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Predicting forest fire effects at landscape scales

Robert H. Gardner, William H. Romme and Monica G. Turner

Introduction

The sudden changes in terrestrial and aquatic ecosystems induced by large forest fires are a significant factor shaping ecosystem dynamics and vegetation patterns at landscape scales (Bonan *et al.*, 1990; Moreno and Oechel, 1994; Overpeck *et al.*, 1991; Romme and Turner, 1991; Swetnam, 1993; Whelan, 1995). It is difficult to predict the landscape-scale effects of forest fires because the relationships between weather, fire, and the dynamics of terrestrial ecosystems require an understanding of fine-grained details of fire ignition and spread, the patterns of vegetation and their response to fire, and the long-term trends and potential shifts in weather and climate (Bessie and Johnson, 1995). In addition, changes in land use patterns in many regions of the world are further exacerbating the problem of prediction as clearing and land abandonment produces a heterogeneous pattern of fuel accumulation, and subsequent changes in the risk of large fires (Ales *et al.*, 1992; Davis and Burrows, 1993). These combined factors have increased the possibility that large areas of forested land may be permanently altered due to shifts in the pattern of vegetation regrowth and succession (Neilsen, 1993). The effects of shifts in disturbance regimes must be anticipated if management plans are to prevent reductions in biodiversity and ensure ecosystem productivity (Hunter, 1993; Gauthier *et al.*, 1996).

Our current understanding of the ecological effect of forest fires is based on a variety of empirical and theoretical studies. Analysis of relationships between fire and weather (for instance, Balling *et al.*, 1992; Johnson and Wowchuk, 1993; Moritz,1997; Renkin and Despain, 1992) have allowed effects to be evaluated over the duration of contemporary records (*ca.* 100 yr), while studies based on intensive sampling of stand histories and dendocronology (for instance, Agee, 1996; Arno, 1980; Romme, 1982; Romme and Despain, 1989; Swetnam and Betancourt, 1990; Swetnam and Baisan, 1996) and stratigraphic charcoal data (Clark, 1990; Millspaugh, 1997) have created records dating back 800 yr or longer. Study of fires

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within stands of the giant sequoia (*Sequoiadendron giganteum*) has produced very long records which have allowed the reconstruction of fire history over the past 2000 years (Swetnam, 1993). As impressive and important as these studies are for establishing relationships between weather, fuels, and fire, simulation models are necessary to evaluate changes in fire regimes due to shifts in climate and the landscape patterns of forested areas.

A variety of simulation methods have been used to establish relationships between the fire regime (e.g., the frequency, severity and extent of disturbances) and the effects that these fires have on the recovery of disturbed areas. It is the purpose of this paper to present an overview of models which provide insight into the prediction of fire effects at landscape scales. The interest is specifically on models which predict spatial patterns of disturbance and recovery. Non-spatial models of fire effects (see Li and Apps, 1995) are not specifically considered unless they have contributed directly to the development of spatially explicit modeling approaches. Therefore, models developed for fire danger rating systems and prescribed burns are not considered in this review. This overview identifies: the important features of landscape-scale models; similarities and differences in predictions; relationships between model complexity and predictability; and an evaluation of the accuracy and reliability of model results. It concludes with a discussion of features that are missing from most landscape models and a comment on the current limits of predictability.

Models of fire effects at landscape scales

A large variety of models have been developed for simulating landscape-scale patterns of fire effects. These models range from simple formulations for investigating theoretical properties of spatial systems to complex formulations requiring extensive computer time needed to simulate the fire ignition and spread, the effect of fire on vegetation, and the eventual recovery of the disturbed area. Comparison among these diverse models is difficult because of the large number of model formulations that have been published, the variety of purposes considered by the different models, and the uniqueness of the landscapes to which they have been applied. One way to organize this task is to define categories of models (and model applications) that can assist in identifying similarities and differences among the different models. It is suggested that a classification scheme with six categories provides a useful perspective (Table 7.1). The classes are: *theoretical models*, which are simple formulations designed to explore fundamental concepts such as critical thresholds and fractal structures (e.g., MacKay and Jan, 1984; Duarte *et al.*, 1994), and self-organized criticality (e.g., Bak *et al.*, 1990); *exploratory models* which are similar to the theoretical models, but are more complex and provide greater details concerning landscape effects (e.g., von Niessen and Blumen, 1988; Ratz, 1995; Green, 1989); *physical models* based on principles of thermodynamics of fire spread as a function of moisture and structure of the fuels being burned that are then extended to landscape scales (e.g., Davis and Burrows, 1993; Keane *et al.*, 1996;

Table 7.1. *Classification scheme for models of fire effects on forested landscapes*

Model types	Characteristics	Applications
A. Theoretical	• Very simple model formulations • Parameters, spatial and temporal scales are often arbitrary	• Explore and characterize behavior of spatial systems • Identify attributes of critical phenomena
B. Exploratory	• Increased complexity with models simulating realistic fire scenarios • Parameters and landscapes may be arbitrary	• Explore dynamics of complex systems, including heterogeneity of fuels • Identify relative importance of factors affecting spatial and temporal dynamics of fires
C. Physical	• Mathematics based on detailed thermodynamics of fire behavior • Parameter values based on experimental measurements • Simulations with realistic landscapes	• Use information on fine-grained dynamics of fire behavior to extrapolate to broad spatial and temporal scales
D. Probabilistic	• Probability rules used to explain local dynamics of ignition and spread • Simulation techniques are extensions of methods of cellular automata	• Hypothesized that simple formulations of fine-grained dynamics allows improved predictions of landscape effects while lowering computational burden
E. Shape	• Use of elliptical geometry of fire shapes to characterize fire behavior	• Hypothesized that elliptical geometry is an accurate representation of fire behavior and can be used to simulate fire effects
F. Statistical	• Use of historical data to establish statistical characteristics of disturbance regimes • Sampling from measured or hypothesized frequency distributions to simulate fire effects	• Use of historical information on fire regimes to characterize and simulate dynamics at broad temporal and spatial scales

