Comparison of the Sensitivity of Landscape-Fire-Succession Models to Variation in Terrain, Fuel Pattern, Climate and Weather

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***Abstract**—The relative importance of variables in determining area burned is an important management consideration although gaining insights from existing empirical data has proven difficult. The purpose of this study was to compare the sensitivity of modeled area burned to environmental factors across a range of independently-developed landscape-fire-succession models. The sensitivity of area burned to variation in four factors, namely terrain (flat, undulating and mountainous), fuel pattern (finely and coarsely clumped), climate (observed, warmer & wetter, and warmer & drier) and weather (year-to-year variability) was determined for four existing landscape-fire-succession models (EMBYR, FIRESCAPE, LANDSUM, and SEM-LAND) and a new model implemented in the LAMOS modelling shell (LAMOS(DS)). Sensitivity was measured as the variance in area burned explained by each of the four factors, and all of the interactions amongst them, in a standard generalised linear modelling analysis. Modeled area burned was most sensitive to climate and variation in weather, with four models sensitive to each of these factors and three models sensitive to their interaction. Models generally exhibited a trend of increasing area burned from observed, through warmer and wetter, to warmer and drier climates. Area burned was sensitive to terrain for FIRESCAPE and fuel pattern for EMBYR. These results demonstrate that the models are generally more sensitive to variation in climate and weather as compared with terrain complexity and fuel pattern, although the sensitivity to these latter factors in a small number of models demonstrates the importance of representing key processes. Our results have implications for representing fire in higher-order models like Dynamic Global Vegetation Models (DGVMs)*

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Introduction

Wildland fire is a major disturbance in most ecosystems worldwide (Crutzen and Goldammer 1993). Fire interacts with weather and vegetation such that forested landscapes may burn quickly whenever fuels are abundant, dry and spatially continuous, especially if there is a strong surface wind (McArthur 1967; Rothermel 1972). The relative importance of variables in determining area burned is an important management consideration although gaining insights from existing empirical data has proven difficult.

Landscape-fire-succession models, that simulate the linked processes of fire and vegetation development in a spatial domain, are one of the few tools that can be used to explore the interaction of fire, weather and vegetation over long time scales. There is a diverse set of approaches to predicting fire regimes and vegetation dynamics over long time scales, due in large part to the variety of landscapes, fuels and climatic patterns that foster frequent forest fires (Swanson and others 1997; Lertzman and others 1998), and variation in modeler's approaches to representing them in models.

Systematic comparisons among models, using a standardised experimental design, offers insight into our understanding of the key processes and parameters affecting diverse ecosystems (Dale and others 1985; Rose and others 1991; Gardner and others 1996; VEMAP 1996; Pan and others 1998; Cramer et al 1999) as well as our confidence in the reliability of model predictions (Bugmann and others 1996; Turner and others 1989). The objective of this research is to compare a range of landscape-fire succession models to gain insight into the relative importance of terrain, fuel pattern, weather and climate in determining modeled area burned, and the extent to which findings can be generalized across a range of ecosystem types.

We selected a set of landscape-fire-succession models and performed a comparison on neutral landscapes to identify the relative importance and sensitivity of simulated fire to terrain, fuel pattern, weather and climate. We originally planned to compare results of models from the twelve classification categories of landscape-fire-succession models of Keane and others (2004) but in reality we limited ourselves to models from three classification categories selected from modelers with the time and resources to undertake the complex simulation design. We compared five models including EMBYR (Gardner and others 1996), FIRESCAPE (Cary & Banks 1999), LANDSUM (Keane and others 2002), SEMLAND (Li 2000), and a new application of the LAMOS modelling shell (Lavorel and others 2000). These models may appear functionally similar but they are quite different in many aspects, including a wide diversity in the simulation of fire spread and ignition, representation of vegetation, and the complexity of climate and fire linkages (Cary and others 2006).

This study does not represent an exercise in model validation. Rather, we selected models that have previously been verified and validated, and one new model, and analysed their behaviour with respect to variation in terrain, fuel pattern, weather and climate. A more comprehensive description of the study is given by Cary and others (2006).

