC, HN) as the basis of comparison between all simulations. For the MT landscape, this was dense, tall spruce-fir forest (27% of landscape), while for the FLAT landscape, the dominant succession class was dense high herb perennial native bunchgrass graminoid (22% of landscape) (Table 1).

We decided to use the Sorenson's index, SI, as a variable that represents similarity of landscape composition relative to reference conditions. SI is often used to measure the similarity between two plant communities or lists of species (Mueller-Dombois and Ellenberg, 1974; Sorensen, 1948). In this study, we used SI to measure the similarity in landscape composition (area occupied by succession class) between a reference and all 100 simulation output time periods. We calculated the SI as

follows:

$$SI = 100 \left( \frac{\sum_{i=1}^n \min(A_i, B_i)}{\text{area}_{LRU}} \right)$$

where the area of each particular succession class  $n$ , common to both reference  $A$  and simulation output interval  $B$ , is summed over all succession classes  $n$ , divided by the total area of the landscape reporting unit (LRU) and then converted to a percentage by multiplying by 100. The resulting value has a range of 0–100, where 100 is completely similar (identical, no departure) and 0 is completely dissimilar (maximum departure).

We used two sets of reference conditions in this study. First, we calculated the composition of the current landscapes (called *current condition baseline*) for the three sized landscape reporting units using the LANDFIRE prototype project map products ([www.landfire.gov](http://www.landfire.gov)). The LANDFIRE prototype project mapped cover type and structural stage (succession class) using Landsat 7 Thematic Mapper satellite imagery coupled with biophysical variables (Zhu et al., 2006). The area occupied by each succession class was calculated from these LANDFIRE map products and used as reference values to compute departure (SI) from the simulation scenarios. Unfortunately, the current landscape composition is so different from the historical time series that the computed SIs were too low and little differences could be detected between scenarios. To obtain a more generalized reference condition, we decided to use the average area occupied by each succession class in the simulation of historical climate and fire regime (CC, HN) as the baseline standard for comparison. This enabled us to quantify the relative change in landscape composition between the historical baseline scenario and each year of the other simulations. We called this reference condition the *baseline standard*.

A randomized block design analysis of variance was performed on the 100 observations taken from the simulated time series for the 18 different model scenario combinations using the three response variables – area burned, area dominant succession class, and SI – to determine statistically significant differences in HRV time series across the factors of climate, fire frequency for each landscape size and complexity. Landscape size and complexity were not included as factors in the ANOVA because there are completely different PVT and succession classes extents for the small, medium, and large landscapes and for the flat and mountain landscapes, which would have added bias to the analysis. A total of six ANOVAs were performed for each response variable, one ANOVA for each combination of topographic complexity (FL, MT) and landscape size (small, medium, large).

Finally, we performed two additional analyses to assess the sensitivity and stability of the SI. First, we calculated the SI between each year of the historical baseline scenario and the baseline standard for each landscape reporting size to assess the sensitivity of the SI to the size of the analysis area. We then compared the SI for the historical baseline scenario, calculated over all succession classes, with the SI, calculated over all combinations of PVT and succession class (a larger number of

classes to compare). This provided us with insights as to the sensitivity of the SI to the number of classes used in the calculation.

### 3. Results

#### 3.1. PVT maps for climate scenarios

The spatial distribution of PVTs on the simulation landscape changed dramatically from the current to the two climate change scenarios. The mountainous landscape (MT) lost most of its low elevation sagebrush and Douglas-fir forests to become dominated by montane spruce-fir PVT, especially for the C6 hot, dry climate scenario (Fig. 3). There were also

increases in timberline spruce-fir, timberline whitebark pine, and wetland herbaceous meadows, especially under C2 climate, with corresponding decreases in Douglas-fir and subalpine spruce-fir forests (Fig. 4A). Basically, it looks as though the montane spruce-fir forests have replaced the majority of the landscape under warmer but somewhat wetter future climates, particularly in the C6 climate scenario. Some timberline types have invaded high elevation alpine and rockland types while the montane spruce-fir has moved both up and down in elevation (Fig. 3).

The flat landscape (FL) had a uniquely different response to climate change compared to the mountainous (MT) (Fig. 4B). Under the C2 climate (warm, moist), we found that all bunchgrass grasslands were lost to sagebrush shrublands with

