Climate change, disturbances and landscape dynamics

R. H. Gardner, W. W. Hargrove, M. G. Turner and W. H. Romme

Introduction

The objectives of the Global Change and Terrestrial Ecosystems (GCTE) core project of the International Geosphere-Biosphere Programme (IGBP) are to predict the effects of changes in climate, atmospheric composition and land use on terrestrial ecosystems, and to determine how these effects lead to feedbacks to the atmosphere and physical climate system (Steffen *et al.*, 1992). These issues are challenging because they require studies of broad-scale patterns of ecological change which consider processes at many scales (Urban *et al.*, 1987; Levin, 1992). For instance, the linkage between climate, fire and terrestrial ecosystem dynamics requires an understanding of fine-grained details of fire ignition and spread, landscape scale patterns of vegetation and their response to fire, as well as changes in the long-term patterns of weather and climate.

The possibility of rapid changes in terrestrial landscapes as a result of drier climate conditions and altered fire regimes is recognized as a serious risk in many regions of the world (Bonan *et al.*, 1990; Overpeck *et al.*, 1991; Romme & Turner, 1991; Swetnam, 1993; Moreno & Oechel, 1994). The effect of climate change on fire regimes has been exacerbated by contemporary changes in land-use patterns and fire suppression efforts, causing fuels to accumulate and the risk of large fire to increase (Ales *et al.*, 1992; Davis & Burrows, 1993). The possible loss of large areas of forested land may result in significant changes in the pattern of vegetation regrowth and succession (Neilson, 1993) with many areas shifting to a new vegetation state (Overpeck *et al.*, 1990). It is the serious implications of these hypothesized effects of climate change that have motivated many IGBP/GCTE studies.

Our current understanding of the interaction between climatic conditions, fire regimes and forested landscapes is based on a variety of empirical and theoretical studies. Analysis of recent trends between fire and weather (e.g. Balling, Meyer & Wells, 1992; Renkin & Despain, 1992; Johnson & Wowchuk, 1993) allowed relationships between weather and fire

to be evaluated over the duration of contemporary records (*c.* 100 years). Studies based on intensive sampling of stand histories and dendochronology (e.g. Romme, 1982; Romme & Despain, 1989; Swetnam & Betancourt, 1990) and stratigraphic charcoal data (Clark, 1990) have extended available records to nearly 800 years. Fires within stands of the giant sequoia (*Sequoiadendron giganteum*) produce the longest records of all, allowing climate variables and fire frequencies to be reconstructed for 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 the hypothesized effects of altered climate and fire regimes on ecosystems lacking long-term fire records. Baker *et al.* (1991) have used model simulations based on statistical relationships between stand age and risk of large fires to quantify changes in amount and spatial configuration of forested regions. Antonovski *et al.* (1992) developed a simple coarse-grained grid-based model that simulated the effects of climate change on fires on boreal systems over a 3000-year period. The results (which Antonovski *et al.* regarded as preliminary) showed unexpected changes in the area burned through time as a consequence of drier climate conditions. A more detailed model was developed by Davis and Burrows (1993) for simulating fire patterns in Mediterranean landscapes. Davis and Burrows adapted Rothermel's (1972) thermodynamic model of fire spread (that includes such factors as fuel type, fuel moisture, wind and topography) and simulated fire patterns in a fine-grained (0.9 ha per cell) grid of California chaparral over a 500 year period. Their tests of the sensitivities of this model to changes in spread rate and frequency of fire ignitions showed that the patch size and age distribution of fires were closely coupled to ignition frequency and the fragmentation of combustible vegetation.

Each of these models provides valuable insight into the long-term consequences of changes in landscape pattern as a result of the adjustment of climatically affected model parameters. However, none has simultaneously considered the effect that climate change has on the year-to-year variation in weather patterns, the subsequent effect that changes in the mean and variance of local weather conditions has on the severity and intensity of fire, and the mitigating or amplifying effects that landscape heterogeneity of fuels (including topography) can have on results. We have developed a model that links fine-grained details of vegetation pattern with the stochastic process of fire ignition and spread by wind and firebrands as a consequence of hypothesized changes in climate. We use this model here to (1) examine how changes in climate affect the frequency and extent of fires; and (2) project the long-term consequences of such changes on the spatial

pattern of forested landscapes. It is hoped that these simulations will provide additional insight into the identification of subtle but significant effects of climate change on landscape patterns.

