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Research article

Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather*

Geoffrey J. Cary[1,2,*], Robert E. Keane[3], Robert H. Gardner[4], Sandra Lavorel[5], Mike D. Flannigan[6], Ian D. Davies[7], Chao Li[8], James M. Lenihan[9], T. Scott Rupp[10] and Florent Mouillot[11]

*[1]School of Resources, Environment and Society, Building 48 Linnaeus Way, The Australian National University, Canberra ACT 0200, Australia; [2]Bushfire Cooperative Research Centre, Australia; [3]USDA Forest Service, Rocky Mountain Research Station, Missoula MT, USA; [4]Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg MD, USA; [5]Laboratoire d'Ecologie Alpine, CNRS, Grenoble, France; [6]Canadian Forest Service, Sault Ste Marie ON, Canada; [7]Ecosystem Dynamics, Research School of Biological Sciences, Australian National University, Canberra, Australia; [8]Canadian Forest Service, Edmonton, Alberta, Canada; [9]USDA Forest Service, Pacific Northwest Research Station, Corvallis Oregon, USA; [10]University of Alaska Fairbanks, Department of Forest Sciences, Fairbanks Alaska, USA; [11]IRD UR060 – CEFE/CNRS, Montpellier, France; *Author for correspondence: (e-mail: geoffrey.cary@anu.edu.au)*

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Abstract

The purpose of this study was to compare the sensitivity of modelled 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. Modelled 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 with a 23-fold increase in area burned, on average, from the observed to the warmer, drier climate. 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. The models that represented fire ignition and spread in a relatively

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complex fashion were more sensitive to changes in all four factors because they explicitly simulate the processes that link these factors to area burned.

Introduction

Forested landscapes may burn quickly whenever fuels are abundant, dry and spatially continuous, especially if there is a strong surface wind. Although this prescription for fire propagation is simple, the landscape-scale changes resulting from fires are complex and difficult to predict (Turner et al. 1989a; Hargrove et al. 2000). The complexity is due in large part to the stochastic pattern of fire ignition (Barrows et al. 1977; Fuquay 1980; Knight 1987), the highly variable rates of fire spread (McArthur 1967; Rothermel 1972) and the long-term process of forest recovery, and these processes are affected by fundamental environmental factors including terrain, fuel pattern, climate and weather. Future shifts in the fire regime due to changing climate, land use, and management policies represent additional, significant uncertainty that is presently difficult to address with existing empirical data (Flannigan and Van Wagner 1991; Clark 1993; Starfield and Chapin 1996; Stocks et al. 1998; Rupp et al. 2000; Cary 2002). Since it is difficult to evaluate the relative importance of terrain, fuel pattern, climate and weather on fire extent, it follows that long-term plans for managing fire within forested landscapes are difficult to develop and controversial to implement (Jackson 1968; Romme 1982; Agee 1993; Crutzen and Goldhammer 1993; Moreno and Oechel 1994).

Simulation models are essential tools for studying the complex dynamics of natural and managed ecosystems (DeAngelis et al. 1998; Baker 1999), especially when future conditions are uncertain (Pan et al. 1998). They also provide a useful synopsis of our current understanding of ecosystem development and change (Keane and Finney 2003). Systematic comparisons among a spectrum of models, using a standardised experimental design, offer insight into our understanding of the key processes and parameters affecting diverse ecosystems (Dale et al. 1985; Rose et al. 1991; Gardner et al. 1996; VEMAP 1996; Pan et al. 1998; Cramer et al. 1999) as well as our confidence in the reliability of model predictions (Bugmann et al. 1996; Turner et al. 1989b). The standardised comparison of diverse models has the additional advantage of allowing the quantification of model effects due to differences in model structure (i.e., differences in resolution, complexity and solution technique) to be distinguished from model effects due to variation in the environmental and biotic interactions that determine change (e.g., weather and landscape structure). Comparisons of this nature also offer greater confidence in simulation results when there is consistency in response across a range of models.

Fire modelling has certainly produced a diverse set of approaches to prediction of landscape-scale effects of changing fire regimes resulting from changes in fire behaviour (Baker 1989; Keane and Finney 2003; Keane et al. 2004). This diversity is due in large part to the variety of landscapes, fuels and climatic patterns that foster frequent forest fires (Swanson et al. 1997; Lertzman et al. 1998), and variation in approaches for representing them in models. The set of causal mechanisms affecting fire regimes tend to be highly correlated and somewhat localized, confounding the integration of cause–effect relationships among landscape fuel and terrain patterns, weather variation, and the simulated fire effects. Much can be gained if a set of models were applied to a common landscape to determine similarities in model behavior across simulation scenarios. A uniform set of empirical protocols to validate multiple models for a variety of ecosystem types is currently unavailable (Baker 1989), making the direct comparison among models highly problematic (Gardner et al. 1980; Gardner et al. 1982; Turner et al. 1989b; Bugmann et al. 1996). The purpose of this paper is to investigate the importance of terrain, fuel pattern, climate, and weather for area burned generated by a range of landscape-fire-succession models using a general method for comparing results across models. The results of the factorial set of simulations were then analysed to assess their sensitivity, in terms of area burned, to variation in factors and complexity of model formulation. Methods presented in this study can be used on other sets of models to compare and model behavior.