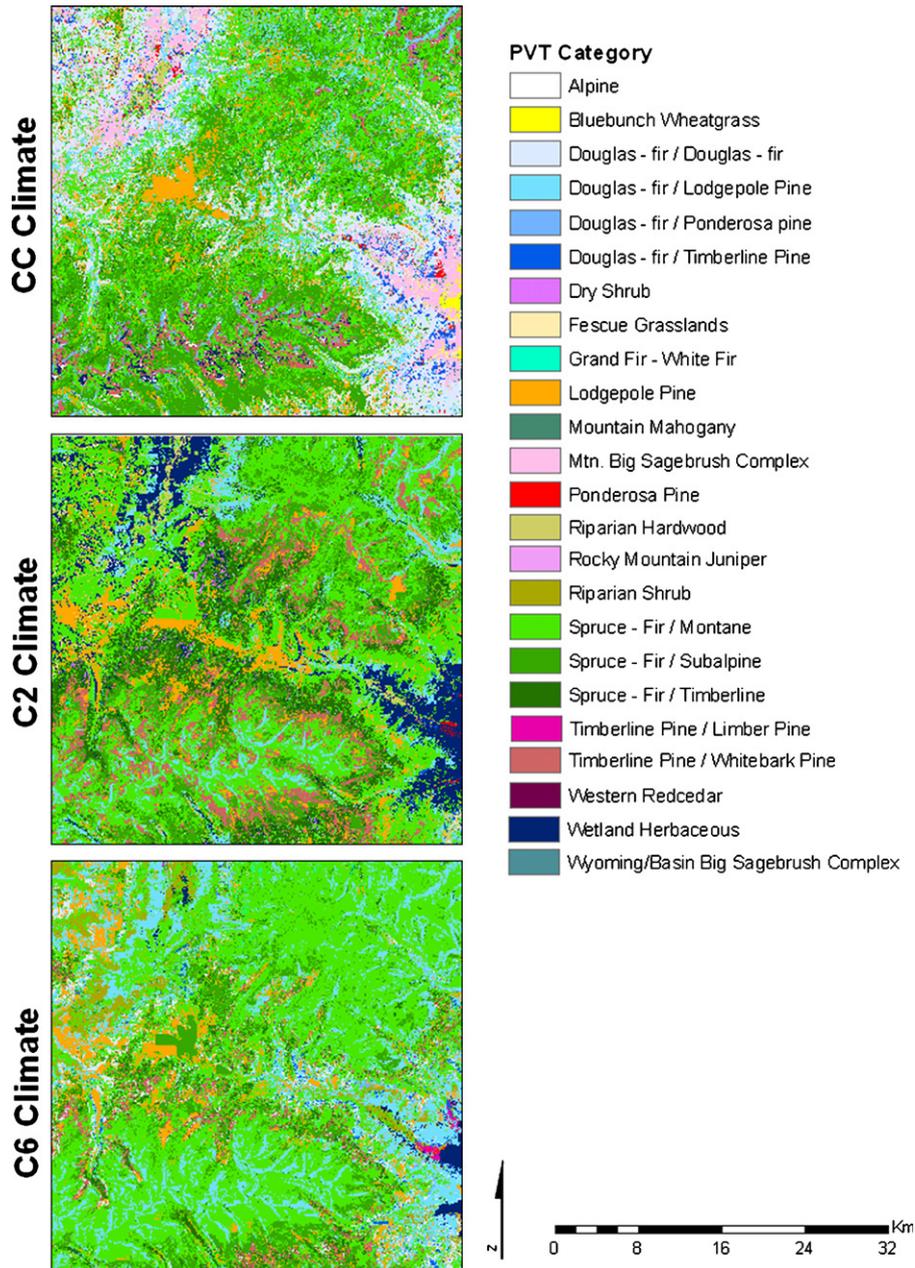


Fig. 3. The mountainous (MT) simulation landscape with the spatial distribution of Potential Vegetation Types (PVT) for the CC, C2 and C6 climate change scenarios.

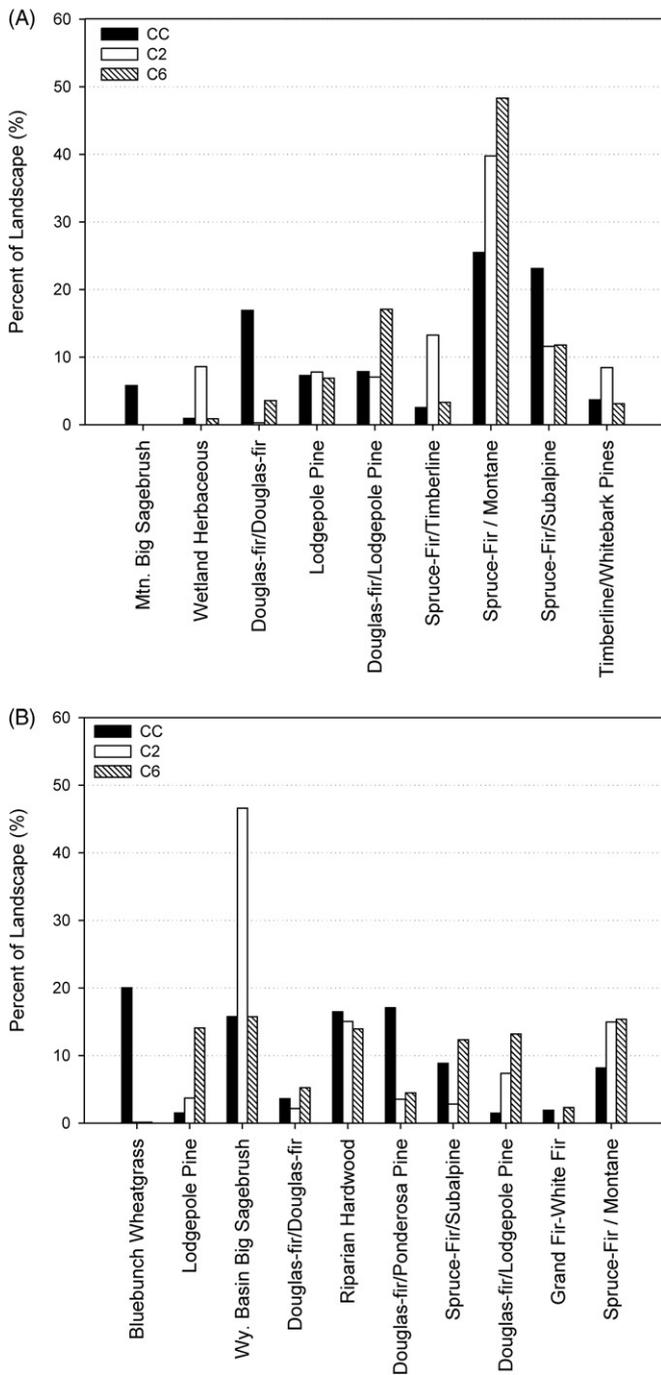


Fig. 4. Percent of landscape in most common PVTs (>3% landscape area) predicted for three climate change scenarios (CC, C2 and C6, see Table 2) for the (A) MT mountainous landscape, and (B) FT flat landscape.

significant declines in Douglas-fir/ponderosa pine and subalpine spruce-fir PVTs. Two PVTs – Douglas-fir/lodgepole and montane spruce-fir – increased in coverage, while the grand fir and subalpine spruce-fir PVTs had significant decreases. PVT distribution under the C6 climate were somewhat different than the C2 climate in that sagebrush PVT levels stayed about the same as current levels but there were significant increases in lodgepole pine, Douglas-fir/lodgepole pine, and montane spruce-fir PVTs. Here it appears that the valley bottoms convert to sagebrush shrublands (especially under C2 climate)

while the montane spruce-fir and Douglas-fir/lodgepole replace the xeric lowland forests (Douglas-fir/ponderosa pine).