Simulating fires at landscape scales

The need to simulate the spatial effect of wildfires at landscape scales has resulted in the development of a variety of models which vary in their complexity and data requirements. For instance, a number of models have been based on concepts from percolation theory and cellular automata (e.g. Kessell, 1976; Green, 1983; Albinet *et al.*, 1986; Ohtsuki & Keyes, 1986; von Niessen & Blumen, 1986; Turner *et al.*, 1989; Green *et al.*, 1990), while others have been developed from more detailed, thermodynamic description of fire spread (e.g. Rothermel, 1972; Kessell, 1976, 1979; Vasconcelos & Guertin, 1992; Davis & Burrows, 1993). Some models have relied on statistical relationships to predict the severity and extent of fire effects (e.g. Johnson & Van Wagner, 1985; Baker, 1992), while others are directly linked to GIS data bases (e.g. Kessell, 1979; Vasconcelos & Guertin, 1992; Clark *et al.*, 1993). Our approach to the problem of simulating fire effects over broad spatial scales has been to develop an event-driven, probability-based model (W. W. Hargrove *et al.*, unpublished observations) that efficiently simulates fire events over large areas and long periods of time. We recently developed algorithms that generate weather conditions during the fire season and linked the fire simulations to a vegetation recovery model, allowing us to test the sensitivity of landscape pattern to the long-term effects of climate induced changes in fire regimes.

EMBYR, the fire model

EMBYR is an event-driven, grid-based simulation model of fire ignition and spread in heterogeneous landscapes. Fire spread is simulated by examining each burning site (50 × 50 m) and determining spread to the eight adjacent sites as a function of fuel type, fuel moisture, wind speed and direction, and topography. In addition, burning sites distribute firebrands to downwind sites, where the probability of ignition of new fires is a function of fuel type and moisture conditions. A qualitative index of fire severity was developed to identify cells where fire intensity was high enough to consume all the trees on the 50 × 50 m cell. Burn severity was calculated as a linear combination of fuel type, fuel moisture, wind speed and the rate the cell burned. The value of the severity index that results in a stand-replacing fire was calibrated by reconstructing the weather events of

1988, simulating the spread of fire, and comparing the simulation results with the proportion and distribution of sites that experienced a stand-replacing fire measured within a 1 × 1 km study site that lies approximately 2 km northeast of the Old Faithful weather station.

A set of model parameters was developed to represent weather conditions and distribution of fuels on the subalpine plateau of Yellowstone National Park. Simulation experiments revealed relationships between model parameters and landscape heterogeneity, and the results of repeated simulations were compared by evaluating risk (the cumulative frequency distribution of the area burned) as a function of the change in weather conditions.

The landscape

Yellowstone National Park (YNP) lies in the interior of the North American continent (mostly in the northwest corner of Wyoming, United States), straddling the Continental Divide. Elevations within the park range from 1600 m in the north where the Yellowstone River leaves the park and flows into Montana, to several peaks above 3000 m along the eastern and northern boundaries. Upper timberline is near 3000 m. Most of the park is between 2000 and 2700 m in the subalpine zone (Despain, 1990).

YNP is about 83% forested, with lodgepole pine (*Pinus contorta* Loudon var. *latifolia* Engelm.) the dominant species. The growth and development of lodgepole forests has been characterized by four stages (Romme & Despain, 1989; Despain, 1990). Young stands that regenerate after fire are classified as LP0 until the time of canopy closure (approximately 40 years). Small dead fuels within these stands are too sparse to carry fire readily and live fuels are usually too green to burn. Consequently, probability of fire spread in LP0 is low under all weather conditions. Young, even-aged lodgepole pine stands that are approximately 40 to 150 years post-fire are classified as LP1. Although tree densities are usually high within these stands, fuels on the forest floor usually are sparse, and crown fires will propagate only in extremely windy conditions. Even-aged closed canopies of lodgepole pine with a developing understorey of Engelmann spruce (*Picea engelmanni* Parry) and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) are classified as LP2. This stage lasts from approximately 150 to 300 years after a fire. Fuels on the forest floor are sparse to moderate, and flammability begins to increase in the later portions of this stage. Finally, LP3 stands have pine, fir, and spruce of all ages and size classes. This stage persists until the next stand-replacing fire with young spruce, fir, and dead fuels accumulating in sufficient density to propagate crown fires under dry conditions even without wind.