Kessell, 1979; Vasconcelos and Guertin, 1992); *probabilistic models* developed as extensions of cellular automata models to simulate fires in heterogeneous landscapes (e.g., Antonovski *et al.*,1992; Clarke *et al.*, 1994; Gardner *et al.*, 1997); *shape models* based on the geometry of fire patterns resulting from variable spread rates produced by wind and topography (e.g., Catchpole *et al.*, 1992; Cheney *et al.*, 1993; Wallace, 1993); and *statistical models* using estimated probability density functions to characterize and/or simulate fire regimes (e.g., Johnson and van Wagner, 1985; Baker *et al.*, 1991).

The proposed classification scheme is based on the observation that there are distinct sets of perspectives, objectives and solution techniques used to study the relationships between forests and disturbances due to fire. For instance, theoretical models usually ask general questions regarding disturbance and self-organization, often relying on simple representations both of forests and fires. Statistical models, on the other hand, rely more on empirical studies as a basis for extrapolation and prediction. These categories were developed in an attempt to characterize as broad a range of models types as possible. The question of interest, then, is how do these different types, and the perspectives they represent, help us to understand and predict fire effects at landscape scales.

The classification scheme suggested here is both arbitrary and simplistic. This is evident, in part, because the categories for different models are not completely exclusive, i.e., some models may belong to more than one category. In addition, the categories are not independent: models (and model parameters) in one category may have been developed from models in another. Nevertheless, the scheme presented here is heuristically useful because it organizes the diversity of model approaches, facilitates comparison between models, and assists in the synthesis of results. The classification is not intended to indicate that one approach is better than another but rather to demonstrate that all approaches are interesting and informative, helping to advance studies of this important area.

One of the challenges of simulating the landscape-scale effect of fires is the great range of temporal and spatial scales which must be considered to adequately represent both fires and the recovery of landscape from these fires. For instance, significant changes in the moisture of herbaceous and fine woody fuels can occur within a single day and will likely change over a few hectares as forest age and composition changes with space. Similarly, the structure of coarse woody fuels provided by the forest varies over hectares but changes little from year to year. Variations in topography (slope, elevation, and aspect) have well-known effects on fuel moisture and the rate of spread and intensity of fires, varying greatly from hectare to hectare but changing imperceptibly from decade to decade. The inclusion of wind is a difficult problem for most models because it varies from minute to minute, shifts with changes in topography, and can be directly altered by the fire itself. Fire ignition events are often separated in time by days or even years, but precise knowledge of the spatial locations of fire starts may be required to adequately predict landscape scale patterns of fire effects. Because temperature affects relative humidity, diurnal

Table 7.2. *The models of different types used as examples in the text*

Model Type[a]	Model Name[b]	Citation
A. Theoretical	BCT90	Bak *et al.*, 1990
	MJ84	MacKay and Jan, 1984
B. Exploratory	VNB88	von Neissen and Blumen, 1988
	RTZ95	Ratz, 1995
C .Physical	FIREMAP	Vasconcelos and Guertin, 1993
	FIRE-BGC	Keane *et al.*, 1996
D. Probabilistic	EMBYR	Gardner *et al.*, 1997
	CLK94	Clarke *et al.*, 1994
E. Shape	CTH92	Catchpole *et al.*, 1992
	WALL93	Wallace, 1993
F. Statistical	JW85	Johnson and Van Wagner, 1985
	DISPATCH	Baker *et al.*, 1991; Baker, 1992

[a] Model types are defined in Table 7.1.

[b] FIREMAP, FIRE-BGC, EMBYR and DISPATCH are names given to the models by the authors in the papers cited. Other names are arbitrary for purposes of identification in the text.

changes in temperature can be important in explaining the spatial pattern of fire effects. Fire spotting is difficult to simulate because it depends on factors causing variation in fuels, forest structure, fire intensity and the location of new fire starts due to landing fire brands. Although the prediction of changes in community structure with time remains an important challenge, the temporal and spatial scales of forest regrowth are easier to include because regrowth is slow (order of decades) and resolutions need not be finer than hectares to adequately describe spatial variation in landscape patterns of forest regrowth. Thus, the simulation of patterns in fire-prone landscapes requires reliable methods for extrapolating processes which occur at many different temporal and spatial scales. In fact, the model categories represented in Table 7.2 are, to a large extent, due to different approaches used to extrapolate effects through time and space. The problem of temporal and spatial extrapolation is a popular theme in ecology (Levin, 1992; Schneider, 1994), but firm principles have yet to emerge allowing the resolution of this dilemma. Therefore, in the comparisons which follow, the problem of predicting across scale will be one basis for comparisons within and between the categories listed in Table 7.1. Finally, detailed analyses of two models are presented for each category (Table 7.2) that illustrate the approach and results. These models were chosen because they illustrate the approach and results typical to each category. Reference to other models which lend insight into the landscape-scale effects of changes in fire regime may be found within the text.