### 3.2. HRV differences across simulation scenarios

An example of an HRV time series from the current climate, historical fire regime on the large mountainous landscape is shown in Fig. 5a along with current landscape conditions and the historical averages that were used as a baseline standard in the computation of SI in this study. The variation in this time series for the five most common succession classes provides the side-boards or boundaries for managing landscapes by quantifying thresholds of acceptable landscape conditions. Changes in area occupied by the dominant succession class on the mountainous landscape over the 2000 year simulation for the three fire regime scenarios are presented in Fig. 5b for the large landscape reporting size to illustrate the influence of fire on landscape dynamics—more fire reduces dense tall spruce-fir succession class and this results in an increase in lodgepole pine succession classes.

We found there were significant differences between all climate and fire scenarios based on results of the ANOVA ( $p < 0.001$ ). Changes in fire regime and climate, as well as interactions between the two factors, significantly affected all three-response variables: burned area, area occupied by the dominant succession class, and SI computed from baseline reference condition. We did not calculate SI using the current condition reference as derived from satellite imagery because the comparison had so few classes (see Fig. 5) that all differences between simulation scenarios were statistically significant ( $p < 0.05$ ). As expected, the highest similarity to the baseline standard was, of course, the CC–HN scenario itself (Fig. 6a and d) and the greatest dissimilarity occurred with a reduction of fire under the C2 climate (SI = 70) (Fig. 6a). Halving or doubling the fire probabilities (HH, HD) resulted in significant changes in landscape composition, as measured by a drop in SI of 13 (HH) and 18 (HD) and also reducing the proportion of area occupied by the dominant succession class (nearly 50% for MT landscape, Fig. 6c). The C2 climate had the lowest SI values – not the C6 as expected – probably because the PVT shift was to warmer, more mesic PVTs that have substantially different succession classes than the hotter and drier C6 PVT shifts (Long et al., 2006).

The change in fire regime had a significant effect on HRV time series characteristics (Fig. 6a and d). A doubling of fire frequencies resulted in a drop in SI of about 15 from the historical normal (HN), while a halving of fire frequencies resulted in a drop of 10 in SI. This was true for the CC and C6 climate scenarios but the reverse was true for the C2 scenario. These departures resulting from changes in fire regime are about the same as the departure resulting from changes in climate regimes in the C2 and C6 scenarios compared to the CC climate scenario under historical fire frequencies (HN). The halving or doubling in fire frequencies also increased the variability in the time series for all climate scenarios.

Response of area burned across the simulation scenarios was quite unexpected with less area burned under the hot-dry

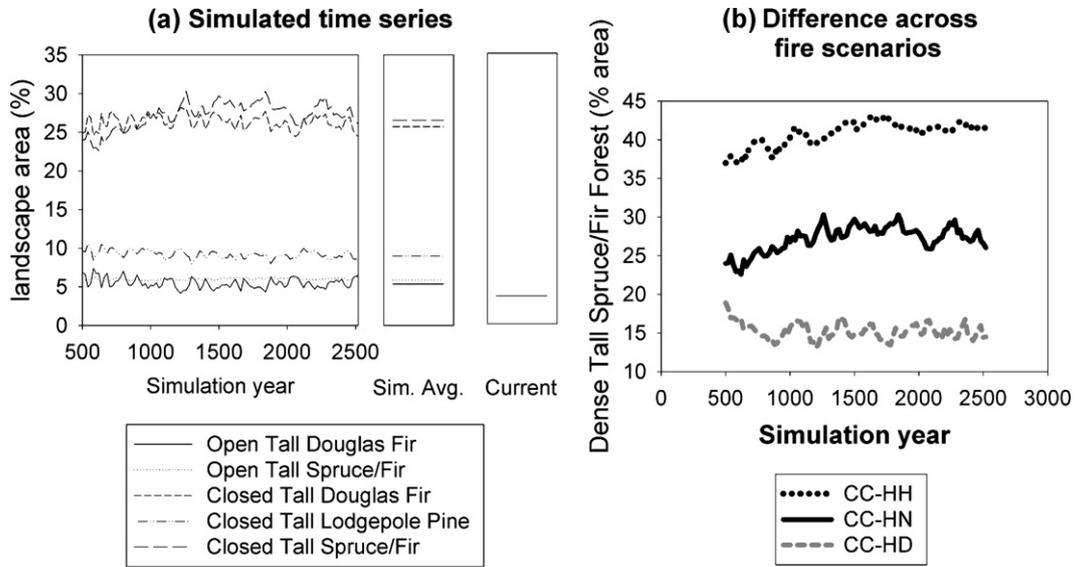


Fig. 5. An portion of a simulated time series for the mountainous (MT) landscape and the large reporting size using the (a) current climate (CC)–historical fire (HN) scenario combination that was used for the baseline standard in computing Sorensen’s index for this study (only the five most dominant succession classes are shown for simplicity; also shown is the simulated average and the composition of the current landscape with only one succession class present), and (b) dominant succession class of dense tall spruce-fir simulated area by simulation year for the three fire scenarios under current climate conditions (CC).