Given the hypothetical nature of some of our simulation landscapes, a necessary outcome of developing standardised conditions for comparison amongst a range of diverse models, this study does not represent an exercise in model validation. Rather, we selected models that have previously been verified and validated (Gardner et al. 1996; Cary 1998; Cary and Banks 1999; Keane et al. 2002; Li 2000), and one new model, and analysed their behaviour with respect to variation in terrain, fuel pattern, weather and climate.

The experiment presented here is part of a three-phase approach, designed to separate effects of different factors on behaviour of model components. Here we focus on comparing the model behaviour resulting from fire spread and ignition modules of models. Subsequent research will address fire effects and vegetation succession.

Models

Keane et al. (2004) classified 44 landscape-fire-succession models according to the level of stochasticity, complexity and level of mechanism of the four primary processes that influence fire and vegetation dynamics (i.e. fire ignition, fire spread, fire effects and vegetation succession). Ideally, the study presented here would have selected models from across all categories of the classification, however, model selection was also constrained by the availability of modellers with sufficient resources to undertake our design. Nevertheless, the five models selected for the comparison (EMBYR, FIRESCAPE, LANDSUM, LAMOS(DS), SEMLAND) represented a spectrum of complexity in model formulation and represented three out of the twelve classification categories presented by Keane et al. (2004). The set of models evaluated here link the mechanisms of fire ignition, spread and extinction, and subsequent vegetation succession, to simulate patterns of fire on large landscapes, over long-time scales using daily weather data. Modelled fire events are combined, over time, into patterns of fire regime. EMBYR is the only model that simulates the ignition of spot fires from the transportation of firebrands. The following section presents a brief description of the models.

EMBYR

EMBYR was designed to represent the landscapes and fire regimes of Yellowstone National Park (Hargrove et al. 2000). Ignition can occur randomly or by specifying locations. Fire spread is simulated by examining each burning site and determining spread to the eight neighbouring sites as a function of fuel type, fuel moisture, wind speed and direction, and slope. In addition, burning sites may distribute firebrands to downwind sites, where the probability of ignition of new fires is determined by local conditions. Fires are propagated by empirical probabilities of fire spread. The probabilities are dependent on the age of the forest stand and the fuel moisture conditions (i.e., probabilities of spread increase with increasing age and decreasing fuel moisture) and are adjusted during the simulation by the local topography, fuel moisture, wind speed and direction. The fire-spread probabilities for EMBYR were developed and calibrated by reconstructing the weather events in Yellowstone National Park for 1988, simulating the spread of fire, and comparing simulation results with empirical information from a series of 1 × 1 km post-fire study sites (Turner et al. 1997).

A qualitative index of fire severity of each burned site is estimated as a function of fuel type, fuel moisture, wind speed and the rate that the cell burned. This index is then used to determine if fire intensity was sufficient to result in a stand-replacing fire. The pattern of forest succession of lodgepole pine (*Pinus contorta*) forests is simulated by a Markov model, with fuels sufficient to sustain crown fires developing as a function of forest stand age.

Simulations with EMBYR are quite rapid because it is an event-driven model, which updates the status of burning cells at time intervals determined by the speed of the fire front. Extensive simulations with EMBYR have demonstrated the sensitivity of landscape pattern to climate-dependent changes in the fire regime. More severe fires occurred when conditions were wetter than normal, while more frequent, smaller fires (and greater landscape fragmentation) occurred when conditions were drier than normal (Gardner et al. 1996). These results are consistent with empirical studies as well as simulation results with other models (e.g. Suffling et al. 1988; Clark 1989, 1990; Romme and Turner 1991; Antonovski et al. 1992; Baker 1992; Davis and Burrows 1993; Swetnam 1993).

FIRESCAPE

FIRESCAPE generates spatial patterns of fire regime (Gill 1975) for *Eucalyptus* dominated landscapes in south eastern Australia (Cary and Banks 1999). It operates on a daily time step that switches to hourly whenever a fire ignites. Ignition locations are generated from an empirical model of lightning strikes (Cary 1998). The probability of ignition is positively associated with the macro-scale elevation at the broad spatial scale, primarily reflecting the effect of mountain ranges on storm occurrence. It is also positively associated with the difference between the elevation of a site and the average elevation measured at a broader spatial scale. Daily weather is generated by a modified version of the Richardson-type stochastic climate generator (Richardson 1981; Cary and Gallant 1997; McCarthy and Cary 2002). Weather variables are simulated so that serial correlations within a variable and cross correlations between variables are maintained (Matalas 1967; Richardson 1981).

The spread of fire from cells to immediate neighbours is a function of elliptical fire spread (Van Wagner 1969) and Huygens' Principle (Anderson et al. 1982), although varying topography, fuel load and wind speed and direction result in non-elliptical fires. The rate of spread of the head fire is determined from fire behaviour algorithm associated with McArthur's Forest Fire Danger Meter (McArthur 1967; Noble et al. 1980). Fuel loads are modelled using Olson's (1963) model of biomass accumulation, which has been parameterised for a range of Australian systems (Fox et al. 1979; Walker 1981; Raison et al. 1983). Fire line intensity (kW m^{-1}) (Byram 1959) is calculated for the spread of fire from one cell to the next for characterising this aspect of the fire regime and for determining the extinction of individual fire events.

FIRESCAPE was used to determine the sensitivity of fire regimes to possible scenarios of climate change (CSIRO 1996) involving increased temperature, decreased humidity, and a shift in the seasonal distribution of rainfall but no effect on wind speed (Cary 2002). A general reduction in the mean inter-fire interval, both at specific localities and more generally within the landscape, was predicted for future climates, indicating FIRESCAPE is highly sensitive to the predicted change in key meteorological variables.