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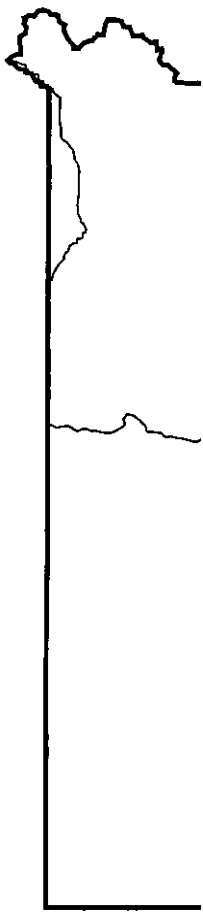

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The area chosen for the simulations (Fig. 9.1) was a 30 × 30 km (90 000 ha) section of land (UTM coordinates: north 3917975, south 4887975, east 550825, west 520825) that lies in the south central portion of the park (Fig. 9.1). The distribution of forest successional stages prior to the extensive fires in 1988 was available in GIS format based on interpretation of low-altitude aerial photographs taken in 1969 and 1972 by D. G. Despain (personal communication). The simulation area contained 78 723 ha of forested land (87.5%), with 56% of that area (43 899 ha) composed of mature LP_3 stands. Only 7035 ha (9%) of the landscape was composed of non-flammable water, rock, etc.

Post-fire recovery of each cell is modelled as an independent Markov process. Parameters for the Markov model were developed from an extensive sampling of increment cores and fire scars within a 130 000 ha study area on

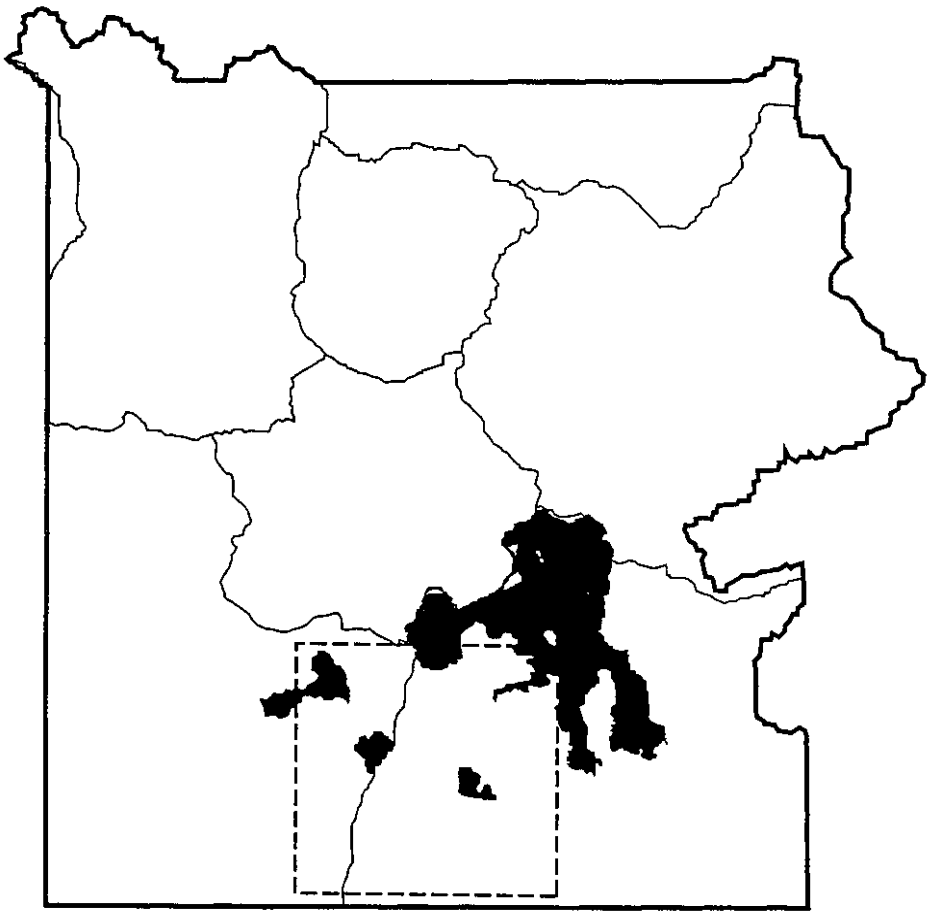

Figure 9.1 *The 30 × 30 km study region within Yellowstone National Park used for the simulations is indicated by the dotted line. Lakes are represented as solid black, and lines show the major roads within the park.*

the subalpine plateau of Yellowstone National Park that resulted in a map of stand age (time since fire) and successional stage in 1985 (Romme & Despain, 1989 and unpublished data). Transition probabilities were estimated by empirically fitting the transition of forest types by assuming that an LP0 stand forms if the burn severity index indicated that a stand-replacing fire occurred, and that LP0 sites can not transform into LP1 until they are at least 40 years of age. At the end of each fire season, each cell was examined and the Markov transition probabilities (0.94, 0.99 and 0.995 for LP0 to LP1, LP1 to LP2 and LP2 to LP3, respectively) used to determine the fuel class of each cell.

