Chapter 12

Understanding Global Fire Dynamics by Classifying and Comparing Spatial Models of Vegetation and Fire

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12.1 Introduction

Wildland fire is a major disturbance in most ecosystems worldwide (Crutzen and Goldammer 1993). The interaction of fire with climate and vegetation over long time spans, often referred to as the fire regime (Agee 1993; Clark 1993; Swetnam and Baisan 1996; Swetnam 1997), has major effects on dominant vegetation, ecosystem carbon budget, and biodiversity (Gardner et al. 1996; Lenihan et al. 1998; Ryan 1991; Starfield and Chapin 1996). These effects include cycling nutrients, regulating succession, maintaining diversity, reducing biomass, controlling insect and disease populations, triggering interactions between vegetation and animals, and maintaining important biological and biogeochemical processes (Johnson 1992; Agee 1993; Crutzen and Goldammer 1993; DeBano et al. 1998). Carbon cycles are intimately linked to fire regimes because of the accumulation and combustion of fuel and post-fire vegetation development (Kasischke et al. 1995; Olsen 1981). Fire has sculpted landscapes for millennia by dictating pattern dynamics and community composition (Knight 1987; Swanson et al. 1997).

Modification of the fire regime due to climate warming (e.g., Cary and Banks 1999) may overwhelm many of the commonly investigated ecosystem responses to climate change, including ecosystem productivity, plant migration, and species extinction (Weber and Flannigan 1997; Ryan 1991; Keane et al. 1998). Large nonlinear changes in vegetation composition and structure are likely to occur in response to climate warming and human land use because of the overriding influence of the fire regime (Flannigan and Van Wagner 1991; Crutzen and Goldammer 1993). Carbon storage in some forest ecosystems may significantly decline if fire increases due to climate warming (Kasischke et al. 1995). Because of the inherent complexity of the interactions of fire, climate, and vegetation across multiple scales, simulation modeling is a critical tool for exploring and understanding climate change implications.

A major problem in projecting ecological change and understanding its mechanisms is the lack of non-equilibrium dynamics in many ecological models. The inclusion of disturbance, especially fire, is essential for dynamic vegetation models to simulate transient changes in vegetation composition and structure. Understanding landscape dynamics in relation to fire and how these dynamics may be altered by climate and land-use changes is critical. Additionally, understanding human impacts on the fire regime is essential for projecting vegetation change in human-modified landscapes, which now occupy large proportions of the globe. Using our current understanding of fire behavior, fire ecology and fire-weather, a set of dynamic fire-climate-vegetation models could be developed to simulate fire effects at temporal and spatial scales relevant to vegetation change.

One approach to addressing the effects of changing climate on fire and vegetation dynamics is simulation modeling. At the global scale there appear to be two options: (1) a suite of landscape models that spatially simulate succession and fire dynamics at local scales, or (2) coarse scale vegetation models, called Dynamic Global Vegetation Models or DGVM, that have been developed to predict vegetation response to climate change at global scales (Neilson and Running 1996; Lenihan et al. 1998; Thonicke et al. 2001). However, there are drawbacks to both. The available landscape models are quite different in design and application, developed for different ecosystems and fire regimes, and as such cannot be brought together for comprehensive global simulations. Second, the incorporation of fire into DGVMs to predict these ecosystem responses at global scales has been problematic because of confounding environmental complexities that govern global fire regimes and the general lack of understanding of which fire regime characteristics are important at coarse scales.

This chapter summarizes an effort by the Landscape Fire Working Group, formed under the aegis of the Global Change and Terrestrial Ecosystems Project (GCTE – Task 2.2.2) to identify those fire processes that are essential to dynamically model landscape vegetation changes. This was accomplished by classifying and comparing existing fine-scale, spatial, non-equilibrium process-based ecological models that simulate the dynamic interactions between climate, fire and vegetation, which we called Landscape Fire Succession Models or LFSMs. By classifying all existing LFSMs, we were able to inventory the diverse methods currently used to simulate vegetation, climate, and fire interactions in a spatial domain. We then selected a set of models from a suite of classification categories to perform an extensive LFSM comparison on neutral landscapes to identify the relative importance and sensitivity of simulated fire to terrain, fuel pattern, climate, and weather. Once the important processes were identified, we developed a set of recommendations for including fire dynamics in DGVMs.