LAMOS(DS)

LAMOS(DS) is an implementation of the LAMOS modelling shell (Lavorel et al. 2000) with a contagious spread fire model working on a daily time step. It is a simple model, sensitive to daily minimum and maximum temperature, precipitation, fuel amount and slope. There are a fixed number of attempted ignitions at random locations over the year.

LAMOS(DS) contains two principle functions; one to estimate pan evaporation (Bristow and Campbell 1984; Roderick 1999; Roderick and Farquhar 2002) which, together with precipitation, simulates a moisture budget, and a second equation to modify spread probabilities to each of eight possible neighbours as a function of slope (Li 2000) and fire intensity. Wind direction is not used in this model. Fire intensity is the product of three linear functions: fuel load (0–1 kg m^{-2}), soil moisture (0–200 mm) and temperature (5–25 °C). Temperature is interpolated between the daily minimum and maximum during the course of the fire 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.

LANDSUM

The LANDscape SUccession Model (LANDSUM) is a spatially explicit vegetation dynamics simulation program wherein succession is treated as a deterministic process using a pathway or frame-based community sequence approach, and disturbances (e.g., fire, insects, and disease) are treated as stochastic processes with all but fire occurring at the polygon scale. Ignition locations are random in LANDSUM and it simulates fire from user-specified wind speed and direction, slope, and binary fuel type (burn, no-burn) determined from the succession stage.

LANDSUM was designed as a management tool for evaluating alternative management scenarios with a minimal set of input conditions (no explicit simulation of fuels, weather or lightning), so climate was not explicitly included in the model. The original LANDSUM (Keane et al. 2002) simulated year-to-year climate variability using an index (1–3 where 1 is a wet year and 3 is a dry year) that was pre-processed from the meteorological data selected for a model run. However, this approach was too coarse and somewhat incompatible for this comparison so a daily weather module was added to LANDSUM. This module computes the daily Keetch–Byram Drought Index (KBDI) and then compares the maximum value to the ranges 200–400, 400–600, and 600+ to decide the climate index. This index was then used to reference scalars of 0.5, 1.0, and 2.0 for fire frequency probabilities and fire size computations. These scalars, along with fire size and probability parameters, were estimated from fire history data compiled by Schmidt et al. (2002) and Keane et al. (1996) for a lodge-pole pine (*Pinus contorta*) dominated landscape in west-central Montana, USA.

SEM-LAND

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. A fire process is simulated in two stages: initiation and spread. The fire initiation stage, for a pixel, continues from the presence of a fire ignition source in a forest stand until most trees in that stand have been burned. Whether most trees in the stand would be burned is determined by the fire initiation probability, which is a function of fuel and weather conditions. Once most trees are burned, the fire has the potential to spread to its surrounding cells, and whether a neighboring cell would be burned is a function of the fire spread probability. The fire spread probability is determined by not only fuel and weather conditions, but also by slope in landscape topography. Relationships defining the influence of weather conditions on fuel moisture, and subsequently on fire spread, are summarized in the Canadian Forest Fire Weather Index system (FWI) (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction system (FBP) (Forest Canada Fire Danger Group 1992; Hirsh 1996) for a range of fuel types.

SEM-LAND was originally developed for the purpose of reconstruction of natural fire regimes (Li 2000), and has also been further refined to address other issues such as climate change impact on landscape structure and forest productivity (Li et al. 2000) and carbon dynamics (Li and Apps 2002), forest age distribution and fire regime (Li and Barclay 2001), fire suppression effect on fire size distribution (Li 2004), relationship between fire frequency and fire cycle (Li 2002), and fire ignition source pattern and fire regimes (Li 2003).

Methods

Simulation experiment

Models were run across a four-factor experimental design involving variation in terrain, fuel, climate and weather (Keane et al. 2003). Weather and climate are essentially different phenomena at fine temporal scales and were treated as orthogonal. Simulation landscapes were 250,000 ha and comprised of an array of 1000 by 1000 square pixels, each 0.25 ha (50 × 50 m) in area. Landscapes edges were treated as distinct, not as being continuous with opposite edges.

Terrain

Variation in terrain was introduced by varying the minimum and maximum (‘valley’ and ‘peak’) elevation, or amplitude, of a two-dimensional sine function with periodicity of 16.7 km (333.3 pixels) to create topography for three landscapes (Figure 1). The three terrain levels were flat, undulating and mountainous characterised by maximum slope values of 0, 15 and 30° and relief of 0, 1250 and 2500 m respectively. For each model, the mean elevation of each terrain map was scaled to the mean elevation of the actual landscape for which the model was initially developed. The value of 1250 m was assigned as the mean elevation of terrain maps for landscapes with actual mean elevation less than 1250 m to avoid the occurrence of areas below sea level in the mountainous terrain map.