Weather generation

The weather in Yellowstone National Park is characterized by short cool summers and long, cold winters with precipitation highest in winter and spring (Dirks & Martner, 1982; Despain, 1987). The summers are usually dry with an average of about 32 mm of rain per month (Renkin & Despain, 1992), resulting in a fire season that lasts from mid June to late September, with large fires most probable during July through September (Overpeck *et al.*, 1990). Weather records used for the 1000 year simulations consist of 30 years of weather data recorded at the Old Faithful weather station and obtained from the WIMS/NIFMID (Weather Information Management System/National Interagency Fire Management Integrated Database) National Historical Fire Weather Database (US Forest Service, Missoula, MT, USA). Recorded variables include date, time, temperature, relative humidity, wind speed, wind direction, and estimates of 10 hour and 1000 hour time lag fuel moisture. The percentage fuel moisture estimates are calculations based on the National Fire Danger-Rating System (Deeming *et al.*, 1978) which measures long-term moisture conditions and serves as a drought severity indicator. The 1000 hour time lag fuel moisture (THFM) was a key variable describing fire dynamics within YNP. Observations of naturally burning fires from 1972 to 1987 revealed that fire spread was extremely unlikely when THFM >16%, but that severe crown fire activity and rapid spread were likely when THFM <13% (Renkin & Despain, 1992). Thus, we focused on these thresholds in fire behaviour relative to THFM (Fig. 9.2).

The simulation of fires over a 1000 year time period by EMBYR required a generation of a data set that realistically represented daily changes in fuel moisture, wind speed and direction, as well as the number and location of fire starts. It was also important for the generated weather to adequately represent seasonal patterns (for instance, relatively wetter spring and autumn

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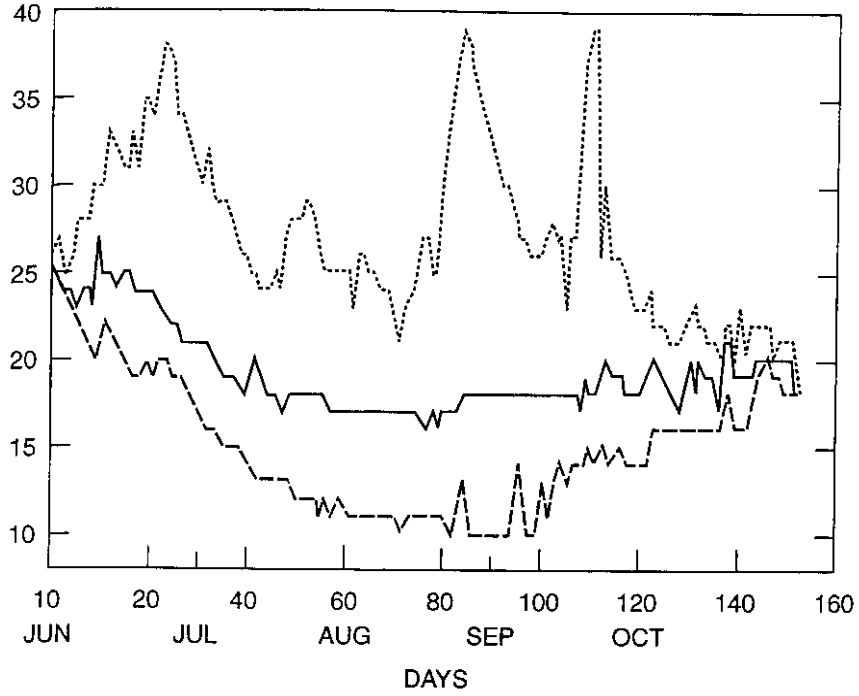

Figure 9.2 *Minimum, median, and maximum 1000-hour time lag fuel moisture (THFM) values summarized from 26 years of weather data taken at the Old Faithful weather station.*

weather, with drier periods in July and August). We designed a procedure to produce daily weather records for 1000 years by systematic sampling from the existing weather records. The objectives of the procedure were to: (1) maintain the appropriate relationships between the daily weather variables of wind speed and direction, fuel moisture and fire starts; (2) randomly select weather records with realistic autocorrelated changes in fuel moisture; and (3) produce weather sequences that provide an unbiased representation of extreme events. To achieve these objectives, an algorithm was developed that: (1) produces an autocorrelated Brownian motion with displacements at each step produced by Gaussian noise (Plotnick & Prestegard, 1993); (2) normalizes the trajectory to produce values that fall between randomly selected minimum and maximum percentiles of THFM (the average minimum and maximum percentiles for 26 years was 0.19 and 0.95, with standard deviations of 0.18 and 0.10 for the minimum and maximum values, respectively); (3) selects daily weather records by matching the randomly generated THFM percentile with the corresponding THFM record from the data (Fig. 9.3); and (4) writes the selected data record to a file for input to EMBYR.