12.2 Background

We define LFSMs as models that simulate the linked processes of fire and succession (i.e., vegetation development) in a spatial domain. Although the complexity of spatial relationships of vegetation and fire dynamics may vary from model to model, all LFSMs, by definition, produce time-dependent, georeferenced results in the form of digital maps or GIS layers. Additional processes may have been incorporated into the LFSM simulation, such as timber harvesting and biogeochemical modeling (explicit simulation of the flow of energy, carbon, water, and other elements within an ecosystem or landscape), but the minimum requirement for a LFSM is the explicit linkage between fire and succession. Climatic processes need not be explicitly incorporated into the LFSM, but, because of our interests in climate change, special attention was given to those models that consider the direct effect of weather on fire occurrence and vegetation change.

A series of six GCTE sponsored workshops attended by a wide variety of international ecological modelers and ecologists was held from 1999 to 2003 to synthesize current landscape fire modeling into an organized framework (see Hawkes and Flannigan 2000). One product of these workshops was an objective, quantitative protocol for comparing LFSM simulations across neutral landscapes (i.e., artificial landscapes where topography and vegetation characteristics are controlled) and regional climates to determine the relative sensitivity of predictions to model structure and complexity (Cary et al. 2006). A standardized set of model descriptive elements (MDE) was developed to qualitatively contrast and compare LFSMs, and the values for these elements were estimated by the modelers and entered into a database (Rupp et al. 2001). Information included in the MDE data base included initial purpose of the model, the ecosystem type being simulated, nature of the vegetation being represented and the method of succession, climate variables and drivers, the temporal and spatial scales of predictions, and computing constraints (Keane et al. 2004).

Using workshop findings and the MDE database information, we identified four essential components in LFSMs that represent the primary processes governing the landscape simulation of vegetation and fire: (1) vegetation succession, (2) fire ignition, (3) fire spread, and (4) fire effects. Any LFSM needed to contain all of these components. We assumed any other ecosystem and landscape process simulated by an LFSM, such as harvesting and insect epidemics, could be added as other components or incorporated into one or more of these four primary components. For example, fuel accumulation would be considered part of the vegetation succession component. We debated whether fire extinguishments – when a spreading fire actually goes out – was another component, but decided it should be part of the spread component (i.e., extinguishment is the lack of spread) for simplicity.

Each component for every LFSM was described by the approach, scale, and strategy by the modelers or authors, and this information was also entered into the MDE database (Reinhardt et al. 2001; Keane and Finney 2003; Keane et al. 2004). The approach defines the general design of the model as probabilistic (based on stochastic processes), empirical (based on relationships described by data), or physical (based on fundamental physical processes). Spatial scales are either regional (1000s of km^2), landscape (10s of km^2), forest stand (<1 ha), or at the level of the individual plant (~m^2). The strategy describes the algorithms, tools, or techniques used to represent a simulation component. Many LFSM components were developed by merging multiple approaches, scales, and strategies.

12.3 Model Classification

The classification effort provided the framework to interpret differences between LFSMs and for stratifying LFSMs for the subsequent comparisons (see Keane et al. 2004 for full details). The classification was based on the four primary processes that influence fire and vegetation dynamics – fire ignition, fire spread, fire effects, and vegetation succession – and the approaches used to represent these processes in the models. The classification space for each component was described in three dimensions by the gradients of stochasticity, complexity, and mechanism that best characterize the simulation of that component. Stochasticity was defined as the amount of randomness inherent in the component design, or the degree at which probabilistic functions influence the simulation of that component. Complexity was defined as the inherent detail incorporated into the design of a simulated component. Models with low complexity have modest sophistication in simulation detail and those with a large number of parameters are considered quite complex. Mechanism was the degree to which fundamental physical or chemical processes are represented in the simulation of a LFSM component. This resulted in 12 evaluation elements (4 components by 3 gradients) for each model. Together, these elements represented a formal description that can be used to objectively compare other models. There is some unavoidable ambiguity in these gradients, but overall we felt these 12 evaluation elements provided a standardized, comprehensive, and somewhat objective context in which to assess LFSMs. In addition, this method can be used to classify and compare other types of models by modifying, eliminating, or adding gradients and components.