Model comparisons

Theoretical models

It is true that all models are in some sense theoretical. What are referred to here as 'theoretical models' are the subset of models with extremely simple formulations designed to explore the behavior of spatial systems with no intention of predicting patterns of fire effects for *actual* landscapes. Thus, in these models, fire spread is often represented as a random process of spread to neighboring sites and spatial and/or temporal dimensions may be arbitrary (Table 7.3). The results of these models can be quite interesting because they reveal fundamental characteristics of fire-dominated landscapes. Although these models have been often ignored by fire ecologists, they are responsible for stimulating new approaches to modeling fires at landscape scales (e.g., Clarke *et al.*, 1994; Gardner *et al.*, 1997; Green, 1989; von Niessen and Blumen, 1988).

Perhaps the simplest imaginable model of fire in forested landscapes is that proposed by MacKay and Jan (1984; referred to as MJ84 in Tables 7.2 and 7.3). The landscape is represented in MJ84 as a two-dimensional lattice with all sites occupied by identical trees. Fire is initiated in the center of the lattice and then spreads to neighboring trees with probability p. The purpose of the MJ84 is to demonstrate the behavior of fire with changes in p and estimate scaling parameters (i.e., the fractal dimension of the number of trees burned with time).

A similar model formulation was studied by Bak *et al.* (1990; BCT90 in Tables 7.2 and 7.3). The stated purpose of the BCT90 model is "...to demonstrate in a toy model the emergence of scaling and fractal energy dissipation." To accomplish this, a two-dimensional lattice was formulated (*note:* higher dimensions can be simulated with this model!) with trees occupying individual sites on the resulting grid. Each site may burn in a single time step and can "grow back" with probability p. The simulation results indicate that the system remains critical (i.e., remains close to the point where fires can propagate across the landscapes) as long as trees continue to grow. The implication is that because forests regrow after fires, landscapes will constantly exist near this critical threshold, with resulting patterns "... reflective of turbulent dynamics of growth and fire" (Bak *et al.*, 1990).

The development of simple models is instructive because they allow one to fully characterize the spatial dynamics of these systems. What is useful for the study of fire-prone landscapes is that dynamics observed in simple models can be expected to apply to more complex landscape models. For instance, it is known that fuels accumulate with time and therefore fire suppression may actually force the system beyond the critical threshold, i.e., the landscape may reach a "hypercritical" state where small changes in conditions (i.e., wind and weather) may result in catastrophic fires. The challenge for fire ecologists is to transform the estimated thresholds of simple theoretical models to measurable thresholds for actual landscapes.

Table 7.3. *Comparison of fire and landscape processes represented by the different models*

	Models[b]											
	Theoretical		Exploratory		Physical		Probabilistic		Shape		Statistical	
Model variable or process[a]	BCT90	MJ84	VNB88	RTZ95	FIREMAP	FIRE-BCG	EMBYR	CLK94	CTH92	WALL93	JW85	DISPATCH
Fuel structure				x	x	x	x	*c*	*c*	x		x
Fuel moisture					x	x	x	*c*	*c*			x
Ignition				*r*	*f*	*pdf*	*pdf*	*f*				*r*
Wind					*t*	*t*	*t*	*c*	*c*	x		
Fire intensity					x	x	x	x	x	x	x	
Fire spotting							x	x				
Topography					x	x	x	x		x		x
t resolution	*a*			*dc*	*hr*	*y*	*e*	*min*	*na*	*min*	*y*	*d*
t extent	*a*			*ml*	*hr*	*cen*	*ml*	*hr-d*	*na*	*hr*	*cen*	*cen-mi*
S resolution (ha)	~0.05	~4	~0.05		04	~10	0.25	0.06	*na*	0.001	*na*	25
S extent (ha)	26	~40k	25	25	~1.6k	50k	90k	3.3k	*na*	30	*na*	1000k
Forest regrowth	*p*					*e*	*m*					*dt*

[a]A blank entry indicates that the model does not consider the variable or process indicated. An x, or other symbol, indicates the process is represented by the model. A *c* indicates that the process is considered by the model, but is held constant during any single simulation. An *na* indicates that this process or variable does not apply to the methods used by the model. The model processes and special symbols are:

Fuel structure: spatially variable combustion characteristics of fuel.

Fuel moisture: dynamic changes in moisture affecting combustion of fuels.

Ignition: *f* is a fixed ignition site, *r* is randomly selected ignitions sites, and *pdf* indicates that a statistical probability distribution was used to calculate the location of fire starts.

Wind: *t* is temporal variation in wind velocity and direction and *c* is constant wind. No model included in this table had both spatial and temporal variation in wind.

Fire intensity: fire temperature and/or duration to estimate disturbance intensity.

Fire spotting: fire propagation beyond the fire line.

Topography: spatial variability of fire effects due to variations in slope and aspect.

t resolution: temporal resolution of simulation: *a* arbitrary, *e* is event-driven simulation, *s* seconds, *d* days, *y* years, *dc* decades, *cen* centuries, and *ml* millennia

t extent: the length of time simulated. Units same as for temporal resolution.

S resolution: spatial resolution in hectares.

S extent: spatial extent of simulation (e.g., ~40k refers to spatial extent of approximately 40 000 ha)

Forest regrowth: reestablishment and regrowth of the forest following fires, *p* is a simple probability, *dt* is deterministic forest regrowth, *m* is a Markov model, and *e* is a ecosystem dynamic model for forest succession.