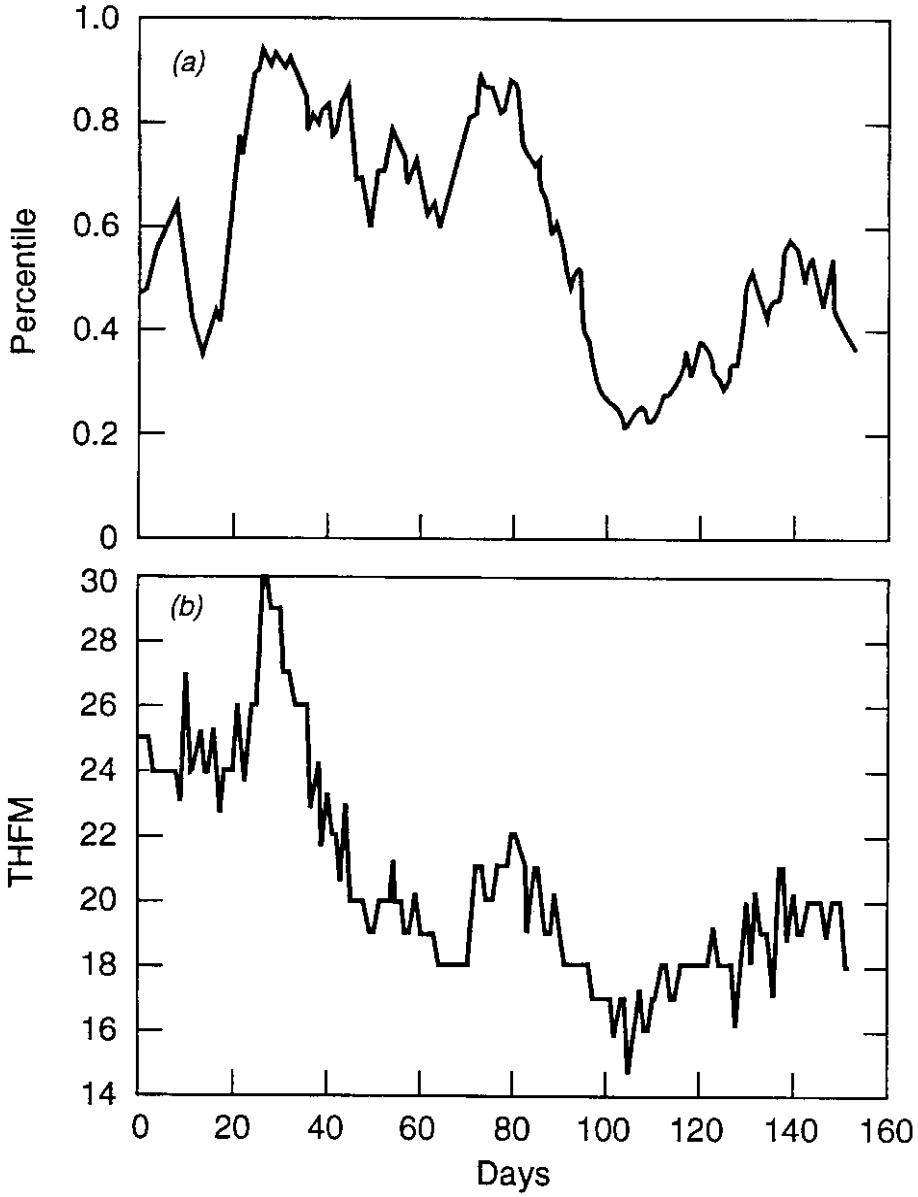

Figure 9.3 *Illustration of weather generation for a single fire season. (a) The percentiles for 1000-hour timelag fuel moisture (THFM) generated by a correlated random walk. (b) The corresponding THFM values selected from the weather records.*

The mid-point displacement method (Barnsley *et al.*, 1988) was used to generate the random trajectories of Brownian motion. This method produced a one-dimensional transect by randomly selecting the end points of the transect and then recursively dividing the line in half, resulting in a sequence of successively finer segments. The variance associated with the 'displacement' of