We conducted an inventory of existing LFSMs using information gained from workshop participants, a review of the literature, and correspondence with modelers. Only LFSMs that were published in some form were considered, and this search found 44 LFSMs that were used in the classification effort. We contacted the developers of these models and asked them to rate the simulation of the four components (succession, fire ignition, fire spread, and fire effects) by the three evaluation gradients (stochasticity, complexity, and mechanism) using a scale from zero to 10 (zero meant that it was not modeled or applicable and 10 represented the highest level of stochasticity, mechanism, or complexity). Some modelers did not reply, so we assigned our own ratings based on a thorough review of publications on the model. The values assigned to each evaluation element were compiled into a database and then analyzed to identify groups of similar models. To ensure consistency across modeler evaluations of their own models, we created another database with our own assignments of evaluation elements based on published literature and our knowledge of the model.

To identify natural clusters or groups, the evaluation element data were ordinated using principal components analysis (PCA) and clustered using TWINSPAN techniques in the PC-ORD package (McCune and Mefford 1999). The See5 statistical software (Quinlan 2003) was also used to cluster the evaluation element data using Ward's minimum variance hierarchical clustering, which is a divisive clustering technique. The ordination and clustering results alone were not sufficient for developing a comprehensive classification because of the high variance in evaluation elements across models. Therefore, we revised the MDE database created from the workshops so that keywords were used to describe various explanatory categories such as approach, strategy, scale and other descriptive attributes by LFSM component. We then compared the frequency of keywords for each category across all LFSMs to qualitatively identify similar characteristics and natural clusters.

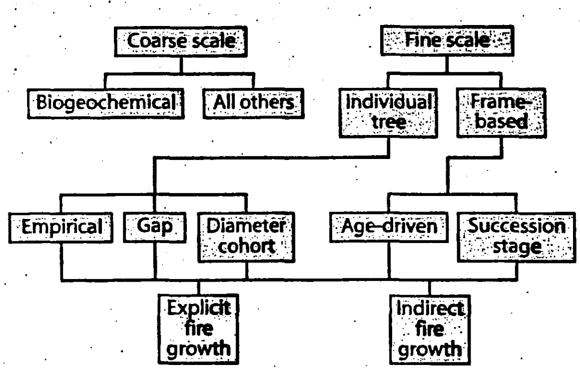

Fig. 12.1. Final set of categories for landscape fire succession models classified using the degree of stochasticity, complexity, and mechanism in the design of the model components of succession, fire ignition, fire spread and fire effects

A general LFSM classification was developed from the fusion of the ordination, clustering, and keyword comparison results (Fig. 12.1). This classification has 12 hierarchically nested classes that are distinguished by their scale of application (coarse vs. fine), representation of vegetation (individual plant cohorts vs. framed-based community), simulation of succession (age, empirical, gap-phase, or successional pathway) and the explicit or implicit simulation of fire spread. The locations of all LFSMs and six classification categories are shown in ordination space in Fig. 12.2. A dichotomous key for the classification was constructed from the MDE database using See5 analysis. We then related common keywords to the dichotomous key to name and identify important branches in the dichotomy.

12.4 Model Comparison

The model comparison was undertaken to identify the relative influence of environmental processes on fire dynamics. It is comprised of three phases of which only results from the first phase are presented in this chapter. In the first phase, we evaluated the sensitivity of fire spread and ignition components without the influence of fire effects and subsequent vegetation development (Phase 2 and 3, respectively). We compared five LFSMs that covered three classification categories for this exercise: LANDSUM, FIRESCAPE, EMBYR, SEMLAND, and a special application of the LAMOS modeling shell called LAMOS-DS (Table 12.1). These models are quite different in many aspects including a wide diversity in their approaches for simulating fire spread and ignition, representation of vegetation, and the complexity of climate and fire linkages (see Fig. 12.2, Table 12.1).