The Models

EMBYR is an event-driven, grid-based simulation model of fire ignition and spread designed to represent the landscapes and fire regimes of Yellowstone National Park (Hargrove and others 2000). The pattern of forest succession of lodgepole pine forests is simulated by a Markov model, with fuels sufficient to sustain crown fires developing as a function of forest stand age. The probability of fire spreading from a burning pixel to each of its neighbors is determined by stand age, fuel moisture, wind speed and direction, and slope. An index of fire severity, based on fuel type, fuel moisture, wind speed and the rate that the cell burned, determines whether fire intensity is sufficiently high to cause a stand-replacing fire.

FIRESCAPE simulates individual fire events that are combined into patterns of fire frequency, fire intensity and season of occurrence (Cary and Banks 1999). Daily weather is generated by a modified version of the Richardson-type stochastic climate generator (Richardson 1981) so that serial correlations within a particular meteorological variable and cross correlations between variables are maintained (Matalas 1967). Ignition locations are generated from an empirical model of lightning strike modified from McRae (1992).

The rate of spread of fire from a burning pixel to its neighbors is assumed to be elliptical (Van Wagner 1969) and is determined by Huygens' Principle, although varying topography, fuel load and wind direction result in non-elliptical fires. Head fire rate of spread is according to the fire behavior algorithms of McArthur (McArthur 1967; Noble and others 1980) with fuel loads modeled using Olson's (1963) model of biomass accumulation which has been parameterized for a range of Australian systems.

LAMOS(DS) is an implementation of LAMOS (Lavorel and others 2000) with a contagious spread fire model working on a daily time step. It is a simple model, sensible to daily minimum and maximum temperature, precipitation, fuel amount and slope. LAMOS(DS) contains two principle functions; one to estimate pan evaporation (Bristow and Campbell 1984; Roderick 1999) which, together with precipitation, produces a moisture budget, and a second equation to modify spread probabilities as a function of slope (Li 2000) and intensity. Fire intensity is the product of three linear functions: fuel load (0 – 1 kg m^{-2}), moisture (0-200mm) and temperature (5-25°C). Temperature during the course of the fire is interpolated between the daily minimum and maximum by a symmetrical sine function. Fires are assumed to begin when temperature is at the daily maximum. Fuel is consumed in proportion to the resulting intensity.

The LANDscape SUccession Model (LANDSUM) is a spatially explicit vegetation dynamics simulation program wherein succession is treated as a deterministic process, and disturbances are treated as stochastic processes (Keane and others 2002). Fire spread is a function of fuel-type, wind speed and direction, and slope using equations from Rothermel (1972) and Albini (1976). The elements that define the fire regime (for example average fire size, ignition probabilities) are input parameters, whereas fire regime is an emergent property for the other models. Ordinarily, the area burned in LANDSUM would not vary amongst the climate factors, however for this comparison, the probability of ignition success was made sensitive to the Keetch-Byram Drought Index.

The SEM-LAND model (Spatially Explicit Model for LANDscape Dynamics) simulates fire regimes and associated forest landscape dynamics resulting from long-term interactions among forest fire events, landscape structures, and weather conditions (Li 2000). A fire process is simulated in two stages: initiation and spread. The fire initiation stage continues from the presence of a fire ignition source in a forest stand until most trees in that stand have been burned. Once most trees are burned, the fire has the potential to spread to its surrounding cells. The probability of fire spread is determined by fuel and weather conditions and slope using relationships from the Canadian Forest Fire Weather Index system (Van Wagner 1987) and Canadian Forest Fire Behavior Prediction system (Forest Canada Fire Danger Group 1992; Hirsh 1996).

The Comparison Design

The comparison involved determining the sensitivity of modeled area burned to systematic variation in terrain, fuel pattern, climate and weather (Cary and others 2006). It incorporated three types of terrain, two types of fuel pattern, three different climates, and the full extent of weather variability for simulation locations. The simulation landscape was an array of 1000 by 1000 square pixels measuring 50 by 50 meters.

Variation in terrain was introduced by varying the minimum and maximum elevation of the simulation landscape by varying the amplitude of the two-dimensional sine function used to represent terrain. The sine functions had a periodicity of 16.67 km (333.3 pixels). Three landscapes representing flat, rolling and mountainous terrain, with maximum slope values of 0°, 15° and 30° respectively and relief of 0 m, 1250 m and 2500 m respectively were generated (figure 1). The average elevation of each landscape was 1250 m.