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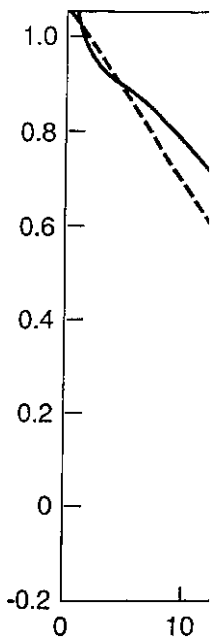

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each segment is reduced by $0.5^{(0.5H)}$ with each recursive division of the line, resulting in an average correlation between past and future increments that is equal to $2^{(2H-1)} - 1$ (Mandelbrot, 1983; Feder, 1988). The parameter H can range between 0.0 and 1.0, with values above 0.5 indicating persistence in trends (Feder, 1988). For our simulations, H was set to 0.7, producing an average correlation of 0.3. The use of the mid-point displacement method to generate percentiles of THFM seemed to capture the natural autocorrelation of THFM values over a 3 week period (Fig. 9.4). The matching of the generated percentile with percentiles of THFM from observed records preserves within-season patterns of fuel moisture change (Figs. 9.2 and 9.3). The selection of the entire record based on this single variable resulted in consistent relationships between fuel moisture, wind speed and direction, and fire ignitions.

The weather sampling procedure was used to create three scenarios by adjusting the mean value from which yearly minimum and maximum percentiles of THFM were generated (Table 9.1). For the 'nominal' scenario, the mean minimum and maximum percentiles were estimated from the historical data to be 0.20 and 0.75, respectively. The 'wetter' scenario was created by increasing these percentiles by 0.05, while the 'drier' scenario was created by decreasing the mean minimum and maximum percentiles by 0.05.

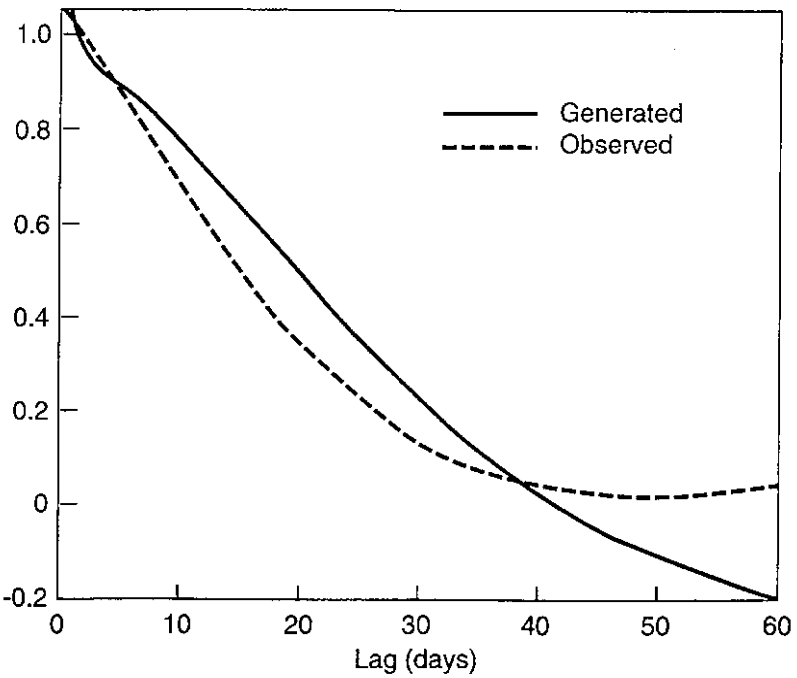

Figure 9.4 *Autocorrelation of simulated and recorded 1000-hour timelag fuel moisture (THFM) values.*

Table 9.1. *Mean minimum and maximum THFM[a] percentiles for generating autocorrelated weather sequences for the three weather scenarios*

	Weather scenario		
	Wetter	Nominal	Drier
Minimum[b]	0.25	0.2	0.15
Maximum[b]	0.80	0.75	0.70

[a]THFM is the percentage moisture content of large (≥ 7.6 cm diameter) fuels that require approximately 1000 hours to equilibrate with atmospheric humidity (Deeming *et al.*, 1978).
[b]The standard deviations for the minimum and maximum were 0.20 and 0.35, respectively, for all weather scenarios.