12.4.1 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 et al. 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. Fire spread is simulated by examining each burning site and determining spread to the eight neighboring sites as a function of fuel type, fuel moisture, wind speed and direction, and slope. A qualitative index of fire severity of each burned site, estimated as a function of fuel type, fuel moisture, wind speed and burn rate, is used to determine when fire intensity is sufficient to result in a stand-replacing fire.

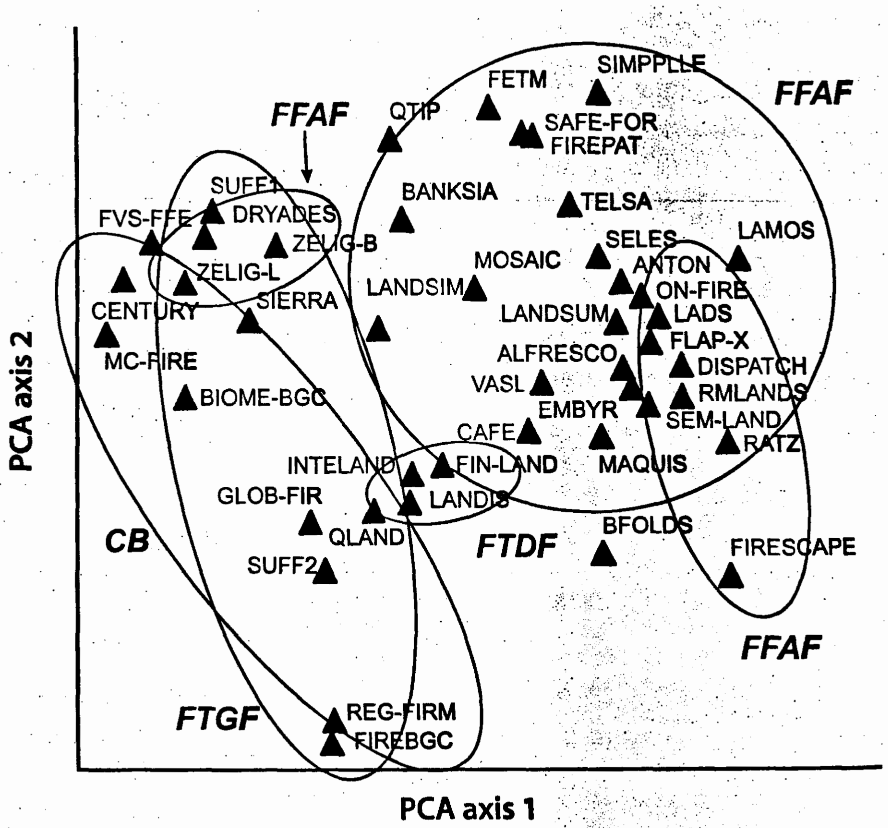

Fig. 12.2.
Delineation of six model classes in ordination space for the developed classification using ratings assigned by the modelers. This shows the relative position between classes and the similarity of models within a class

Table 12.1. Landscape fire succession models included in the model comparison effort with a general description of its application

Model name	References	Ecosystem	Geographic area	Weather database
EMBYR	(Gardner et al. 1996; Hargrove et al. 2000)	Lodgepole pine forests	Central Rockies, USA	Glacier National Park
FIRESCAPE	(Cary and Banks 1999; Cary 2002)	Eucalypts forest	Southeastern Australia	Australian Capital Territory
LAMOS(DS)	(Lavorel et al. 2000)	Any	Portugal	Corsica, Italy
LANDSUM	(Keane et al. 1997; Keane et al. 2002)	Any	Northern Rockies, USA	Glacier National Park
SEM-LAND	(Li 2000, 2001)	Spruce-fir forests	Canada	Edmonton, Alberta

EMBYR propagates fire by user-defined 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.