Fuel pattern was varied to represent finely clumped and coarsely clumped fuel patterns (figure 2). The finely clumped fuel pattern was comprised of ten by ten pixel (25 ha) clumps of varying fuel ages, whereas the coarsely clumped fuel pattern was comprised of fifty by fifty pixel (625 ha) clumps. Maps of fuel ages were generated by randomly allocating values from the series 0.1, 0.2, 0.3, ….1.0 to both finely and coarsely clumped fuel maps so that values were represented evenly across the landscapes. Ten replicate maps of each fuel pattern type were randomly generated for the model comparison. Fuel maps were transformed differently for each model to produce either fuel load or fuel age related maps that were meaningful to individual models (see Cary and others 2006). The maps of different fuel types were characterised by the same average fuel load or age, however the arrangement of different aged fuels varied between map types.

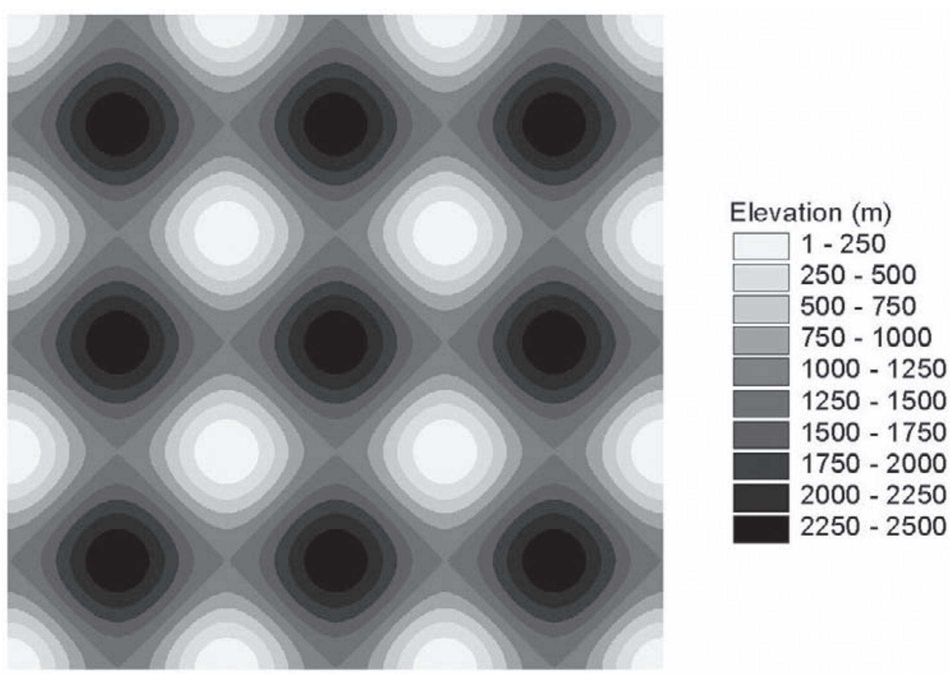

Figure 1—Pattern of elevation in mountainous landscape used in comparison of landscape-fire-succession models.