[b]Model names are the same as those listed in Table 7.2.

Exploratory models

Exploratory models are distinguished from theoretical models by an increased level of realism in model processes and parameters and an attempt to identify the importance of these factors as they affect the spatial and temporal dynamics of fire-prone landscapes. While theoretical models concentrate on reaching a fundamental understanding of spatial dynamics, exploratory models also emphasize the practical application of results.

The model presented by von Niessen and Blumen (1988, VNB88 in Tables 7.2 and 7.3) provides a good example of this distinction. The purpose of the VNB88 model was to continue to explore the critical character of forest fires (i.e., small variations of parameters which may produce huge differences in results), but to do so within a framework more representative of fires within forested landscapes. The additional features of VNB88 developed to accomplish this objective include: the use of a double lattice to represent both surface and crown fires; individual sites that can represent a single tree or a group of trees; and the inclusion of anisotropic effects of wind on fire spread. The model's time step remains somewhat arbitrary (i.e., it is equal to the average time it takes a tree(s) on a site to burn) and fire spread is restricted to the ignition of four nearest neighbor sites. The fuel layer is homogeneous and the recovery of the forest from fire is not modeled. Thus, VNB88 incrementally builds on methods used by theoretical models, but with additional relevant detail to simulate dynamics of surface and crown fires and wind.

The results of numerous simulations by von Niessen and Blumen (1986, 1988) with variants of the VNB88 model showed that the critical threshold (i.e., the conditions which may produce fires which burn across the landscape) was independent of the form of the model, but the value of the parameters describing critical behavior vary from model to model depending on difference in parameters and assumptions. Hence, the VNB88 model demonstrates that quantitative methods used to measure critical values for actual landscapes will be model dependent.

A second example of an exploratory model, also based on methods derived from cellular automata methods (Wolfram, 1984; Hogeweg, 1988; Caswell and Etter, 1993) as was VNB88, is given by Ratz (1995, RTZ95 in Tables 7.2 and 7.3). The purpose of the RTZ95 model was to test the effect of long-term patterns of disturbance by fire on the spatial structure of forests. The key factor of this model is the capability of testing the alternative effects of change (or no change) in flammability of forest stands with age. The RTZ95 model simulates fires on a 200 × 200 grid of forest stands with each grid site equal to 4 ha. Fire spreads isotropically to nearest neighbor stands and the recovery of the stand after fire is deterministically modeled. Although age-dependent changes in flammability have been discussed by several authors (e.g., Johnson and Van Wagner, 1995; Johnson, 1992; Renkin and Despain, 1992; Romme, 1982), the effects of changes in flammability on the spatial structure of fire-prone landscapes remains poorly understood (Ratz, 1995).

One interesting result of the RTZ95 model is that a variety of spatial patterns

can be attributed to fire disturbances (Ratz, 1995), with more complex patterns produced with the assumption of age-dependent flammability of forest stands. Because of data limitations, only a restricted set of comparisons between model simulations and data were possible. (It is worth noting that this is the first example presented here of a model attempting comparison of results with patterns of fire effects in landscapes.) Even though the comparison was limited by the lack of sufficient data, the level of agreement between model results and data was rather good (Ratz, 1995) indicating that the model formulation was relevant for simulating landscape-scale dynamics of fire disturbance. In spite of the different assumptions regarding age-dependent flammability, all simulations produced large fires (i.e., the critical thresholds were always exceeded).

Green (1989) developed an interesting exploratory model which simulated fire, seed dispersal, life history characteristics of individual "species", environmental gradients, and successional dynamics. The spatial scale of the lattice used to model plant growth and fire spread is arbitrary with time steps of a single year. The attributes of each cell include the vegetation type and time since the last fire. Fires were ignited at random and the elliptical pattern of fire shape simulated via frequency distributions (see the following discussion of *Shape Models*). The results showed a wide range of patterns produced by the interaction of species life history characteristics, environmental gradients, and disturbance. For instance, vegetation "clumping" occurs even when environmental gradients are absent because short-range dispersal of seeds provides local competitive advantages. Fires cause patches to coalesce into vegetation zones separated by sharper borders than those produced by the gradients alone. Also, local patterns of seed production allowed established populations to exclude invaders.

None of the exploratory models is intended to be a realistic representation of actual landscapes. Never the less, the contribution these models have made to our understanding of fire-prone landscapes is significant. Results of a variety of models show that the fire regime dominates the landscape patterns of vegetation, that the spatial arrangement of fuels (and not simply the total amount) and forest regrowth are important variables affecting the probability of future disturbances. Because these models are not as simple as the theoretical models, analytical solutions are either elusive or impossible. Fortunately, the high speed of current computers and the simplicity of the model formulations allows spatial dynamics over large areas and long time spans to be conveniently simulated and analyzed.

Physical models

The physical models of fire spread are direct descendants of the pioneering work of Rothermel (1972) that produced a well-used set of computer models of fire behavior (Albini, 1976; Andrews, 1986; Cohen, 1986). The Rothermel model has been implemented in BEHAVE (Andrews, 1986) as a set of equations to estimate the spread rate of fires as a function of heat released and the physical and chemical characteristics of the fuels. The advantage of this approach is that these equations

(along with other related variables and parameters) have all been determined under precisely controlled experimental conditions. Knowledge of the rate of spread allows the geometry of fires in homogeneous fuels to be predicted and estimates of the perimeter length, area, and intensity of fires to be made. The motivating factor in the development of BEHAVE, and other related models of fire behavior, is that information about time-dependent changes in fires as a result of changes in fuels, wind and weather is important for allocating resources and protecting lives while fighting fires.