FIRESCAPE generates spatial patterns of fire regime (Gill 1975) for *Eucalyptus* dominated landscapes in southeastern Australia (Cary and Banks 1999). It operates on a daily time step that changes to hourly whenever a fire ignites. Daily weather is generated using a type stochastic climate generator (Richardson 1981; Matalas 1967; Cary and Gallant 1997; McCarthy and Cary 2002) and ignition locations are generated from an empirical model of lightning strike locations (Cary 1998). The spread of fire from cells to immediate neighbors is a function of elliptical fire spread (Van Wagner 1969) and Huygens' Principle (Anderson et al. 1982). Head fire rate of spread is determined from the equation form of McArthur's Forest Fire Danger Meter (McArthur 1967; Noble et al. 1980) and fuel loads are modeled using Olson's (1963) model of biomass accumulation which has been parameterized for a range of Australian systems (Fox et al. 1979; Raison et al. 1986). Fire line intensity ($kW\,m^{-1}$) is calculated for the spread of fire from one cell to the next for characterizing this aspect of the fire regime and for determining the extinction of the individual fire events.

LAMOS-DS is an implementation of LAMOS (Lavorel et al. 2000) with a contagious fire spread 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 tion to modify spread probabilities as a function of e (Li 2000) and intensity. Fire intensity is the prod- of three linear functions: fuel load (0–1 kg m^{-2}), mois- (0–200 mm) and temperature (5–25 °C). Tempera- during the course of the fire is interpolated between daily minimum and maximum by a symmetrical sine ction. Fires are assumed to begin when temperature t the daily maximum. Fuel is consumed in propor- to the resulting fireline intensity.

The LANDscape SUccession Model (LANDSUM) is patially explicit vegetation dynamics simulation gram wherein succession is treated as a determin- ic process using a pathway or frame-based com- nity sequence approach, and disturbances (e.g., fire, ects, and disease) are treated as stochastic processes th all but fire occurring at the polygon scale (Keane al. 1997, 2002). LANDSUM simulates fire spread from er-specified wind speed and direction, slope, and el type (burn, no-burn) determined from the succes- on stage using equations from Rothermel (1972) and bini (1976).

The SEM-LAND model (Spatially Explicit Model for ANdscape Dynamics) simulates fire regimes and as- ociated forest landscape dynamics resulting from long- rm interactions among forest fire events, landscape tructures, and weather conditions. A fire process is imulated in two stages: initiation and spread (Li 2000, 001). The fire initiation stage continues from the pres- nce of a fire ignition source in a forest stand until most rees in that stand have been burned. Once most trees re burned, the fire has the potential to spread to its sur- ounding cells, and whether a neighboring cell would e 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 land- scape topography. The Canadian Forestry Fire Weather Index system (FWI) (Van Wagner 1987) and the Cana- dian Forest Fire Behavior Prediction system (FBP) (For- est Canada Fire Danger Group 1992; Hirsh 1996) were used to drive weather, fire spread, and fuel moisture in- teractions in the model simulation.

12.4.2 The Comparison Design

The comparison involved evaluating the effects of varia- tion in terrain, fuel pattern (i.e., vegetation), climate, and weather on the simulated annual number of fire ignitions and area burned using a set of neutral landscapes and native simulation parameters (i.e., simulation parameters quantified for the region for which the model was devel- oped). The simulation landscapes were represented by a 1000 × 1000 array of square 50 m pixels. Variation in terrain was introduced by generating three landscapes with a systematic pattern of valleys and peaks – flat, un- dulating, and mountainous – characterized by maximum slope values of 0°, 15° and 30° and relief of 0 m, 1250 m and 2500 m respectively (Fig. 12.3a) created by a two-di- mensional sine function with periodicity of 16.67 km (333.3 pixels).

Two patterns of fuel treatment – finely clumped and coarsely clumped spatial pattern – were evaluated (Fig. 12.3b,c). We created 10 replicates of finely and coarsely clumped fuel maps by randomly allocating val- ues from the series 0.1, 0.2, 0.3, ..., 1.0 (inclusive) to ei- ther 50 × 50 pixel (625 ha) clumps (coarsely clumped) or 10 × 10 pixel (25 ha) clumps (finely clumped) so that val- ues were evenly represented across landscapes. Fuel maps were transformed differently for each model to produce either fuel or age related maps that were meaningful to individual models (Cary et al. 2006).