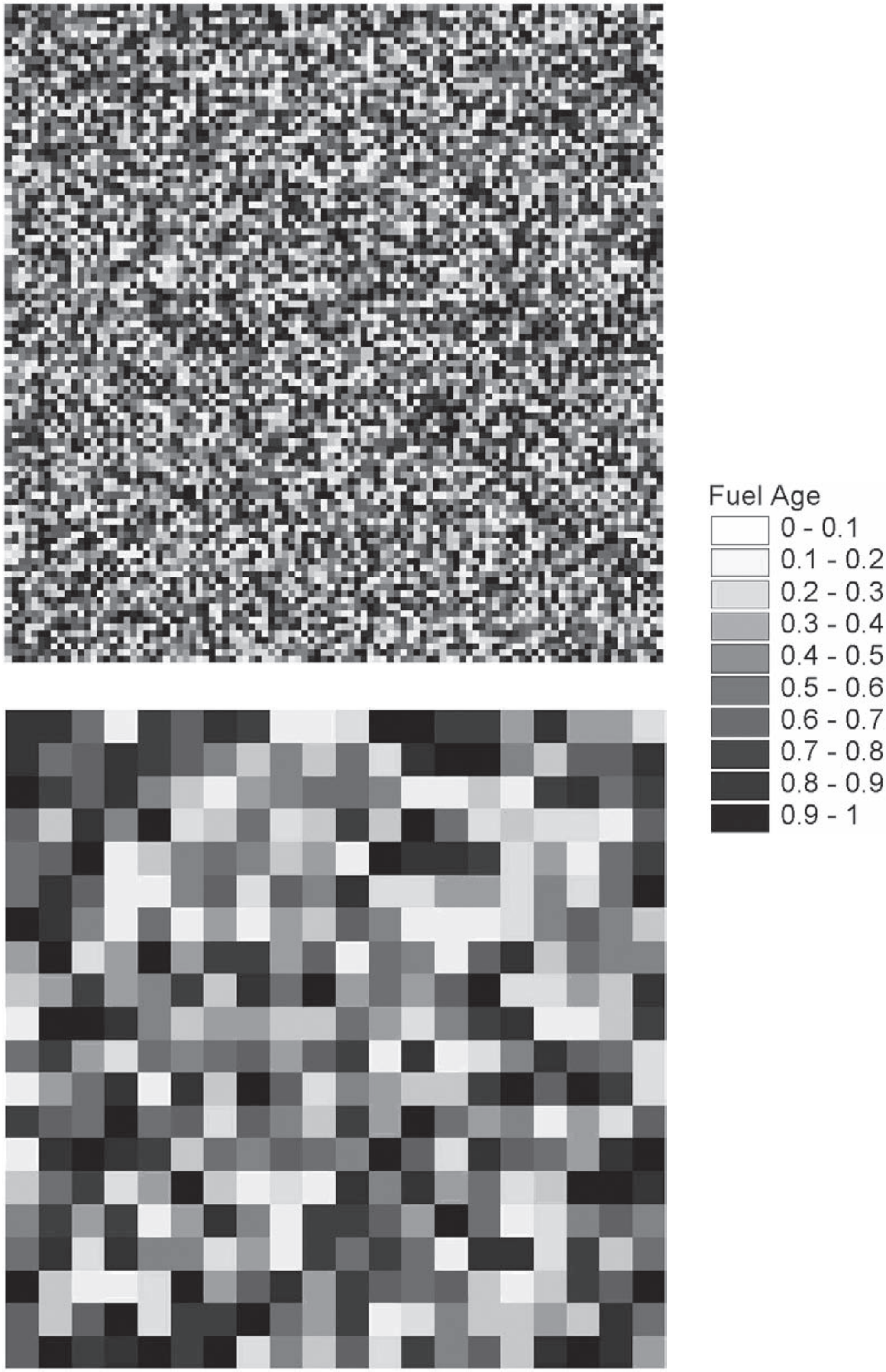

Figure 2—Replicate of each type of fuel pattern map used in comparison of landscape-fire succession models: a) finely clumped (25 hectare patches) and b) coarsely clumped (625 hectare patches) fuel pattern (values range from 0 to 1.0 and are transformed into fuel age or fuel load separately for each model.

Weather and climate are essentially different phenomena at fine temporal scales and were treated as orthogonal. Variation in weather was introduced for most models by selecting ten representative years of daily weather records for the landscape where the model has undergone most rigorous validation (table 1). For EMBYR, weather data from Glacier National Park, MT, was used. The ten weather years were selected so that the distribution of annual average daily temperature and annual average daily precipitation in the selected set best matched the variation in the weather record available (around 40 years for most models) (See Cary and others 2006). Three types of climate were included in the design, including observed, warmer/wetter, and warmer/drier climate. Daily values for the warmer/wetter and the warmer/drier climate were derived from the 10 weather years of observed climate by adding 3.6 °C (mid-range of projected global average temperature increase (1.4 to 5.8°C) (IPCC 2001) to daily temperature, and by decreasing daily precipitation by 20 percent for the warmer/drier climate and increasing daily precipitation by 20 percent for the warmer/wetter climate.

A total of 1,800 year-long simulations were run for each model (except for LANDSUM) from the 180 unique combinations of terrain (flat, mountainous, mountainous), fuel pattern (finely and coarsely clumped), climate (observed, warmer/wetter, warmer/drier), and weather (ten one-year replicates), given that there were ten replicate maps of each fuel pattern. Approximately 20 percent of the LANDSUM simulations did not experience fire and this resulted in a poor estimate of the probability and size of fires, because of the shortness of the simulation periods. This was rectified by performing ten

Table 1—Available weather data for study regions and associated models.