Reasons to adapt this detailed model to landscape-scale problems of fire effects include:

(i) the successful representation of experimental systems by the Rothermel equations. Other models either do not estimate changes in the rate of spread and intensity of fire as a function of the physical characteristics of fuels and weather or use some adaptation of the Rothermel formulation to do so;
(ii) the extensive experience applying models such as BEHAVE for fire control and management has produced confidence in the methods as a valid representation of fire behavior; and
(iii) the use of highly detailed, fine-grained models as the basis for estimating changes over broad areas and long time spans continues to have wide appeal.

However, using models such as BEHAVE for predicting fire effects at landscape scales is a daunting task. Changes in fuel moisture, packing and geometry of fuels as well as changes in wind speed and direction, and humidity must all be estimated across the entire fire front. Often these variables are either unknown or unmeasurable at landscape scales. The experience with the real-time application of BEHAVE for estimating worst-case scenarios during the 1988 Yellowstone fires is informative in this regard (Rothermel, 1991). Because weather conditions were so extreme, and the effects of fire spotting (i.e., the initiation of new fires by transport of burning material beyond the fire line) on the ignition of new crown fires was so important, alterations in assumptions of fuel type were necessary to simulate the rapid spread of fires experienced in Yellowstone in 1988 (Rothermel, 1991). Furthermore, the nature of the fuels and weather forecasts were uncertain (i.e., the weather conditions in Yellowstone in 1988 were extreme) causing prediction of fire behavior to depend on expert experience as much as on the model simulations (Rothermel, 1991).

The Rothermel equations for simulating landscape effects of fire have been adapted for chaparral ecosystems by Malanson (1984) and Davis and Burrows (1993), demonstrating a strong linkage between vegetation fragmentation, frequency of fire ignition and landscape patterns of post-fire vegetation. An adaptation of these equations for forested landscapes has been proposed by Vasconcelos and Guertin (1992; FIREMAP in Tables 7.2 and 7.3). The FIREMAP model involves

the conversion of the continuous form of the equations for fire spread of BEHAVE (Andrews, 1986) to a discrete form which allows gridded landscape data to be used to characterize the spatial heterogeneity of fuel types. This discrete transformation also permits digital elevation data to be used to estimate changes in fire behavior with changes in topography. During a simulated fire the computer program reads in the landscape data and calculates fire characteristics at each time step for each cell. The process is repeated for each successive update in weather conditions and new output maps are then generated. The analysis of map layers allows the time-dependent changes in fire spread and intensity to be analyzed. Although the temporal and spatial extent of the simulations performed with FIREMAP are limited (Table 7.3), the spatial characterization of fire spread and the effects of the spatial variability in fire intensity are important for estimating landscape-scale changes in ecosystem dynamics as the result of shifting fire regimes. In spite of the limitations of FIREMAP, the comparison of model simulations with patterns recorded during a single fire event indicates that this representation may satisfactorily mimic observed patterns (Vasconcelos & Guertin, 1992).

The most extensive application of the physical-based approach has been recently published by Keane *et al.* (1996*b*; FIRE-BGC in Tables 7.2 and 7.3). FIRE-BGC was designed to integrate a series of fire disturbance models for fire ignition (FIRESTART) and spread (FARSITE; Finney, 1998) with a forest succession models to replace disturbed forests (FIRESUM; Keane *et al.*, 1989) and estimate ecosystem attributes of the affected areas (FOREST-BCG; Running and Coughlan, 1988). Other models are used to generate weather scenarios and evaluate the historical patterns of fire occurrence (see Keane *et al.*, 1996*a* for additional details). The simultaneous simulation of multiple models is effected by communication among UNIX workstations executing each model within this complex system. The intriguing aspect of linkage of models operating over different temporal and spatial scales is that it is possible to track multiple ecosystem properties (e.g., evapotranspiration, net primary production, nitrogen availability, standing crop biomass of forest, etc.) simultaneously as they are altered by fire and as they, in turn, alter the fire regime. However, this complexity makes it difficult to identify the importance of model assumptions, verify the validity of the computer formulation and linkage, and test the sensitivity of model response to alternative sets of parameters and input values. Of course, these issues are not unique to this model – only the dynamics of the simple theoretical models can be throughly analyzed. The problem of complexity and the propagation of error is an important issue in extrapolating results to landscape scales (Gardner *et al.*, 1982; Milne, 1992; Turner *et al.*, 1989).

The results of a series of simulations with FIRE-BGC for a 200-year period of a 50 000 ha region within Glacier National Park (Keane *et al.*, 1996*a*,*b*) showed increases in net primary productivity and available nitrogen when fires were included in the simulations, with standing crop biomass and evapotranspiration showing an expected decrease when fires were included. The interesting result is that tree increment data generated by model simulations agreed well with available

tree-ring data from Glacier National Park. This type of comparison is unique among fire models because it uses information that is independent of the data used to develop and calibrate the model.