Simulations were performed using weather relevant to the location where the model had been previously parameterized and tested, although we attempted to stan- dardize the amount of variability represented across the weather years chosen for each model. Ten, year-long se-

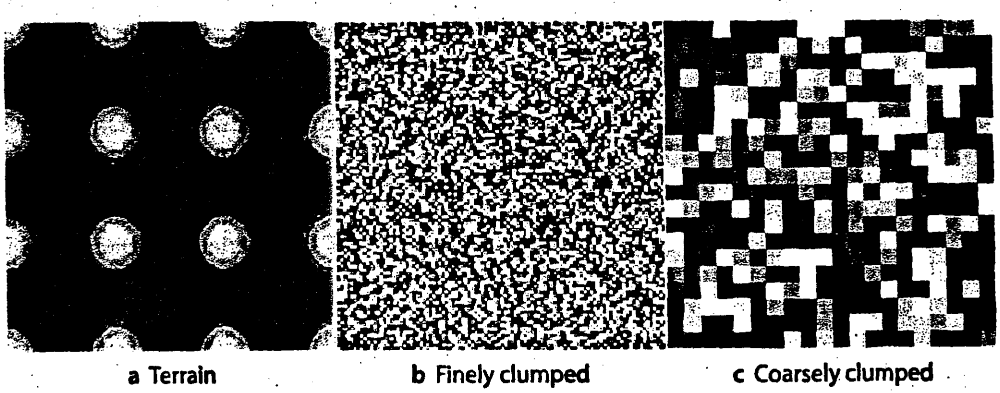

Fig. 12.3. Neutral landscapes used as inputs in the model comparison effort. a topography is represented by an "egg carton" shape with lowest and highest elevation indicated by *lightest* and *darkest color* respectively, b the finely clumped fuel landscape was created by randomly assigning fuel types or associated vegetation types to each pixel on the simulation landscape in 25 ha patches, and c the coarsely clumped fuel pattern was created by randomly assigning fuel types within 625 ha patches

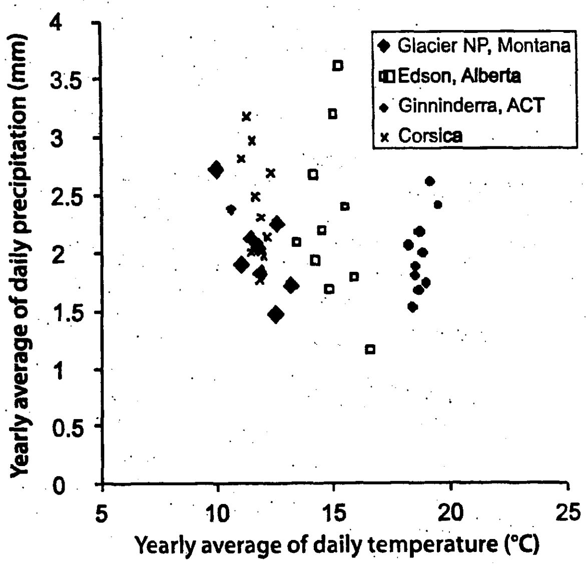

Fig. 12.4. Comparison of average daily temperature and precipitation from Glacier National Park (Montana), Edson (Alberta), Ginninderra (Australian Capital Territory) and Corsica (Italy) weather databases. The temperature data for Glacier National Park and Ginninderra are daily maximum temperatures. The temperature for Corsica is daily average temperature and for Edson it is observed at 1200 LST

quences of daily weather were selected from available data for each model so that the distributions of average annual temperature and precipitation in the selected weather years (Fig. 12.4) matched the corresponding distributions in the available data sets. The differences among the weather set for a particular model represents the weather treatment in our design.

Our design included three climates – observed, warmer/wetter and warmer/drier. The observed climate was comprised of the weather sequences outlined above. The other climates were derived by adding 3.6 °C (mid-range of projected global average temperature increase of 1.4 to 5.8 °C) (IPCC 2001) to daily temperature and by incrementing daily rainfall amounts by −20% (warmer/drier) and +20% (warmer/wetter).

A total of 1 800 year long simulations were run for each model from the 18 unique combinations of terrain (flat, undulating, 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. Fires affected fuel load/age within each simulation but, since simulations were for only a single year, no vegetation succession algorithms were invoked. The sensitivity of area burned to terrain, fuel pattern, climate, and weather was assessed from the variance explained (r^2) by each variable and their interactions determined from a fully factorial ANOVA performed in the SAS statistical package. Prior to our analyses, we transformed area burned by the natural logarithm to remove highly skewed residuals that resulted from untransformed data.