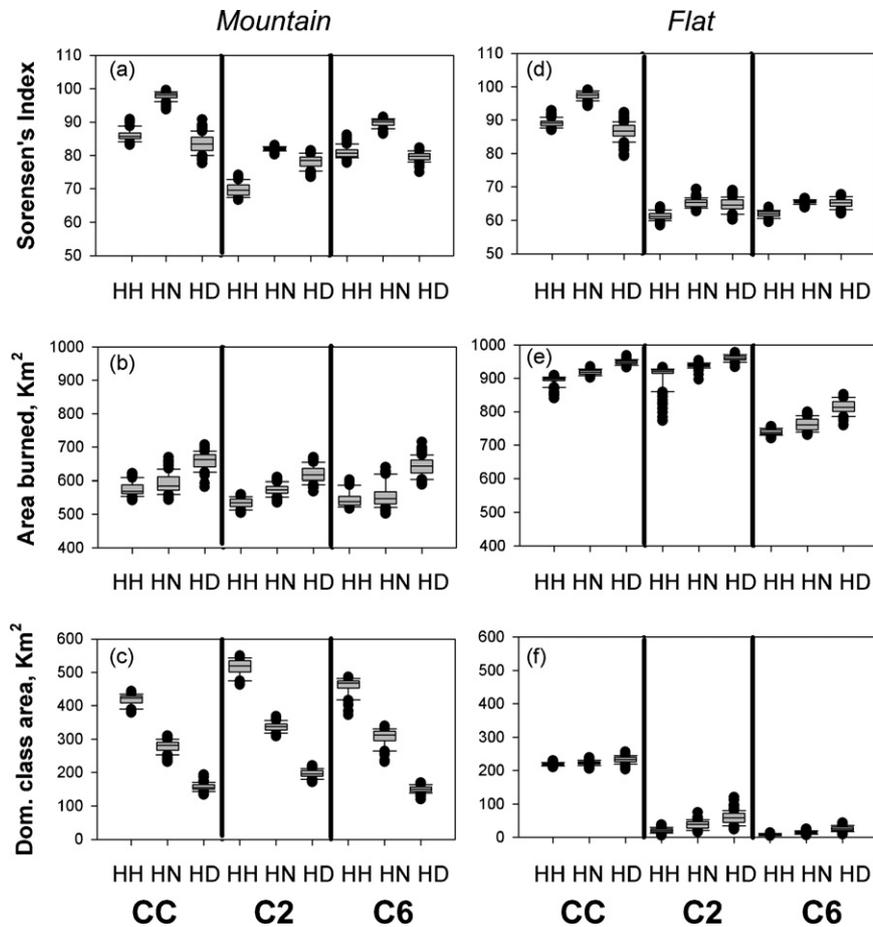


Fig. 6. Box and whisker plots depicting statistical descriptions of each simulation scenario for both landscapes using the three response variables of Sorensen’s index (a and d), area burned (b and e), and dominant succession class (c and f). Sorensen’s index (SI) was calculated using the standardized baseline reference created by the simulation of current climate with historical fire parameters (CC, HN) compared to the nine climate–fire regime scenario combinations. Area burned is a 20-year sum. Definitions of abbreviations can be found in Table 2.

climate scenario (C6; Fig. 6b and e), even with the doubled fire frequencies on the flat landscape (Fig. 6e). The low area burned under the C6 climate scenario for the flat landscape is due to the conversion of bunchgrass PVT, which has high fire frequencies, to PVTs with lower frequencies (i.e., sagebrush types). More area burned on the flat landscape because it is composed of PVT-succession class combinations with higher fire frequencies and less barriers to fire spread when compared with the mountainous landscape. Again, an increase or decrease in fire (HH, HD) nearly always resulted in higher variability in the area burned time series. It was interesting that the area burned was markedly different across fire regime scenarios but quite similar across climate scenarios.

The time series of the most dominant succession class was noticeably different across both fire and climate scenarios for both topographic settings (Fig. 6c and f). An increase in fire reduced tall, dense spruce-fir on the MT landscape, yet marginally affected the extent of bunchgrass on the FL landscape. In contrast, the change in climate to warmer conditions (C2, C6) dramatically reduced bunchgrass on FL landscapes but only slightly affected area covered by tall, dense spruce-fir. This demonstrates the complexity of predicting climate change effects across diverse landscapes.

#### 4. Discussion

In this study, we found that predicted future climate change appears to cause major shifts in landscape vegetation dynamics (Fig. 6) and this shift is further enhanced if fire regimes should change independently of empirically modeled biophysical conditions. Since shifts in PVT also result in changes in the native fire regime because fire parameters are input to the model by PVT-succession class combinations, it is difficult to determine from this simulation study if changes in fire regimes are more important than climate impacts to landscape composition. But, it does appear that the influence of changing fire regimes on future landscapes may be just as important as changing vegetation dynamics, both caused by new climates. Therefore, the simulated time series created from LANDSUM that used historical biophysical parameters may not be good references for the management of future landscapes. Indeed, changing climates could alter the potential response of landscapes to disturbance and vegetation development such that historical conditions may no longer be relevant (Fig. 6). These HRV shifts may not be large (SI changes of 10–20%), but they are statistically significant, and therefore compel managers to address potential climate changes in the planning process. This can be done by replicating our methods where PVTs are migrated across the landscape using environmental gradients or it can be done by using sophisticated simulation approaches where mechanistic landscape models are used to explicitly simulate climate–disturbance–vegetation interactions in a spatial domain (Keane et al., 2007). Our results also illustrate the importance of simulation modeling to the future of land management.

The high departure of the warm, moist climate (C2) from the current (CC) is somewhat perplexing, especially when

compared to the hot, dry (C6) climate, and illustrates the high degree of uncertainty in predicting future effects of climate change (Neilson et al., 2005). We feel this is probably due to the uncertainty in our regression tree models which are more sensitive to changes in moisture conditions than temperature (Frescino and Rollins, 2006) (Table 3). Because temperatures are only marginally higher (2 °C) but precipitation is much greater in the C2 (Table 3), the environmental gradients contained in the regression tree responded with a shift to PVTs that might be considered cooler (subalpine and montane spruce-fir, Fig. 3) but were actually more mesic. In fact, it appears that the cooler but wetter PVTs invade lower drier PVTs with C2 climate because our regression tree gradient model predicted greater shifts in PVT when more water was available (Table 4). This does not agree with conventional wisdom which holds that PVTs will tend to move up the mountain along an elevational gradient (Romme and Turner, 1991; Bartlein et al., 1997). We found a more complicated climate response pattern which was primarily dictated by water availability. Another example of this was when the lower elevations on the flat landscape went from grasslands to xeric shrublands because water became less available under C6 climate (Fig. 4B). More research is needed to evaluate if our results are in the realm of ecological possibility or a side-effect of our statistical model.