Fuel

The two levels in the fuel factor were: (i) finely clumped and (ii) coarsely clumped spatial pattern

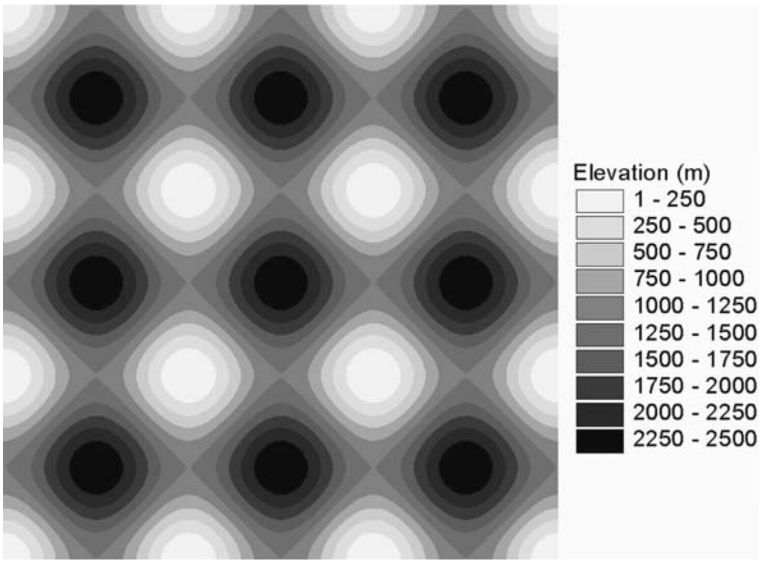

Figure 1. Pattern of elevation in mountainous landscape used in comparison of landscape-fire succession models.

of fuel (Figure 2). Ten replicates of the finely and coarsely clumped fuel maps were generated by randomly allocating values from the series 0.1, 0.2, 0.3, ….1.0 (inclusive) to either 50 by 50 pixel (625 ha) clumps (coarsely clumped) or 10 by 10 pixel (25 ha) clumps (finely clumped) so that values were evenly represented across landscapes. Fuel maps were transformed differently for each model by computing either fuel type or age values that were meaningful to individual models (Table 1).

Weather

Each model required a unique set of weather parameters, and no single weather data set satisfied the diverse requirements of all models. Therefore, simulations were performed using weather relevant to the location where the model had been previously parameterised and tested because we did not want to introduce uncertainty by using input data outside each model's validation domain. However, the amount of variability between replicate weather-years was standardised across all models.

Year-long sequences of daily weather were chosen from the available data sets, of slightly variable length, from locations where models were originally developed, or had been implemented (Table 2). For FIRESCAPE, data generated from an algorithm that produces sequences of weather with similar statistical qualities as observed data from the region (Cary and Gallant 1997) is the primary weather component.

For each model, 10 replicate weather years were drawn from full data sets so that they best matched the variation in average daily maximum temperature (°C) and average daily precipitation (mm) across all years (Table 2). This was achieved by repeatedly randomly selecting ten weather years from the full data set and determining the goodness of the fit of the cumulative probability distribution of the randomly selected set of weather years to that of the full data set for both temperature and precipitation simultaneously (See Figure 3). The goodness of fit was determined by a measure of deviance, calculated separately for temperature and precipitation by summing the squared residuals (difference between cumulative probability for observed data and that for random sample) for each temperature (or precipitation) data point in the observed data set. The total deviance was then defined as:

$$\mathrm{TD} = \sqrt{(\mathrm{DT}^2 + \mathrm{DP}^2)}$$

where TD is the total deviance from observed cumulative probability distributions; DT is the deviance from observed temperature cumulative probability distribution; and DP is the deviance from observed precipitation cumulative probability