12.5 Results and Discussion

12.5.1 Model Classification

Results from the model classification effort illustrate the great diversity in model approaches used to simulate vegetation and fire dynamics. This diversity will always preclude a perfect classification because modellers will always emphasize those processes that are important to the local ecosystem or landscape for which the model was developed. For example, many models simulated fire effects as the simple killing of all trees because most fires were stand-replacing for their native landscape. The fire effects component had the least influence in the classification of LSFMs because of the low diversity and low complexity in fire effects simulation across models. In contrast, succession and fire spread were the components that most heavily influenced the clustering and ordination results because of the wide variety of simulation techniques represented. Succession was most important because the three evaluation gradients (complexity, stochasticity, and mechanism) were not closely related in succession simulations. Classification design is nearly always governed by its intended application, so there will never be the ideal LFSM classification for all purposes.

The three gradients used in the classification were not perfectly orthogonal. Highly complex models tend to include many mechanistic functions that tend to have a low degree of stochasticity (Gardner et al. 1999), and they often were built specifically to remove the stochasticity, so that these approaches could be mutually exclusive and the gradients correlated. Some highly complex systems, such as lightning dynamics, must be represented by stochastic functions because of insufficient knowledge and computer resources. We only found significant correlation between the complexity and mechanism gradients ($R^2 = 0.71$, $p < 0.0132$).

The classification can be used for many purposes by providing (1) a common language for communication between managers, modelers, and research scientists, (2) a means to quickly and efficiently characterize or describe a model relative to others, (3) a starting point for managers to select the most appropriate model to implement for their areas of interest, (4) a method for scientists and other modelers to select the most appropriate models for particular situations, and (5) the context to evaluate or compare simulation approaches for each component to build new models or refine old ones. The classification contains 12 categories based on gradients of complexity, stochasticity, and mechanism so it is only useful if these gradients are important to selecting, evaluating, or comparing models. This classification approach can be used for other applications by selecting different evaluation gradients or different components.

12.5.2 Model Comparison

The primary finding of the comparison effort is the overriding influence of climate and weather on fire dynamics (Table 12.2). The natural log-transformed area burned was most sensitive to climate (4 models), weather (4 models), and their interaction (3 models) (Table 12.2). Only FIRESCAPE showed any sensitivity to terrain and only EMBYR showed sensitivity to fuel pattern. The variance explained by weather year was much greater than that explained by the climate treatment for EMBYR, LANDSUM and SEM-LAND simulations. The converse was observed for FIRESCAPE and LAMOS-DS, perhaps because the inter-annual variation between the weather replicates for these locations was lower than for other weather stations despite efforts to standardize this across all models. Differences in variance in area burned explained by the weather replicate treatment may result from differences in inter-annual variability in weather between sites, not differences in model formulation *per se*. Nevertheless, the finding of the importance of inter-annual variability in weather (compared with climate) to fire regime has important implications for the inclusion of fire into higher order models, like DGVMs, because our results indicate increased variability in daily weather may result in greater simulated burned area than large shifts in mean temperature and precipitation.

There are a number of important differences between the models used in this comparison. First, fire regime is an input in LANDSUM whereas it is an emergent property for the other models. Ordinarily, the area burned in LANDSUM would not vary among the climate treatments, 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 (EMBYR, SEM-LAND) or both the number of ignitions and the area burned resulting from them (FIRESCAPE, LAMOS-DS). Second, there are differences in representation of processes associated with fire ignition and spread. Using the gradient scores from the classification effort, we found that the variance in area burned appeared to be primarily related to the fire ignition module. It was highest for models with complex, mechanistic, deterministic ignition modules (Fig. 12.5).