Probabilistic models

Probabilistic models are ones which simulate the spread of fire on a gridded landscape via probabilistic rules that are similar to those used in cellular automata models (Wolfram, 1984). Because probabilistic models are similar to the theoretical and exploratory classes of models, it might seem more logical to present probabilistic models before discussing the physical models. However, the probabilistic models are also directly related to the physical models. The model of Clarke *et al.* (1994; CLK94 in Tables 7.2 and 7.3) begins by a discussion of the landscape-scale application of the Rothermel equations and a justification of a simpler representation of the processes modeled by BEHAVE. The model of Gardner *et al.* (1997; EMBYR in Tables 7.2 and 7.3) also relies on the experimental results of models based on the Rothermel equations to estimate parameters of the probability, rate of spread, and fire intensity.

The purpose of the CLK94 model (Table 7.1) is to provide a simple and reliable representation of fire intensity and spread using methods based on percolation theory that can efficiently simulate the spatial pattern of fires at landscape scales. The CLK94 model considers a diverse set of characteristics (Table 7.3) that are relevant to assessing landscape effects, including the representation of spatial variability in fuel structure, temporal variability in wind speed and direction, and the effect of topography on fire spread and intensity. It is worth noting that only the two probabilistic models (i.e., CLK94 and EMBYR, Table 7.3) and the FARSITE model explicitly consider the effects of fire spotting on the spread and pattern of fire effects.

The development of the CLK94 model was motivated by the desire to use remotely sensed thermal infrared imagery to calibrate the model and view real-time estimates of the spatial patterns of fire spread. Because CLK94 was not designed for the study of landscape effects of fire, a number of factors are held constant for any given simulation (for instance, fuel structures, moisture contents, and ignitions are fixed, Table 7.3), the spatial and temporal scales are set to values appropriate for simulating single fire events, and the effect of fires on the forested ecosystems is not considered. In spite of these limitations, the model structure is of interest to landscape studies because it is possible to use Monte Carlo simulations of the model to produce spatially explicit estimates of risk (risk maps are spatial estimates of the probability of an individual site being burned: see Clarke *et al.*, 1994). The use of risk maps is an appropriate method for evaluating fires in heterogeneous landscapes because small random changes in unmeasurable variables (e.g., sudden bursts of wind, slight changes in fuel moisture, etc.) makes the direct comparison of actual fires with a single model simulation quite misleading. What is more appropriate is to be able to state that an actual fire is a likely member of the ensemble of simula-

tions produced by the model under a set of conditions representative of the observed fire. Significant changes in these risk maps are appropriate evidence of landscape-scale effects of a given fire regime.

Many of the features of EMBYR are quite similar to those of CLK94. EMBYR propagates fire by user-defined sets of probabilities of fire spread from cell to cell. 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). In addition, during the simulation the probabilities are adjusted for each site depending on topography and shifts in wind speed and direction. Fire spotting is simulated by lofting burning embers downwind from the fire front (Gardner *et al.*, 1997). Weather records can be input directly into EMBYR or generated from instrumental records. Simulations with EMBYR are quite rapid because it is an event-driven model updating only the status of burning cells. Monte Carlo methods can also be applied to estimate spatial patterns of risk with EMBYR (Hargrove *et al.*, in press). Because EMBYR was specifically designed to simulate fire at landscape scales, a Markov model of forest recovery is included. The spatial and temporal scales of landscape simulations are coarser grained with broader extent than CLK94.

Monte Carlo simulations with EMBYR over 1000 years for three different weather conditions (i.e., weather conditions typical of the past 30 years, slightly wetter conditions, and slightly drier conditions) has demonstrated the sensitivity of landscape pattern to changes in the fire regime (Gardner *et al.*, 1997). Fewer but more severe fires occur when conditions were wetter than normal, and more frequent, smaller fires resulting in greater landscape fragmentation occurred when conditions were drier than normal. These results are consistent with both empirical and simulation studies that show that small changes in climate can produce dramatic differences in the fire regime (e.g., Antonovski *et al.*, 1992; Clark, 1989, 1990; Baker, 1992; Suffling *et al.*, 1988; Romme and Turner, 1991; Davis and Burrows, 1993; Swetnam, 1993).

Shape models

Catchpole *et al.*, (1992) have noted that the ". . . simple ellipse has been a most useful model of the perimeter of a free-burning wildland fire." These authors maintain that only three inputs are required to simulate the shape of a fire: the intensity of the fire front, the elliptical shape factor, and the backfire spread rate. Although this approach has been criticized when fuels are non-uniform (e.g., Green, 1989; Clarke *et al.*, 1994), other studies have shown that the ellipse is a satisfactory model of fire spread under uniform fuel conditions (e.g., Anderson, 1983; Alexander, 1985). The shape models are, in fact, easily derived from the equations developed by Rothermel for the physical models assuming that fuels are homogeneous and continuous and weather conditions are constant because the ". . . elliptical fire shape implies a variation in the spread rate at different angles to the prevailing wind direction."

Catchpole *et al.* (1992) suggest that the elliptical model could be used to generate tables of fire size and effect for different fuel types and burning conditions, allowing rapid simulations of fires at landscape scales. Because the elliptical model most closely matches reality in a homogeneous fire environment, with steady-state weather conditions, model output provides risk estimates for areas were fuel loadings and topography are known (Catchpole *et al.*, 1992). Wallace (1993; WALL93 in Tables 7.2 and 7.3) developed a more general model using elliptical geometry to simulate fire patterns in landscapes with variability topography and fuels. Unfortunately, errors in WALL93 simulations tend to produce unacceptably large errors with time and space – indicating a property which may be related to the geometric methods used by the shape models.