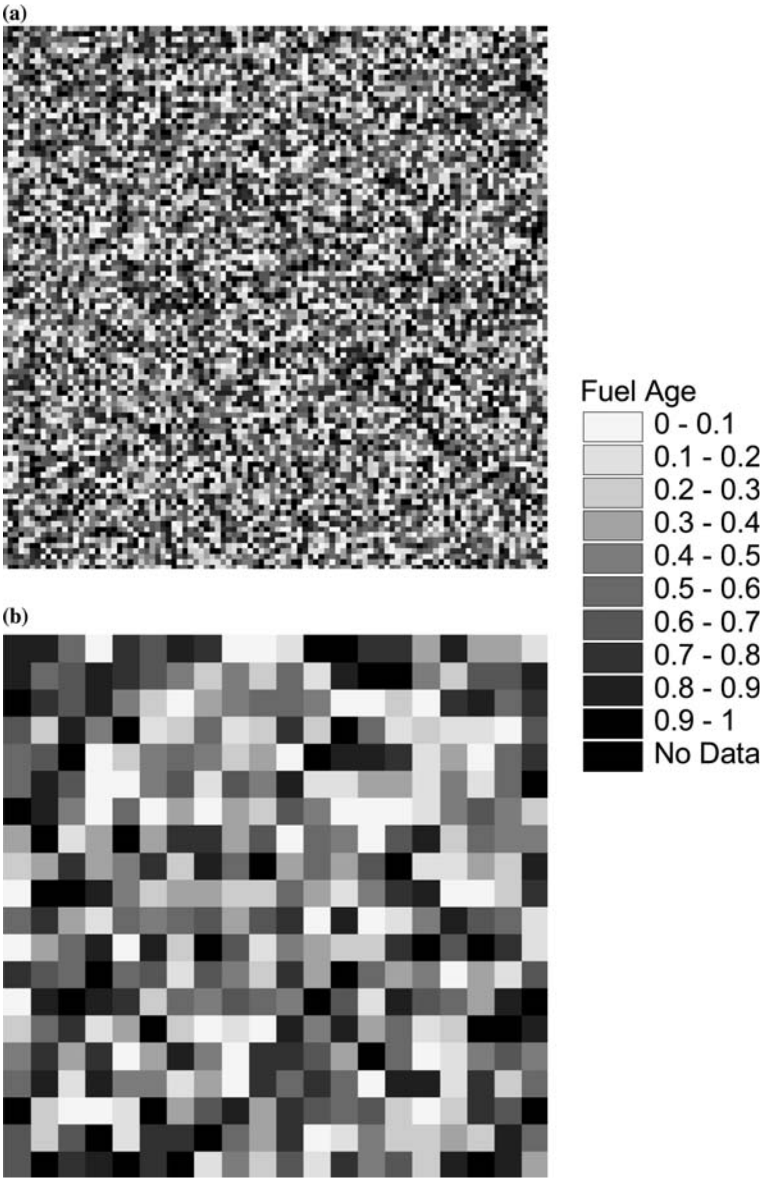

Figure 2. Replicate of each type of fuel pattern map used in comparison of landscape-fire succession models: (a) finely clumped (25 ha patches) and (b) coarsely clumped (625 ha patches) fuel pattern (values range from 0 to 1.0 and are transformed into fuel age or fuel load separately for each model.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

distribution. The best fitting set of selected weather years after 10^6 trials was used to represent the variation across the weather years available (Figure 4). The process was repeated for all climate locations.

Simulations in FIRESCAPE, LANDSUM and SEMLAND were performed using weather relevant to the region for which they were developed (Table 2), while those in EMBYR were performed with weather data from Glacier National Park, a somewhat related Rocky Mountain location. Simulations in LAMOS(DS), a more generally applicable model, were performed with weather from Corsica.

Climate

The three levels in the climate factor were: (i) observed climate; (ii) warmer and wetter climate; and (iii) warmer and drier climate. Daily values for the

Table 1. Vegetation type and fuel-map transformation rules for individual models.

Model	Vegetation type	Transformation for fuel map
EMBYR	Lodgepole pine	Classified into four classes of sequential stages of vegetation from the youngest fuel (LP0) (fuel map pixel value <0.25) to the climax community allocated to the oldest fuel (LP3) (fuel map pixel value >0.75).
FIRESCAPE	*Eucalyptus* forest	Multiplied by 1.6 kg m^{-2}, the average steady state litter loading observed for high elevation (>1500 m) sites in the Australian Capital Territory region (Cary 1998)
LAMOS(DS)	General	Multiplied by 1.0 kg m^{-2}
LANDSUM	Lodgepole pine – Douglas fir forest	Classified into eight classes of sequential stages of vegetation succession in from the youngest fuel (fuel map pixel value <0.12) to the climax community allocated to the oldest fuel (fuel map pixel value >0.88)
SEM-LAND	Boreal forest	Multiplied by maximum fuel load for boreal forest study area

warmer and wetter weather and the warmer and drier weather were derived by adding 3.6 °C (mid-range of projected global average temperature increase (1.4–5.8 °C) (IPCC 2001) to maximum and minimum temperature each day (or temperature at 1200 LST for SEM-LAND), and by multiplying daily rainfall amounts by 1.2 and 0.8 respectively.

Simulation methodology and data analysis

Sensitivity to terrain, fuel pattern, climate and weather factors

A total of 1800 year-long simulations were run for each model (3 terrain × 2 fuel pattern × 10 weather years × 3 climates). Fires affected fuel load/age within each simulation but, given that simulations were of single years, no vegetation succession algorithms were invoked. The total area burned per year (m^2) was recorded for each one-year simulation.

From prior experience, it was known that most models would experience numerous fires during each year-long simulation run, except for LANDSUM, in which approximately 20% of simulations would not experience fire because of insufficient simulation length, resulting in a poor estimate of the probability and size of fires. This was rectified by performing ten 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.

Data analysis

The sensitivity of modelled ignitions and area burned to terrain, fuel pattern, and climate was measured by the variance in area burned explained by each of the factors and all possible interactions. Variance explained (r^2) was determined from a fully factorial ANOVA performed in the SAS statistical package (SAS 2000). Plots of residual values against fitted values were constructed for each analysis. Analyses performed on untransformed area-burned data produced residuals that were highly skewed, and variance in residuals that were highly variable across fitted values. Transformation of area burned by natural logarithm produced patterns of residuals that we considered acceptable for our analyses.

Variance explained was plotted against the complexity, mechanism and stochasticity of fire ignition and fire spread modules (Keane et al. 2004) to explore the relationship between model formulation and overall model sensitivity.

Results

Ln-transformed area burned was most sensitive to climate and weather factors, with four models sensitive to each factor and three models sensitive to the weather-climate interaction (Table 3). FIRESCAPE was the only model where ln-transformed area burned was sensitive to terrain (and the interaction between terrain and weather, and that between terrain, climate and weather). Further, ln-transformed area burned was only sensitive to fuel pattern (and the interaction between fuel pattern and weather factors) in EMBYR. Some other factors (and their interactions) resulted in significant differences in ln-transformed area burned amongst their levels (Table 3).