The effect of climate change on landscape dynamics is only indirectly modeled in this study. Instead of explicitly modeling the effect of climate on fire dynamics, individual plants, species, or communities as done in numerous other climate change modeling efforts (Lenihan et al., 1998; Cary and Banks, 1999; Bachelet et al., 2000, 2001; Mouillot et al., 2002), we represented climate change effects by moving functional environments (PVTs) around the landscape using empirical modeling (CART). While this seems overly simplistic, it often represents the only alternative available for the many state-and-transition models used in land management. The primary assumption behind this approach is that response of PVT distributions to future climates can be represented by the set of environmental gradients derived from current climate, and the successional development and disturbance dynamics on the migrated PVTs will be the same as they were historically (Beckage et al., 2005). And, we also assume that the assumptions of the statistical CART model are not violated as the climate changes. While these assumptions may not be met for some landscapes, this approach could perform just as well as other more mechanistic and detailed efforts and more research is needed to validate this approach to recognizing climate change effects.

Many studies have predicted climate change effects on forest species using the gradient approach employed in this study where statistical models are created from species distribution data and environmental gradients. Iverson and Prasad (1998, 2002) successfully used regression tree analysis to predict future abundance of tree species in the eastern US from various climate change scenarios. Hamann and Wang (2006) used output from a Canadian Global Circulation Model (GCM) to define new environmental gradients that were then related to biogeoclimatic ecological classification categories using

canonical discriminant analysis to predict future distributions of forest types. Logistic regression was used to map eastern US tree species and community types under three GCM climate scenarios (Randolph and Lee, 1996). Overpeck et al. (1991) related GCM output to pollen data using response functions to predict future species migrations. All of the above studies recognize scale problems, limited biophysical data, and inaccurate representation of functional gradients as primary limitations in their approaches; results that are identical to those found in this study. This study is one of the first to evaluate climate change effects on potential vegetation types rather than individual plant species.

The implications of this study are that managers must not only evaluate landscape management strategies in the context of the past by using HRV techniques (Landres et al., 1999; Keane et al., 2002b; Hann, 2004), but they must also determine if the proposed landscape treatments will create structures or compositions that will be common in the future (Lindner, 2000). The latter can be done using the climate change empirical analysis coupled with the simulation methods presented here to create a time series representing “future range and variation” of landscape composition and structure that can then be compared to the consequences of the management action to determine departure from future conditions. This dual evaluation of looking backward and forward would ensure that there is no loss of important landscape elements from the past that will be important for sustaining healthy landscapes in the future. Our approach of re-mapping PVTs with future climate data may be too simplistic for some highly complex ecosystems and landscapes, and a more mechanistic simulation approach may be warranted (Bugmann, 1996; Neilson et al., 2005).

#### 4.1. Limitations

We found that the calculation of SI was sensitive to the size of the landscape and the number of classes (Fig. 7). There was a 4–10% difference between SIs calculated for the small landscape size and the large landscape for the same simulation and topographic setting (Fig. 7A). It appears that the simulated landscapes become more similar to the reference (less departed with higher SI values) as the size of the landscape increases, and, as landscapes size decreases, the variability of the computed SI increases. These results agree with those found by Karau and Keane (2007).

We also found that SI values decreased 3–10% when they were calculated using the more numerous PVT-succession class combinations (over 50 classes) as opposed to using succession classes only (around 20 classes) (Fig. 7B). This index was sensitive to the number of classes because, as the number of classes increases, there is an increased likelihood that pixels will fall into a different category. Also evident was an increase in variability as the number of classes increased. While these problems did not result in large differences in our comparison of SI between simulated data sets, it was problematic in the comparison between the standard baseline reference condition (average simulated data) and the remotely sensed current

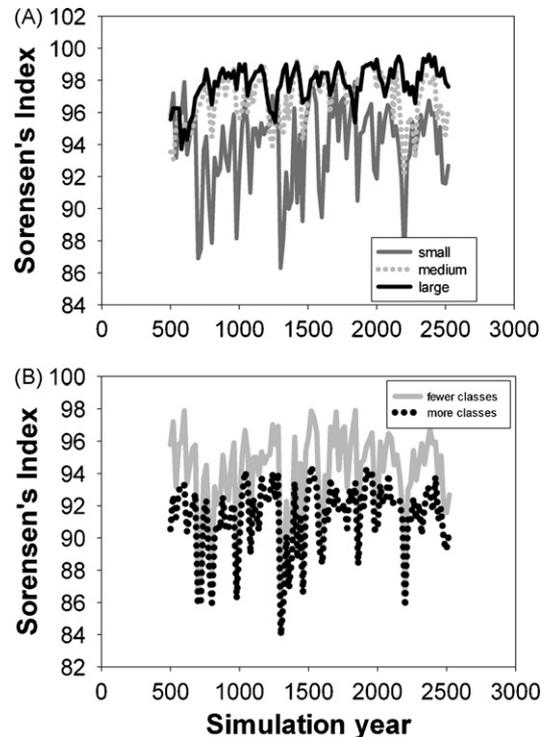


Fig. 7. Sensitivity analysis for the Sorensen's index (SI) for the mountainous landscape (MT) under historical fire regimes and current climate (HN, CC). (A) The effect of the size of the landscape reporting unit on calculated SI. (B) The effect of the number of classes on calculation of SI where *fewer classes* denotes a simulation where only 20 PVT-succession class combinations were used, and *more classes* represents a simulation using about 50 combinations of PVT and succession classes.

condition reference. The simulated time series typically had more than four times as many as satellite mapped succession classes. This resulted in low similarity between the simulated data and the satellite mapped data. The sensitivity of the Sorensen's index to the number of classes and landscape size suggests that this index is both resolution and scale dependent, respectively, and therefore should be used with some caution. However, these dependencies do not detract from the utility of SI as a relative measure of change in our study because our use of a common historical average landscape composition as the basis for comparison greatly reduces the chance of capricious outcomes.