Fire starts

The location of each fire start was randomly selected with probabilities estimated from the historical records (dating back to 1972) of natural fires within the study region. Because records were not extensive for this region of the park (the total number of records equals 262), probabilities for the entire area were estimated by aggregating the 50 × 50 m cells into larger units of 2750 m on a side (1406.25 ha). A two-dimensional spline with tension (Mitas & Mitasova, 1988; Mitasova & Mitas, 1993) was then used to interpolate a smooth surface through these points at a resolution of 50 × 50 m, with the constraint that all locations except lakes and rivers had a small but finite (0.0002) possibility of ignition. The ignition probabilities were greater at higher elevations, but the relationship between fire starts and elevation was complex due, in part, to the pattern of storms within YNP and the irregular distribution of non-flammable sites (<8% of the total area, or 7035 ha).

A separate FORTRAN program preselected locations for fire starts from the spatial probability distribution and wrote this information to a data file (starts.dat). During each simulation, when the weather record indicated that a start occurred, EMBYR reads the next record from starts.dat to obtain the coordinates for the fire start.

Model simulations were tested by comparison against historical records of fires that occurred during the 1979 and 1981 seasons. We know that the rate and extent of fire spread are sensitive to the variation of weather conditions, especially wind speed and direction (W. W. Hargrove *et al.*, unpublished observations). Because detailed weather records for historical fires are not available, it does not seem reasonable to compare each fire with a single model simulation. However, Monte Carlo simulations with EMBYR can be used to charac-

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terize the frequency distribution of stand-replacing fires (W. W. Hargrove *et al.*, unpublished observations). When the actual fire events of 1979 and 1981 were compared with the frequency distribution of Monte Carlo simulations produced by EMBYR, the actual fires could not be distinguished from the simulations. Further details and an illustration of this comparison with EMBYR simulations can be viewed on the World Wide Web at URL http://www.esd.ornl.gov/ern/embyr/embyr.html.

Simulation of alternative climates

EMBYR was used to conduct 1000 year simulations for each of three weather scenarios: nominal, reflecting the weather of the past 20 years, drier than present, and wetter than present. Monte Carlo simulations with 10 replicates were conducted for each scenario. Data for each simulation included a gridded map of the distribution and successional stage of forested sites, the topography of the region, the probability surface for selecting locations for fire starts, and the randomly generated weather data for each weather scenario. During the simulation, EMBYR examined the weather records to determine the date for the next ignition, a random ignition site was selected from the fire starts probability layer, and the spread of the fire was simulated until the fire was extinguished. The severity of the fire (the effect of the fire on the vegetation) was recorded and, at the end of the year, the vegetation map was updated via the Markov recovery model. The number of ignitions, the size of the fires, the number of burned sites and changes in the amount of LP_0, LP_1, LP_2 and LP_3 were recorded each year during the simulation.

Spatial patterns of the forest vegetation at the end of each 1000 year simulation were quantified to estimate the cumulative effect of fires on the amount and arrangement of LP_3 stands. The statistics of interest were the size of the largest cluster of LP_3 sites, the total number of LP_3 clusters, and the area-weighted average cluster size (Saw). Individual sites were labelled as members of the same cluster if any one of the eight neighbouring sites (that is, adjacent or diagonal neighbours) were of the same successional stage. The more common method of cluster identification excludes the four diagonal neighbours and is inconsistent with EMBYR's rule for fire spread to the eight adjacent and diagonal neighbours.

Results

Variation in minimum and maximum THFM percentiles from the wetter to drier weather scenarios (Table 9.2) resulted in a 4.5% decrease in the frequency of days within the wettest THFM class (>16%). The frequency of

Table 9.2 *Results of the weather generation procedure. Percentage of days in three THFM[a] classes and muber of ignitions during the fire season (June 1 to October 15) for a single iteration of 1000 years of weather*

	Weather scenario			THFM class
	Wetter	Nominal	Drier	
Percentage of days				
	95.1	93.4	90.6	>16%
	4.2	5.5	7.6	12–16%
	0.7	1.1	1.8	<12%
Number of ignitions				
Total ignitions	7588	7838	8315	
Mean daily ignitions	0.05	0.051	0.054	

days within the moderate class (12–16%) increased by 3.4% and the frequency of days within the driest class (<12% THFM) increased from 0.7% to 1.8%. Although the total number of ignitions increased by 8.7% from wettest to driest, the average number of ignitions per day was large enough in all three scenarios to ensure that ignitions did occur (Table 9.2).