Statistical models

The statistical description of the past history of fires has allowed the estimation of frequency distributions describing the average fire interval, fire frequency, average age of the vegetation, and the renewal rate of disturbed forests. Johnson and Van Wagner (1985) in a much cited paper have demonstrated that the Weibull distribution is the most suitable form for representing the fire regime, because the Weibull allows the hazard function (or the estimate of the instantaneous rate of burning) to vary as a function of the age of the vegetation. (The exponential distribution assumes a constant hazard function and is a special case of the Weibull distribution.) The Weibull distribution allows estimates to be made of the distribution of times since last fire or the probability of having fires within any given time span. The application of methods proposed by Johnson and Van Wagner (1985) result in projections of the effects of the current disturbance regime over time and space. Because the method assumes a constant regime, the parameters for the Weibull must be re-estimated for different landscapes and/or climatic regimes or for different time periods within the same landscape. In addition, the statistical method does not provide spatially explicit information of fire size and effect, seriously limiting its application to landscape studies.

Although the statistical approach developed by Johnson and Van Wagner (1985) lacks a spatial component, the method has been adapted and applied at landscape scales by modifications allowing the estimation of the effect of spatial patterns of disturbance. One example of this adaptation is the DISPATCH model (Baker *et al.*, 1991; Baker, 1992), which was designed to address the effect of changing climate (i.e., shifts in the disturbance regime) on vegetation patterns at landscape scales. Consequently, DISPATCH is constructed so that it is possible to simulate landscape change from hundreds to thousands of years over very large areas (Table 7.3), allowing the effect of heterogeneity of fuels, temporal changes in moisture, and changes in topography on disturbances to be considered (Baker *et al.*, 1991; Baker, 1992).

The simulation procedure used by DISPATCH involves random selection of weather conditions from pre-specified synoptic climate types, random selection of

a disturbance with sizes set by unique negative exponential distributions associated with each synoptic climate, and random propagation of disturbance as a function of vegetation type, age, elevation, and topography until the specified disturbance size is reached. Because disturbance spreads randomly from cell to cell, the DISPATCH model resembles a combination of a statistical model and a theoretical (or cellular automata) model.

The results with DISPATCH have shown that landscape structure fluctuates widely even if a disturbance regime remains constant for over a 250-year period (Baker *et al.*, 1991). Shifting patterns of land use and climate indicate that management techniques are unlikely to be able to reconstruct pre-settlement conditions of forested landscapes (Baker, 1992). Obviously, these simulations represent a "test of hypothesis" of the nature of interactions at landscape scales and should not be expected to be precise predictions of the future states of the landscape (Baker, 1992). This caveat is true of all landscape models – simulations over long temporal and spatial scales will always be difficult to verify. In many ways the purposes of landscape models are similar to the theoretical models that explore the dynamics of interacting processes. The only difference might be that the parameters for the landscape models have been developed from a stronger empirical base and are intended to represent actual landscape and weather conditions.

Discussion

Fires are important events shaping the dynamics of terrestrial ecosystems in many regions of the world (Turner *et al.*, 1994; Whelan, 1995; Goldammer and Furyaev, 1996). Forest fires directly affect community composition and structure (Heinselman, 1981; Noble and Gitay, 1996) and result in significant releases of greenhouse gases (Auclair and Carter, 1993; Cofer *et al.*, 1996). Ecosystem effects due to forest fire are significant with the consumption of biomass resulting in modifications of soil temperature and chemistry (Goldammer and Furyaev, 1996), the removal of seeds and seed sources in high intensity fires (but also the removal of seed predators), significant changes in cycling of nutrients and some loss of soils due to subsequent erosion (Meyer *et al.*, 1992; Trabaud, 1994), and the redistribution and eventual sequestration of elemental carbon (Clark and Richard 1996; Kasischke *et al.*, 1995). The combined effects of community and ecosystem alteration due to fires often result in conditions which favor the continued propagation of new fire regimes (Bergeron, 1991). The long-term consequences of these changes remain difficult to anticipate because changes in climate and land-use (including fire suppression) are causing continual shifts in fire regimes (e.g., Johnson and Larsen, 1991) with the result that landscape patterns will be in a constant state of disequilibrium (Ales *et al.*, 1992; Boychuk *et al.*, 1997; Johnson *et al.*, 1990; Turner and Romme, 1994). Because current methods of analysis and prediction have emphasized the fine-grained dynamics of fire behavior and the corresponding management practices that reduce fire hazard, the long-term interactions of forest ecosystems with different fire regimes has been neglected.

Empirical and theoretical studies of the effects of fire in forested landscapes are beginning to reveal interesting and unexpected relationships, including the following:

(i) Theoretical models have demonstrated that the pattern of recovery and regrowth of forests experiencing frequent fires results in the self-organization of these landscapes to a critical threshold where the connectance of fuels is sufficient to sustain very large fires (Bak *et al.*, 1990; Green, 1989; Hargrove *et al.*, in press; von Niessen and Blumen, 1986). The exact value of the critical threshold (i.e., the degree of connectance of fuels) depends on both climate and the rate of recovery of the forest (Gardner *et al.*, 1997; Hargrove *et al.*, in press; Swetnam and Betancourt, 1990). Because landscape patterns of systems near the critical threshold reflect the effects of turbulent dynamics (Bak *et al.*, 1990), the variability of forest structure at fine scales can be expected to be very high.