Table 2. 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 modeling.	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 a.m. 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(DS)

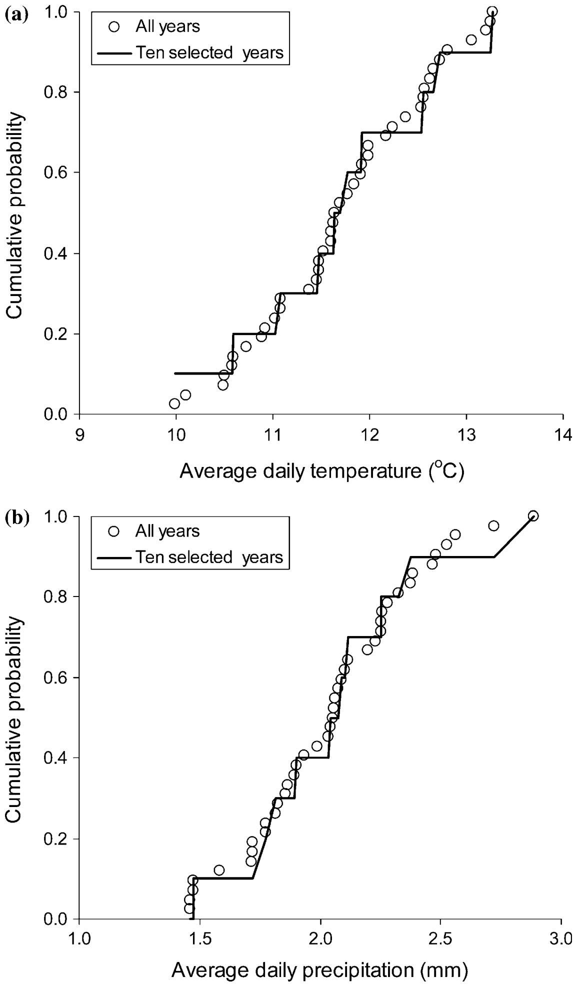

Figure 3. Cumulative probability of (a) average daily maximum temperature and (b) yearly average of daily precipitation in the complete weather data set for Glacier National Park, Montana, represented by open circles. The cumulative probability of the set of 10 replicate weather years that best matches that of the full data set is shown as the solid lines.

However, they explained insufficient variation in area burned to be considered important.

Area burned increased from the observed, through the warmer, wetter and the warmer, drier climates for the four models sensitive to the climate factor (Table 4). Increasing relief of terrain generated increasing area burned in FIRESCAPE (Table 5), while finely clumped fuel pattern resulted in a lower area burned in EMBYR (Table 6).

A greater amount of variance in area burned was explained (Figure 5) by environmental factors for models that are characterised by complex, mechanistic and more deterministic ignition modules, as classified by Keane et al. (2004). Little or no relationship was observed between the levels of complexity, mechanism and stochsticity of the fire spread module of models and variance in area burned.

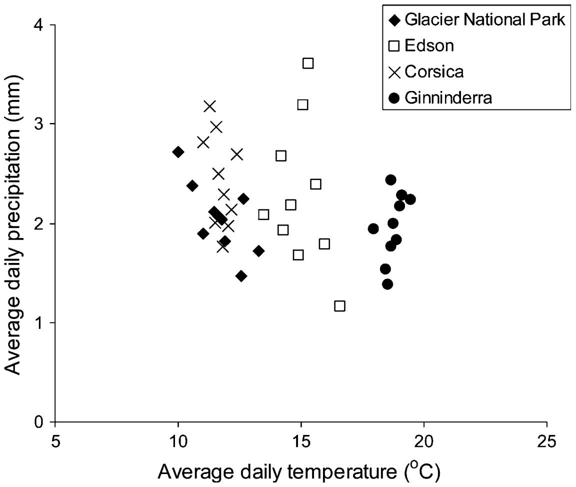

Figure 4. Comparison of average daily temperature and precipitation from Glacier National Park (Montana), Edson (Alberta), Ginninderra (Australian Capital Territory) and Corsica. The temperature data for Glacier National Park and Ginninderra are daily maximum temperatures. The temperature for Corsica is daily average temperature and for Edson it is observed at 1200 LST.

Discussion

Simulated area burned was most sensitive to the weather factor in most cases (Table 3). This is somewhat expected given that weather years for any particular location (south eastern Australia; Rocky Mountains, USA; central Alberta, Canada; and Corsica) were chosen to capture the full range of inter-annual variation in weather experienced there. Initially, weather was not specified as a separate factor and the large amount of variation associated with it was lumped into the error term of the ANOVA, resulting in much smaller and seemingly unimportant r^2 values for the terrain, climate and fuel pattern factors. This indicates that, in general terms, it is important to characterise inter-annual variation in weather properly to simulate realistic spatial patterns of fire regime.

The variance explained by the weather factor was greater than that explained by climate for

Table 3. 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.

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

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 *. Note that not all significant sources are considered important.

Table 4. Average ln-transfomed area burned (standard deviation) for different climate factors for FIRESCAPE, LAMOS(DS), LANDSUM and SEMLAND.

Climate factor	Area burned (ln m^2) (standard deviation)			
	FIRESCAPE	LAMOS(DS)	LANDSUM	SEM-LAND
Observed	15.6 (1.5)	17.3 (2.6)	12.8 (5.6)	13.3 (0.5)
Warmer/wetter	17.7 (1.2)	20.2 (2.5)	15.8 (3.6)	13.8 (0.7)
Warmer/drier	18.1 (1.1)	20.5 (1.9)	17.2 (1.1)	14.7 (1.0)

Table 5. Average ln-transformed area burnt (m^2) (standard deviation) for the Fuel factor in EMBYR.