Since the LANDSUM model does not contain a linked mechanistic simulation between climate–fire–vegetation, it is unable to predict emergent vegetation and fire dynamics as climates shift. This renders our approach less sensitive to potential feedback relationships between climate and the acceleration of disturbance rates in the context of a changing landscape composition. Moreover, the finest level of resolution for describing vegetation is the succession class (based on species dominance) and PVT (based on species potential to inhabit a unique biophysical setting). It is entirely possible that future climates will cause major changes in species assemblages and the pathways of vegetation development used in LANDSUM (Table 1) will be entirely different as the PVT migrates across the landscape. Moreover, the important characteristics of these new plant communities, such as

flammability, composition, and ability to survive fire, may also alter fire regimes and fire effects. Wildland fire regimes are tied to PVT in LANDSUM yet it is possible that the new set of succession classes in a migrated PVT pathway will have different fire frequencies and sizes. Last, this approach does not account for the variability of weather under new, evolving climates, which is the real driver of landscape dynamics (Bachelet et al., 2001; Millar et al., 2004). Most modeled gradients are predicted from annual averages so the variation of weather variables within the year was not used to predict climate change effects.

## 5. Conclusions

Results of this study indicate that the management of today's landscapes requires both a view to the past and a look to the future. It appears that changes in climate, whether caused by the burning of fossil fuels or other more natural factors, will inevitably change landscapes through disturbance and species dynamics. The potential for a landscape to respond to this change will depend on a variety of characteristics, including topography, current landscape structure and composition, and native fire regimes. Managers need to recognize the historical dynamics of landscapes to ensure there is no loss of important landscape elements, but at the same time, managers will need to evaluate if current management will create landscapes that will be within reasonable bounds for future landscape conditions. Simulation modeling will play an important role in this evaluation by generating time series of landscape composition and structure for both historical and future landscapes. These series can then be compared against various landscape management alternatives to determine the best strategy for maintaining landscape integrity in this era of rapid climate change. The problem now is determining the future climate and developing comprehensive models for land management that predict ecosystem responses to these climate changes.

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## References

- Arno, S.F., 1979. Forest regions of Montana. USDA Forest Service Intermountain Research Station General Technical Report INT-218. 39 pp.
- Arno, S.F., 1980. Forest fire history of the northern Rockies. *J. Forestry* 78, 460–465.
- Arno, S.F., Simmerman, D.G., Keane, R.E., 1985. Forest Succession on Four Habitat Types in Western Montana. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station, Ogden, UT, USA, p. 74.
- Bachelet, D., Lenihan, J.M., Daly, C., Neilson, R.P., 2000. Interactions between fire, grazing and climate change at Wind Cave National Park, SD. *Ecol. Modell.* 134, 229–244.
- Bachelet, D., Neilson, R.P., Lenihan, J.M., Drapek, R.J., 2001. Climate change effects on vegetation distribution and carbon budget in the United States. *Ecosystems* 4, 164–185.
- Barrett, S.W., Arno, S.F., Key, C.H., 1991. Fire regimes of western larch-lodgepole pine forests in Glacier National Park, Montana. *Can. J. Forest Res.* 21, 1711–1720.
- Bartlein, P.J., Whitlock, C., Shafer, S.L., 1997. Future climate in the Yellowstone National Park Region and its potential impact on vegetation. *Conserv. Biol.* 11, 782–792.
- Beckage, B., Platt, W.J., Panko, B., 2005. A climate-based approach to the restoration of fire-dependent ecosystems. *Restor. Ecol.* 13, 429–431.
- Boyчук, D., Perera, A.H., Ter-Mikaelian, M.T., Martell, D.L., Li, C., 1997. Modelling the effect of spatial scale and correlated fire disturbances on forest age distribution. *Ecol. Modell.* 95, 145–164.
- Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J., 1984. Classification and Regression Trees. Wadsworth, International Group, Belmont, CA, 432 pp.
- Bugmann, H.K.M., 1996. A simplified forest model to study species composition along climate gradients. *Ecology* 77, 2055–2074.
- Caratti, J.F., 2006. The LANDFIRE Prototype Project Reference Database. In: Rollins, M.G., Frame, C. (Eds.), The LANDFIRE prototype project: nationally consistent and locally relevant geospatial data for wildland fire management. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-175. Fort Collins, CO, USA, pp. 222–245.
- Cary, G.J., Banks, J.C.G., 1999. Fire regime sensitivity to global climate change: an Australia perspective. In: Innes, J.L., Beniston, M., Verstraete, M.M. (Eds.), *Advances in Global Change Research: Biomass Burning and its Inter-relationships with the Climate System*. Kluwer Academic Publishers, London, UK.
- Cary, G.J., Keane, R.E., Gardner, R.H., Lavorel, S., Flannigan, M.D., Davies, I.D., Li, C., Lenihan, J.M., Rupp, T.S., Mouillot, F., 2006. Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern and climate. *Landscape Ecol.* 21, 121–137.
- Cattellino, P.J., Noble, I.R., Slatyer, R.O., Kessell, S.R., 1979. Predicting the multiple pathways of plant succession. *Environ. Manage.* 3, 41–50.
- Daubenmire, R., 1966. Vegetation: identification of typical communities. *Science* 151, 291–298.
- Davis, K.M., Clayton, B.D., Fischer, W.C., 1980. Fire ecology of Lolo National Forest habitat types. USDA Forest Service. p. 77.
- De'ath, G., 2002. Multivariate regression trees: a new technique for modeling species-environment relationships. *Ecology* 83, 1105–1117.
- Egan, D., Howell, E.A. (Eds.), 2001. *The Historical Ecology Handbook*. Island Press, Washington, DC, USA.
- Flannigan, M.D., Amiro, B.D., Logan, K.A., Stocks, B.J., Wotton, B.M., 2005. Forest fires and climate change in the 21st century. *Mitigation Adapt. Strategies Global Change* 11, 847–859.
- Frescino, T.S., Rollins, M.G., 2006. Mapping potential vegetation type for the LANDFIRE Prototype Project. In: Rollins, M.G., Frame, C. (Eds.), The LANDFIRE prototype project: nationally consistent and locally relevant geospatial data for wildland fire management. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-175. Fort Collins, CO, USA, pp. 222–245.
- Hamann, A., Wang, T., 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. *Ecology* 87, 2733–2786.
- Hann, W.J., 2004. Mapping fire regime condition class: a method for watershed and project scale analysis. In: Engstrom, R.T., Galley, K.E.M., De Groot, W.J. (Eds.), 22nd Tall Timbers Fire Ecology Conference: Fire in Temperate, Boreal, and Montane Ecosystems. Tall Timbers Research Station, pp. 22–44.
- Holsinger, L., Keane, R.E., Parsons, R., Karau, E., 2006. Development of biophysical gradient layers. In: Rollins, M.G., Frame, C. (Eds.), The LANDFIRE prototype project: nationally consistent and locally relevant geospatial data for wildland fire management. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-175. Fort Collins, CO, USA, pp. 9–22.
- IPCC, 2007. Climate change 2007: the physical basis. In: Summary for Policymakers, IPCC Secretariat, Geneva, Switzerland, p. 18.
- Iverson, L.R., Prasad, A.M., 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. *Ecol. Monogr.* 68, 465–485.