Location	Data type	Variables	Model
Glacier National Park, Montana	42 years, daily observations.	Daily maximum temperature (°C) Daily minimum temperature (°C) Daily precipitation (cm)	EMBYR LANDSUM
Edson, Alberta	34 years (1960 – 1993) of daily observation (observations at 1200 LST) from approximately the 1st April to 30th September, inclusive.	Temperature (°C) Relative Humidity (%) Windspeed ($km.h^{-1}$) Rainfall (mm) Daily FFMC*, DMC*, DC*, ISI*, BUI* Daily Fire Weather Index Number of days since rain * variables related to Fire Weather Index	SEM-LAND
Ginninderra, Australian Capital Territory	42 years of simulated weather based on Richardson-type weather simulator (Richardson, 1981) modified for all variables required for fire behaviour modelling.	Daily maximum temperature (°C) Daily minimum temperature (°C) Daily west-east wind speed ($km.h^{-1}$) Daily south-north wind speed ($km.h^{-1}$) Daily 9 am atmospheric vapour pressure (kPa) Daily precipitation (mm)	FIRESCAPE
Corsica	38 years (1960 – 1997) of daily observations.	Daily average temperature (°C) Daily precipitation (mm) Daily PET (mm)	LAMOS

simulation replicates for each unique combination of terrain, fuel pattern, fuel pattern replicate, climate, and weather replicate, and averaging them to produce a better estimate of area burned. Fires affected fuel load/age within each simulation but, since simulations were for only a single year, no vegetation succession algorithms were invoked. The total area burned per year (m^2) was recorded for each one-year simulation.

The sensitivity of simulated area burned to terrain, fuel pattern, climate and weather was assessed from the variance explained by each of the variables and all possible interactions. Variance explained (r^2) was determined from a fully factorial ANOVA performed in the SAS statistical package. Variance explained is a more meaningful measure than statistical significance when comparing the importance of environmental variables, particularly when dealing with simulated data. It facilitates the comparison of the importance of a range of variables on area burned, across a range of models with different input requirements and calibrated for widely separated landscapes characterised by quite different climate systems and weather syndromes. Plots of residual values against fitted values were constructed for each analysis. Analyses performed on untransformed area-burned data produced residuals which were highly skewed and the variance in residuals that was highly variable across fitted values. Transformation of area burned by the natural logarithm produced patterns of residuals that we considered acceptable for our analyses.

Results

Simulated area burned was more sensitive to climate and weather than to fuel pattern and terrain (table 2). Ln-transformed modeled area burned was considered sensitive to variation in climate for FIRESCAPE, LAMOS, LANDSUM and SEM-LAND while it was considered sensitive to variation in weather for EMBYR, FIRESCAPE, LANDSUM and SEM-LAND. The interaction between these two variables was considered important for EMBYR, LANDSUM and SEM-LAND. For models sensitive to climate, there was a trend for increasing area burned for warmer climates (warmer/drier and warmer/wetter) compared with the observed climate, with the warmer/drier climate being characterised by larger area burned than the warmer/wetter climate in two of four cases (see Cary and others 2006).

Only FIRESCAPE showed sensitivity to variation in terrain (and the interaction between terrain and weather, and that between terrain, climate and weather). Modeled area burned was highest for mountainous terrain and least for flat terrain. Only EMBYR showed sensitivity to variation in fuel pattern (and the interaction between fuel pattern and weather factors). Modeled area burned was higher for the coarsely clumped fuel pattern than for the finely clumped pattern (see Cary and others 2006).

Discussion

The variance in modeled area burned was greater for weather than climate for EMBYR, LANDSUM and SEM-LAND, compared with FIRESCAPE and LAMOS, perhaps because the inter-annual variation between the weather years for these locations was lower than for other sites. Nevertheless, sensitivity of modeled area burned to weather was considered important for four

Table 2—Relative Sums of Squares attributed to different sources of variation in the comparison of sensitivity of ln-transformed area burnt to terrain (Terrain), fuel pattern (Fuel), climate (Climate) and weather factors (Weather), and their interactions. Factors and their interactions are considered important if they explain more than 0.05 and 0.025 of total variance respectively. Factors and interactions considered unimportant are blank. Significant factors and interactions ($P < 0.05$) are indicated by *.