Fuel pattern	Area burned (ln m^2) (SD)
Finely clumped	15.9 (1.7)
Coarsely clumped	17.5 (1.2)

Table 6. Average ln-transformed area burnt (m^2) (standard deviation) for the terrain factor in FIRESCAPE.

Terrain	Area burned (ln m^2) (SD)
Flat	16.1 (1.4)
Rolling	17.0 (1.6)
Mountainous	18.3 (1.1)

EMBYR, LANDSUM and SEM-LAND simulations. 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 et al. 2001; Flannigan and Wotton 2001). The converse was observed for FIRESCAPE and LAMOS(DS), perhaps because the inter-annual variation between the weather years for these locations was lower than for other sites (Figure 4), although average annual temperature and precipitation may not be representative of the patterns of severe weather that most likely result in large areas burned. Therefore, differences of variance in area burned explained by the weather factor may result from differences in inter-annual variability in

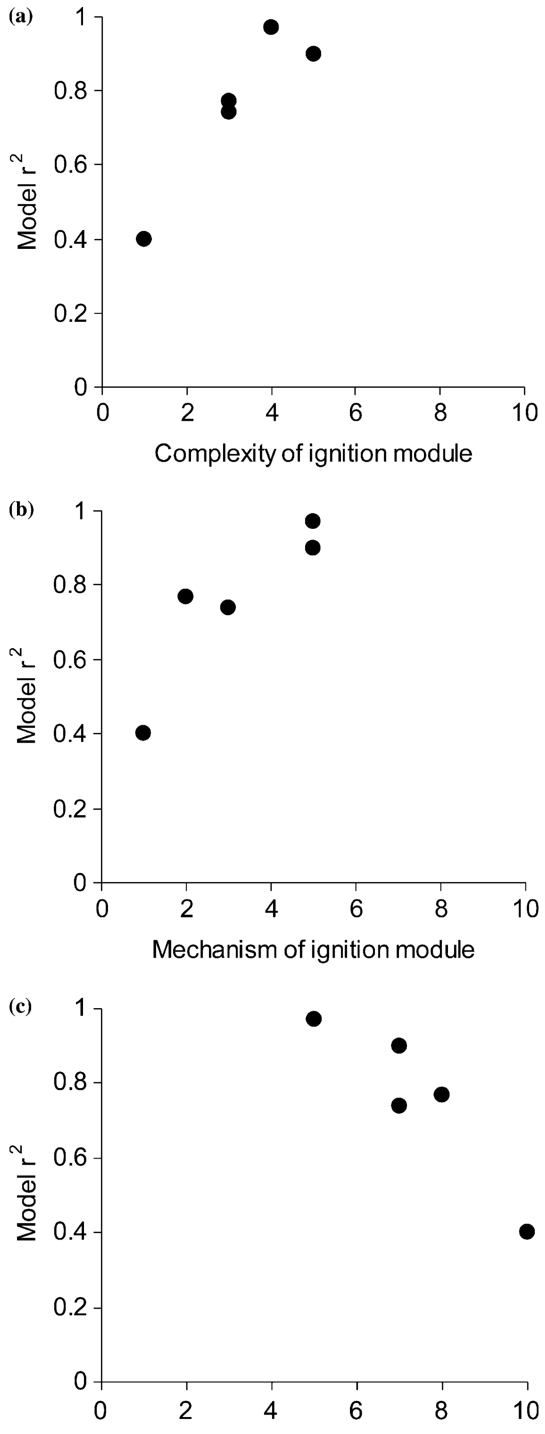

Figure 5. Relationship between (a) complexity, (b) level of mechanism and (c) stochasticity of fire model ignition modules and model r^2 from the comparison of landscape-fire succession models. Scores of complexity, mechanism and stochasticity are on a scale from 0 to 10 (0 meant that it was not modelled or applicable and 10 represents the highest level of stochasticity, mechanism, or complexity) from Keane et al. (2004).

weather between sites, not differences in model formulation *per se*.

There is a clear relationship of increasing area burned from observed, through warmer and wetter to warmer and drier climate. This is largely repeatable amongst models for which climate was important in explaining variation in area burned (Table 4). Several authors have provided simulated evidence for increasing area burned or frequency of fire under warmer climates (Clark 1990; Cary and Banks 1999; Li et al. 2000; Cary 2002), possibly due to a longer fire season (Wotton and Flannigan 1993; Stocks et al. 1998). The climate factor was not important for EMBYR, despite an earlier observation that a wetter climate resulted in larger, more severe fires (Gardner et al. 1996), arising from impact of climate on vegetation succession.

Our design did not investigate the importance of succession because individual simulation runs were single years, largely because our initial focus was on the sensitivity resulting from the fire ignition and spread components of models, with investigation of the importance of succession planned for future research. An important implication of this is that in our design, a change in climate does not affect succession processes directly, meaning that we did not expect to replicate the results from earlier research which included the effect of succession in an experimental design (e.g. Gardner 1996; Rupp et al. 2000).

Fuel pattern was relatively unimportant, except in the case of EMBYR. Fire spread in EMBYR is partly a function of fuel condition of the source and target pixels of any 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 (Table 5). This a realistic representation of fire spread, nevertheless, fuel pattern accounts for a comparatively small amount of variance in EMBYR compared to climate and weather in the other models.