- Iverson, L.R., Prasad, A.M., 2002. Potential redistribution of tree species habitat under five climate change scenarios in the eastern US. *Forest Ecol. Manage.* 155, 205–222.
- Karau, Eva, Keane, Robert E., 2007. Determining the spatial extent of a landscape using simulation modeling. *Landscape Ecol.* 22, 993–1006.
- Keane, R.E., Cary, G., Davies, I.D., Flannigan, M., Gardner, R.H., Lavorel, S., Lenihan, J.M., Li, C., Rupp, T.S., 2007. Understanding global fire dynamics by classifying and comparing spatial models of vegetation and fire dynamics. In: Canell, J., Pataki, L.P.P. (Eds.), *Terrestrial Ecosystems in a Changing World—GCTE Synthesis Book*. Cambridge University Press, Cambridge, United Kingdom.
- Keane, R.E., Cary, G., Davies, I.D., Flannigan, M.D., Gardner, R.H., Lavorel, S., Lennihan, J.M., Li, C., Rupp, T.S., 2004. A classification of landscape fire succession models: spatially explicit models of fire and vegetation dynamic. *Ecol. Modell.* 256, 3–27.
- Keane, R.E., Cary, G.J., Parsons, R., 2003. Using simulation to map fire regimes: an evaluation of approaches, strategies, and limitations. *Int. J. Wildland Fire* 12, 309–322.
- Keane, R.E., Long, D., Basford, D., Levesque, B.A., 1997. Simulating vegetation dynamics across multiple scales to assess alternative management strategies. In: *Conference Proceedings – GIS 97, 11th Annual Symposium on Geographic Information Systems – Integrating Spatial Information Technologies for Tomorrow*. GIS World, INC, Vancouver, British Columbia, Canada, pp. 310–315.
- Keane, R.E., Garner, J., Teske, C., Stewart, C., Paul, H., 2002a. Range and variation in landscape patch dynamics: implications for ecosystem management. In: *Proceedings from the 1999 National Silviculture Workshop*. USDA Forest Service Rocky Mountain Research Station, Kalispell, MT USA, pp. 19–26.
- Keane, R.E., Holsinger, L., 2006. *Simulating Biophysical Environment for Gradient Modeling and Ecosystem Mapping Using the WXFIRE Program: Model Documentation and Application*. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, p. 61.
- Keane, R.E., Holsinger, L., Pratt, S., 2006. Simulating historical landscape dynamics using the landscape fire succession model LANDSUM version 4.0. In: Rollins, M.G., Frame, C. (Eds.), *The LANDFIRE prototype project: nationally consistent and locally relevant geospatial data for wildland fire management*. USDA Forest Service Rocky Mountain Research Station General Technical Report RMRS-GTR-175. Fort Collins, CO, USA, pp. 277–314.
- Keane, R.E., Parsons, R., Hessburg, P., 2002b. Estimating historical range and variation of landscape patch dynamics: limitations of the simulation approach. *Ecol. Modelling* 151, 29–49.
- Kessell, S.R., Fischer, W.C., 1981. Predicting postfire plant succession for fire management planning. USDA Forest Service, Intermountain Research Station General Technical Report INT 94. 19 pp.
- Landres, P.B., Morgan, Penelope, Swanson, F.J., 1999. Overview and use of natural variability concepts in managing ecological systems. *Ecol. Appl.* 9, 1179–1188.
- Lenihan, J.M., Daly, C., Bachelet, D., Neilson, R.P., 1998. Simulating broad scale fire severity in a dynamic global vegetation model. *Northwest Sci.* 72, 91–103.
- Lindner, M., 2000. Developing adaptive forest management strategies to cope with climate change. *Tree Physiol.* 20, 299–307.
- Long, D.G., Losensky, J., Bedunah, D., 2006. Vegetation succession modeling for the LANDFIRE Prototype Project. In: Rollins, M.G., Frame, C. (Eds.), *The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management*. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 215–275.
- Millar, C.I., Westfall, R.D., Delany, D.L., King, J.C., Graumlich, L.J., 2004. Response of subalpine conifers in the Sierra Nevada, California, USA to 20th-century and decadal climate variability. *Artic Antarctic Alpine Res.* 36, 181–200.
- Morgan, P., Bunting, S.C., Black, A.E., Merrill, T., Barrett, S., 1996. Past and present fire regimes in the Interior Columbia River Basin. In: Close, K., Bartlette, R.A. (Eds.), *Proceedings of the 1994 Interior West Fire Council Meeting and Program*. Fire Management Under Fire (Adapting to change) International Association of Wildland Fire, Fairfield, Washington, Coeur d'Alene, ID, pp. 77–87.
- Mote, P.W., Salath, E.P., Peacock, C., 2005. Scenarios of future climate for the Pacific Northwest. A report prepared for King County (Washington)'s October 27, 2005 climate change conference "The Future Ain't What It Used to Be: Preparing for Climate Disruption". Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle. <http://cses.washington.edu/db/pubs/abstract462.shtml>.
- Mouillot, F., Rambal, S., Joffre, R., 2002. Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. *Global Change Biol.* 8, 423–437.
- Mueller-Dombois, D., Ellenberg, H., 1974. *Aims and Methods of Vegetation Ecology*. John Wiley and Sons, New York, USA.
- Neilson, R.P., Pitelka, L.F., Solomon, A.M., Nathan, R.J., Midgeley, G.F., Fragoso, J.M., Lischke, H., Thompson, K., 2005. Forecasting regional to global plant migration in response to climate change. *Bioscience* 55, 749–760.
- Noble, I.R., Slatyer, R.O., 1977. Post-fire succession of plants in Mediterranean ecosystems. In: *Symposium on Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems*, Palo Alto, CA, USA, pp. 27–36.
- Nonaka, E., Spies, T.A., 2005. Historical range of variability in landscape structure: a simulation study in Oregon, USA. *Ecol. Appl.* 15, 1727–1746.
- Overpeck, J.T., Bartlein, P.J., Webb, T., 1991. Potential magnitude of future vegetation change in Eastern North America: comparisons with the past. *Science* 254, 692–695.
- Pfister, R.D., Arno, S.F., 1980. Classifying forest habitat types based on potential climax vegetation. *Forest Sci.* 26, 52–70.
- Pratt, S.D., Holsinger, L., Keane, R.E., 2006. Modeling historical reference conditions for vegetation and fire regimes using simulation modeling. In: Rollins, M.G., Frame, C. (Eds.), *The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management*. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 277–314.
- Randolph, J.C., Lee, J.K., 1996. Climate change effects on forests of the eastern United States. In: *GIS 93 Symposium: GIS Applications in Natural Resources*. GIS World, Vancouver, British Columbia, Canada, pp. 399–407.
- Rollins, M.G., Frame, C., 2006. *The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management*. U.S. Department of Agriculture, Forest Service Rocky Mountain Research Station, Fort Collins, CO, p. 435.
- Rollins, M.G., Keane, R.E., Zhu, Z., 2006. An overview of the LANDFIRE Prototype Project. In: Rollins, M.G., Frame, C. (Eds.), *The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management*. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 5–43.
- Romme, W.H., Turner, M.G., 1991. Implications of global climate change for biogeographic patterns in the greater Yellowstone ecosystem. *Conserv. Biol.* 5, 373–386.
- Rulequest Research, 2006. See5/C5.0 software for constructing classifiers in the form of decision trees and rulesets. [www.rulequest.com](http://www.rulequest.com).
- Running, S.W., Thornton, P.E., 1996. Generating daily surfaces of temperature and precipitation over complex topography. In: Goodchild, M.F., Parks, B.O., Steyaert, L.T. (Eds.), *GIS and Environmental Modeling: Progress and Research Issues*. GIS World Books, Fort Collins, CO, pp. 93–98.
- Salathe, E.P., Mote, P.W., Wiley, M.W. Considerations for selecting down-scaling methods for integrated assessments of climate change impacts. *Int. J. Climatol.*, in press ([http://www.atmos.washington.edu/~salathe/papers/SalatheMoteWiley\\_IJOC.pdf](http://www.atmos.washington.edu/~salathe/papers/SalatheMoteWiley_IJOC.pdf)).
- Sorensen, T.A., 1948. A method of establishing groups of equal amplitude in plant sociology based on similarity species contents and its application to analyses of vegetation on Danish commons. *K. Dan. Videnskab. Selsk. Biol. Skr.* 5, 1–34.