(ii) One useful property of systems near the critical threshold is that scaling rules can be developed to extrapolate fine-grained interactions to much larger areas (Beer and Entin, 1991; Orbach, 1986; Stauffer and Aharony, 1992). Scaling rules have been applied to different formulations of probabilistic models simulating fires within forested landscapes (MacKay and Jan, 1984) and the results found to be robust across different formulations (von Niessen and Blumen, 1986). This result is quite important because the study of forested areas requires that dynamics be predicted for very large regions. However, forest ecologists have yet to fully explore this result for other model types with the goal of developing simpler, more efficient models.

(iii) It is generally accepted, as noted previously, that forests subject to frequent fires are unlikely to be in state of equilibrium – either in terms of landscape-scale patterns of disturbance and regrowth, species composition and community structure, or ecosystem dynamics. What is equally important, especially for long-term projections of effects, is that this disequilibrium requires precise information regarding initial conditions (Keane *et al.*, 1996*a*) and that shifting regimes will confound management practices intended to maintain specific sets of conditions (Baker, 1992).

(iv) Coupling ecosystem models with models of fire disturbance has produced several interesting and unanticipated results including increased levels of available nitrogen, increased net primary productivity and reduced levels of biomass and evapotransipration (Keane *et al.*, 1996*a*, *b*). Further efforts to link ecosystem models with models of fire behavior of other forested landscapes is especially needed.

(v) Small shifts in climate can produce dramatic shifts in fire regime, with subsequent changes in the age structure and the spatial arrangement of mature forest (Gardner *et al.*, 1997).

(vi) The high level of uncertainty associated with the dynamics of disturbed systems, and the lack of understanding of processes operating at landscape scales (e.g., fire spotting, changes in synoptic weather conditions, local effects of fire on wind, etc.) requires that model projections be expressed in terms of risk of change (Clark *et al.*, 1994; Hargrove *et al.*, in press; Fosberg *et al.*, 1996).

The categories developed for this review were intended, in part, to illustrate the broad range of purposes and assumptions characteristic of each model type. Although other classification schemes have been offered (e.g., Li and Apps, 1995), all such schemes are confounded by fundamental differences in the structure of the models and differences in the data used for their development and application. Only when simultaneous simulations of models are performed can the importance of specific differences in processes considered and structure of models be evaluated. What is interesting is that the models within our six categories share three distinct "threads" of development from: (i) the fire behavior methods based on the Rothermel model of fire spread (Rothermel, 1972); (ii) probabilistic models using a gridded landscape and methods adapted from the methods of cellular automata; (iii) and statistical models based on sampling of fire frequency and size from empirically derived frequency distributions. The shared features among apparently different models makes differences in model structure and performance even more difficult to evaluate.

It is equally clear that current models do not fully represent all factors important in predicting landscape-scale patterns of fire disturbance. For instance, the process of fire spotting remains poorly understood and infrequently included in fire models; the dynamics of winds during fire events are difficult to quantify in space and time making the scale-dependence of their effects difficult to evaluate; the description of the spatial heterogeneity of fuels, fuel moisture and weather remains coarse and uncertain; and factors contribution to land-use change are usually neglected. The inclusion of realistic dynamics of forest regrowth and succession, as well as the coupling of community and ecosystem dynamics, has only recently been attempted (Keane *et al.*, 1996*a*). These methods need to be expanded to a broader spectrum of forest types and climatic zones.

Clearly the inclusion of these additional variables would serve to greatly increase the complexity of current models. However, there are clear dangers to increases in model complexity, in part because the uncertainties associated with these details may overwhelm the reliability of model predictions. The additional complexity makes the process of model verification more difficult and the addition of unknowns may increase the bias associated with predictions. There are, however, corresponding dangers in the exclusive use of simple models. Key processes that affect both fine-grained dynamics and broad-scale trends may be absent from simple models unless systematic comparisons between models and data are performed. Although this problem is an old and familiar one (Gardner *et al.*, 1982;

Bartell *et al.*, 1988), these issues are only now being considered in the adequacy and reliability of disturbance models which must make predictions over extremely broad temporal and spatial scales.

Three suggestions are offered here to resolve some of these difficulties. First, it is important to remember that the results of model simulations are simply the logical consequence of a series of hypotheses and assumptions. The relevant question then is, how different would the projections be if one or more assumptions were relaxed, different processes included or disregarded, and an alternative set of hypotheses tested? This important question can best be evaluated by cross-comparison of model sensitivities with relevant empirical studies and the quantification of differences in response between models. Examples of such comparisons can be found in other modeling studies (e.g., Melillo *et al.*, 1995; Rose *et al.*, 1991*a*, *b*). Inter-model comparisons, which use similar data sets and disturbance scenarios to assess model sensitivities, will allow the relative importance of specific processes to be quantified. Second, there must be a renewed effort to develop simple yet reliable models for extrapolation of results across scales. Comparisons of differences between models depending on their temporal and spatial resolution can be inferred from Table 7.3. However, rigorous sets of model experiments are necessary to estimate errors and uncertainties associated with the cross-scale predictions. If scaling rules can be developed for complex models then the effects of climate change (which acts at broad scales) might be revealed in changes in disturbance regimes and corresponding shifts in forest structure. Finally, the study of fire in natural systems must be expanded to include systems altered by changes in land use. In many regions of the world changes in agricultural practices are increasing the risk of fire, while in other regions forest fragmentation is reducing the risk of large fires. These shifts in land use confound the estimates of net carbon storage and nutrient release from forest disturbance.

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