Fire spread in the majority of the models (FIRESCAPE, LAMOS(DS), LANDSUM, SEMLAND) exhibits a positive, non-linear relationship with slope (McArthur 1967; Rothermel 1972). Distributions of slope across the terrain factors were, in general, broad enough to encompass the distribution of real slopes across simulation locations, although it is recognised that steeper slopes do occur and this factor may have played a more dominant role if they were included. Nevertheless, terrain only explained an important amount of variation in FIRESCAPE. Fire spread in this model is not more responsive to slope than for other models. Rather, FIRESCAPE includes an important terrain-induced effect not represented in the other models, the effect of terrain on weather. Area burned increased from the flat, through undulating, to mountainous terrain (Table 6). The effect of the 2500 m relief on site weather in FIRESCAPE is considerably greater than the magnitude of the climate factor, with 'peaks' considerably cooler, moister and more humid than 'valleys' which are markedly warmer, drier and less humid than the average elevation. Therefore, the effect of the mountainous terrain is that it provides for a greater percentage of the landscape in a fire-prone state (lower elevation sites) than affecting area burned because of increased slope. The influence of the undulating landscape is similar but less important. A flat landscape with a low elevation would likely result in an even greater area burned. Therefore, effectively representing the effect of terrain on weather in landscape fire models is fundamental if this aspect of the terrain factor is to influence model results in a realistic fashion.

Sensitivity of models to fuel pattern and terrain may be a function of mean fire size in relation to fuel patch size and scale of terrain features respectively. While the objective of this experiment was to investigate the sensitivity of total area burned, we calculated the mean fire size for each model to investigate its relationship with sensitivity to fuel pattern and terrain. The mean fire size for EMBYR (272 ha) represented the median across the set of models and was similar to that for FIRESCAPE (216 ha) and less than that for LANDSUM (429 ha). If sensitivity to fuel pattern were a function of mean fire size, then it might be expected that all three models would be sensitive to fuel pattern given that fuel patch size for the finely clumped and coarsely clumped patterns was 25 and 625 ha respectively. Further, the similarity of mean fire size for FIRESCAPE, EMBYR and SEM-LAND, relative to LAMOS(DS) (24,102 ha) and SEM-LAND (5 ha) indicate that it is relatively unimportant compared with the effect of elevation on site climate.

Interactions amongst factors were generally unimportant in explaining variance in area burned (Table 3). Not surprisingly, the most important interactions were between climate and weather factors. Modifying the climate tended to change the relationship between weather factor and area burned. For example, in LANDSUM four weather replicates under observed climate demonstrated a relatively low area burned while it was considerably higher for the remainder. For the warmer and wetter climate, one weather replicate exhibited low area burned, while for the warmer and drier climate, all weather replicates exhibited a high area burned. Other interactions were comparatively unimportant.

A number of factors and interactions resulted in significant differences amongst their levels ($P < 0.05$) but were unimportant for explaining variance in area burned (Table 3). This resulted from the large amount of variation introduced primarily from the weather and climate factors, but also the terrain factor in FIRESCAPE and the fuel factor in EMBYR. 'Variance explained' is a more meaningful measure when comparing the importance of environmental variables in determining landscape dynamics such as area burned, particularly when dealing with simulated data. It allowed us to compare the importance of a range of factors 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. Comparing models directly on area burned, rather than on variance in area burned explained, would likely have introduced a large amount of variation, resulting from models being formulated for different landscapes and climates, and in different ways.

These findings have particular significance for the inclusion of fire in Dynamic Global Vegetation Models (DGVMs). The lack of sensitivity of area burned to 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 the year-to-year variation in weather may translate into larger effects on area burned than long-term changes in mean temperature and precipitation brought about by climate change.

There are advantages and disadvantages in conducting multiple-model comparison studies. Models from this study were developed independently before the modellers came together for an objective model comparison. Therefore, the models provide semi-independent lines of evidence in the experimental design. However, it is difficult to quantify the extent to which the standardised model input meets the assumptions of different models, and whether meeting different assumptions affects the results of the experiment. For example, some models recognise a finite number of fuel ages (four for EMBYR and eight for LANDSUM), while fuel age is continuous for the other models. The assumptions of each model can be met by translating the input data to meet the requirements of each model, however it is unclear what the effect of this is on model results.

Also, there are a number of important differences between the models compared. In LANDSUM, the elements that define the fire regime (e.g., 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. For other models, climate affects either the area burned from the same number of ignitions or both the number of ignitions and the area burned. Second, there are differences in representation of processes associated with fire ignition and spread (Figure 5). Models that represent ignition in a more complex, mechanistic fashion are capable of exhibiting greater sensitivity to environmental factors overall. Selecting a model with particular levels of complexity, mechanism and model stochasticity effectively determines the sensitivity of modelled results to variation in input parameters.

Our approach involved the standardisation of model input and output to facilitate meaningful comparison between quite different models. This approach 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. For example, there is the potential to modify our method to look at the importance of a range of other factors, including management of fuel and of ignition probability.

Conclusions

Climate and weather are generally more important factors than fuel pattern and terrain in determining area burned in simulated landscapes. Area burned generally increased for warmer, drier climates, compared with that for observed climates, although irrespective of the actual climate, variation in weather is also important. Complex models are generally more sensitive to a greater number of factors because they explicitly simulate the relevant underlying mechanistic processes. The comparison methodology presented here can easily be modified to compare sets of models in different application areas, including gap models (Botkin 1993; Shugart 2001) and biogeochemical models, with disparate ecosystems and climate characteristics.

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