- Steele, R., 1984. An approach to classifying seral vegetation within habitat types. *Northwest Sci.* 58, 29–39.
- Stocks, B.J., Fosberg, M.A., Lynaham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Lin, J.-Z., Lawrence, K., Hartley, G.R., Mason, J.A., McKenney, D.W., 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. *Climatic Change* 38, 1–13.
- Thornton, P.E., Law, B.E., Gholz, H.L., Clark, K.L., Falge, E., Ellsworth, D.S., Goldstein, A.H., Monson, R.K., Hollinger, D.Y., Falk, M., Chen, J., Sparks, J.P., 2002. Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests. *Agric. Forest Meteorol.* 113, 185–222.
- Thornton, P.E., Hasenauer, H., White, M.A., 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: an application over complex terrain in Austria. *Agric. Forest Meteorol.* 104, 225–271.
- Thornton, P.E., Running, S.W., White, M.A., 1997. Generating surfaces of daily meteorological variables over large regions of complex terrain. *J. Hydrol.* 190, 214–251.
- Ward, B.W., 2005. Mapsee5 classification tree prediction software. Version 0.5. LANDFIRE National Project ([www.landfire.gov](http://www.landfire.gov)). 5775 Highway 10 West, Missoula, Montana, USA.
- Wimberly, M.C., 2002. Spatial simulation of historical landscape patterns in coastal forests of the Pacific Northwest. *Can. J. Forest Res.* 32, 1316–1328.
- Zhu, Z., Vogelmann, J., Ohlen, D., Kost, J., Chen, S., Tolk, B., Rollins, M.G., 2006. Mapping existing vegetation composition and structure. In: Rollins, M.G., Frame, C. (Eds.), *The LANDFIRE Prototype Project: Nationally Consistent and Locally Relevant Geospatial Data for Wildland Fire Management*. USDA Forest Service Rocky Mountain Research Station, Fort Collins, CO, USA, pp. 195–215.