		Model				
Source	**DF**	**EMBYR**	**FIRESCAPE**	**LAMOS**	**LANDSUM**	**SEM-LAND**
Terrain	2		0.293*			
Fuel	1	0.217*	*		*	*
Terrain x Fuel	2		*			
Climate	2	*	0.418*	0.278*	0.178*	0.370*
Terrain x Climate	4		*			
Fuel x Climate	2	*				*
Terrain x Fuel x Climate	4		*			
Weather	9	0.329*	0.087*	*	0.333*	0.542*
Terrain x Weather	18		0.025*		*	
Fuel x Weather	9	0.031*	*			*
Terrain x Fuel x Weather	18	*				
Climate x Weather	18	0.096*	*	*	0.224*	0.046*
Terrain x Climate x Weath	36		0.025*			
Fuel x Climate x Weather	18	*				
Terr x Fuel x Clim x Weath	36					
Model	179	0.744	0.905	0.401	0.766	0.971

Note that not all significant sources are considered important.
(Source: Cary and others 2006)

out of five models. The overriding importance of weather for fire activity has been highlighted in numerous studies (see Flannigan and Harrington 1988; Swetnam 1993; Bessie and Johnson 1995; Hely and others 2001; Flannigan and Wotton 2001). Our finding regarding the importance of weather across a range of models highlights the importance of adequately incorporating variability in weather into landscape-fire-succession models.

Several authors have provided simulated evidence for increasing area burned or frequency of fire under warmer climates (Clark 1990; Cary and Banks 1999; Li and others 2000; Cary 2002), possibly due to a longer fire season (Stocks et al 1998; Wotton and Flannigan 1993). This is consistent with our general findings. Climate was not considered important for EMBYR although earlier studies have indicated that a wetter climate would result in larger fires (Gardner and others 1996). A possible explanation for the discrepancy is that, in this study, simulations were only one year in length and vegetation succession effects were not incorporated. We are planning new research where simulations will be centuries long, allowing for the importance of vegetation succession to be explored.

Fuel pattern was relatively unimportant, except in the case of EMBYR. Fire spread in EMBYR is partly a function of the nature of fuel in the source and target pixels of any fire spread event. Frequently changing fuel condition in the finely clumped fuel pattern resulted in a decrease in area burned compared with the coarsely clumped pattern. While this is a realistic representation of fire spread, fuel pattern accounts for a comparatively small amount of variance in EMBYR compared to climate and weather in the other models.

Terrain was considered important for FIRESCAPE, despite all models incorporating a similar positive effect of slope on fire spread. FIRESCAPE is the only model that varies weather with terrain. The mountainous terrain provides a greater proportion of the landscape which is warmer and drier (in the "valleys"), compared to the rolling and flat landscapes, given that all landscapes were characterized by an average elevation of 1250 m. Representing the effect of terrain on weather in landscape fire models is fundamental if this aspect of the terrain factor is to influence models results in a realistic fashion.

Our results have implications for representing fire in higher-order models like Dynamic Global Vegetation Models (DGVMs). The relative unimportance of fine scale fuel pattern indicates that coarse scale DGVMs may not need to incorporate pattern of vegetation within simulation cells, although this depends on the importance of vegetation succession on area burned, which was not tested in this experiment. On the other hand, landscape scale pattern in terrain was demonstrated to be fundamentally important using the one landscape-fire-succession model that incorporates the effect of terrain on weather. Also, the general finding of the importance of inter-annual variability in weather (compared with climate) has important implications for the inclusion of fire into DGVMs because an increase in inter-annual weather variability resulted in greater effects on area burned than the climate variable in some cases.

The results from this study are concerned with comparing landscapes where the mean fuel age/load is constant across simulations but varies in the arrangement of fuel (fuel pattern). We are presently using our approach to compare the sensitivity of modeled area burned to variation in approach/extent of fuel management and ignition probability. It also has considerable potential for conducting comparisons amongst groups of other types of models producing variation in landscape dynamics, and for further comparison amongst landscape-fire succession-models.

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