12.6 Summary and Conclusions

It was clear from the results of the comparison that the inclusion of both climate and daily weather variation into fire models is essential for simulating fire regime. This is especially important if the effects of climate change on fire dynamics are important. Fires burn the most area in warm, dry years, especially when coupled with antecedent drought, and the frequency of these droughty years

Table 12.2. Relative sums of squares attributed to different sources of variation in the comparison of sensitivity of ln-transformed area burned to terrain (terrain), fuel pattern (fuel), climate (climate) and weather replicate (weather), and their interactions. Treatments and interactions considered unimportant (explaining less than 0.05 and 0.025 of total variance respectively are blank). Significant treatments and interactions ($P < 0.05$) are indicated by an asterisk (*). Note that not all significant sources are considered important

Source	DF	Model				
		EMBYR	FIRESCAPE	LAMOS	LANDSUM	SEMLAND
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

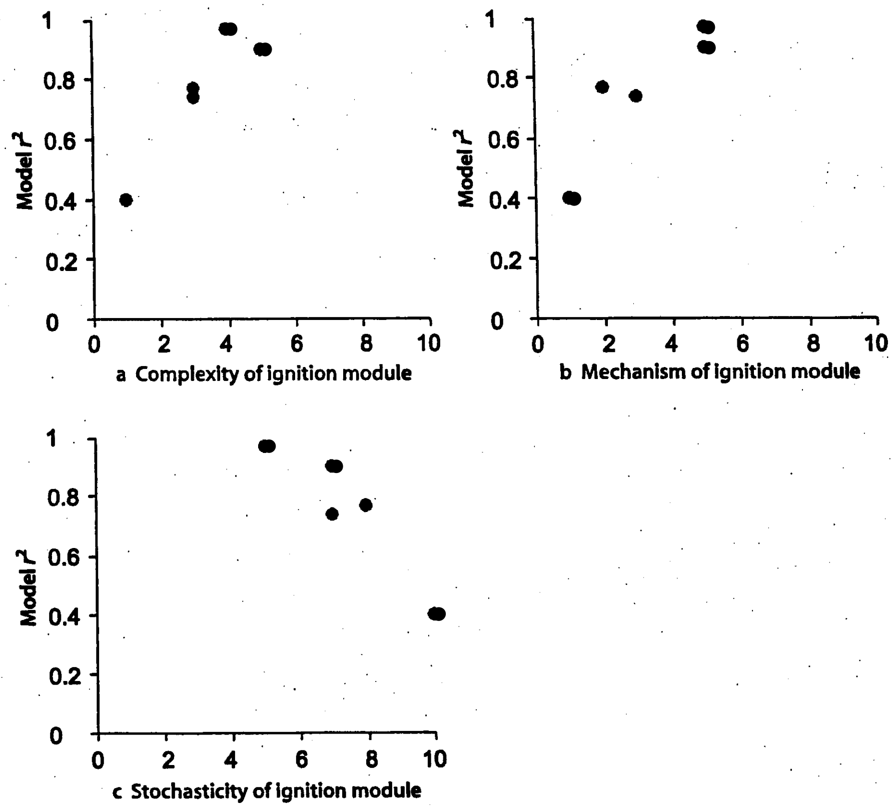

Fig. 12.5. Relationship between level of a complexity, b stochasticity, and c mechanism of fire model ignition modules assessed from the classification effort and model r^2 computed from the comparison effort

eventually defines the fire regime. Furthermore, variation in weather must be adequately captured to effectively simulate climate change responses to fire and vegetation. A surprising result was the relatively low sensitivity of fuel pattern in influencing fire regime. This may mean that coarse scale DGVMs need not be concerned with the pattern of vegetation or the spread of fire within large simulation pixels. The relative insignificance of terrain in determining fire ignition and spread dynamics may also mean that coarse scale models need not account for topographic complexity with the simulation unit when estimating burned area.

The results from the classification can be applied to compare other simulation experiments. Subsequent phases ot he the model comparison need to evaluate ignition and area burned over longer simulation years (100 years) to assess the sensitivity of succession and fire effects on the simulation of fire regime. This should provide a foundation to dynamically represent fire and vegetation in coarse scale DGVMs or LFSMs by taking into account fire plant functional types (Díaz and Cabido 1997). Next, there will be a need to modify the comparison method to evaluate the effect of fuel treatments and fire suppression on fire dynamics by simulating various fuel treatment patterns and management ignition patterns with the weather scenarios for current climate. Results from this effort could provide valuable information on the effectiveness of fuel treatments under severe weather conditions.

Acknowledgments

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