Among the three scenarios, fewer fires occurred in the wetter scenario (Table 9.3). The cumulative frequency distribution of fire sizes (Table 9.3) shows little difference for percentiles ≥75, but the distribution is skewed above the 75th percentile, with different patterns for the extreme events. For instance, the 95th and 99th percentiles for the wetter scenarios are nearly 1.5 times larger than the drier scenario (Table 9.3). Occurrence of less frequent but more extreme events in the wetter scenario was confirmed by examining the return interval of fires in three different size classes (Table 9.4). The average number of years between all fire events anywhere within the simulated landscape was 7.2, 5.7 and 4.4 for the wetter, 'nominal' and drier scenario, respectively. However, fires larger than 20 000 ha occurred once every 1000 years in the wetter scenario, but only once every 1626 years in the drier scenario (Table 9.4). The time required to burn an area equal to the total forested region of the landscape used in the simulation (Fig. 9.1, total forested area = 78 723 ha) was longest in the wetter scenario (2043 years) and shortest in the drier scenario (1626 years, Table 9.4).

The average area burned per year can be estimated by regressing the total area burned from the beginning of the simulation against time (years). Results of these regressions (Table 9.5) showed that rates of burn ranged from 145.6 ha/year for the wetter scenario to 176.3 ha/year for the drier scenario, with the 'nominal' scenario having an intermediate rate of 158.6 ha/year. The R^2 for all three regressions were high and the standard errors of the slopes were

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Table 9.3 *Selected percentiles of the area burned per year (ha) and the total number of fires resulting from 10 sets of 1000 year simulations of EMBYR for three weather scenarios*

	Weather scenario		
Percentile	Wetter	Nominal	Drier
1	0.25	0.25	0.25
5	0.25	0.25	0.25
25	1.5	1.0	1.0
50	8.5	6.8	7.8
75	294.8	265.8	357.8
95	7141.0	6403.8	4727.8
99	18384.0	16279.0	13125.0
Total Number	1391	1744	2256

"THFM is the percentage moisture content of large (≥7.6 cm diameter) fuels that require approximately 1000 hours to equilibrate with atmospheric humidity (Deeming *et al.*, 1978). The classes represent wet conditions (>16%), moderately dry conditions (12–16%), and very dry conditions (<12%).

low (Table 9.5), resulting in differences between slopes being highly significant ($P<0.0001$).

The total area of LP_3, the oldest age class of lodgepole pine stands, at the end of each 1000 years indicated that the amount of LP_3 was highest in the wetter scenario and lowest in the drier scenario (Table 9.6). The reduction in amount of LP_3 from wetter to drier conditions results in a corresponding increase in younger lodgepole stands when the climate was drier. As a consequence, the coefficient of variation for LP_0 stands was highest with a general decline in relative variability as the forest stands increased in age. However, the sudden transformation of LP_3 stands to LP_0 resulting from a stand-replacing fire caused the coefficient of variation of LP_3 stands to be somewhat greater than for LP_2 stands (Table 9.6).

The spatial arrangement of LP_3 sites was analysed at the end of each 1000 year simulation (the computational expense associated with this spatial analysis made it impractical to perform the analysis more frequently). Total number of LP_3 clusters increased by 40% from the wetter to the drier scenarios (Table 9.7). The coefficient of variation of the total number of clusters (that is, the per cent variability between model simulations) decreased by over 50% from the wetter to drier scenario. The increase in fragmentation produced by drier conditions was indicated by the increased number of

Table 9.4 *The rotation period and return interval of fires of three different size classes resulting from 10 sets of 1000 year simulations of EMBYR for three weather scenarios*

	Weather scenario		
	Wetter	Nominal	Drier
Fire return interval (years)[a]			
All fires	7.2	5.7	4.4
>2500 ha	71.4	52.1	45.5
>20000 ha	1000	1250	1667
Rotation period (years)[b]	2043	1818	1626

[a]Fire return interval is the mean number of years between successive fires of a given size class occurring anywhere within the study area.
[b]The rotation period is the estimated time required to burn an area equal to the total forested region of the landscape used in the simulation (Fig. 9.1).

Table 9.5 *Regression analysis of the cumulative area burned from 10 sets of 1000 year simulations of EMBYR for three weather scenarios*

	Weather scenario		
Regression[a]	Wetter	Nominal	Drier
β(hay/year)	145.6	158.6	176.3
SE	1.06	0.68	0.50
R^2	0.93	0.97	0.98

[a]The statistics were estimated by regressing the cumulative area burned (ha) on the year the burn occurred. The units for β, the slope of the regression, are hectares per year. SE is the standard error of the slope and R^2 is the ratio of regression sum of squares to total sum of squares. The statistics were estimated by SAS's GLM procedure (SAS Institute, 1990). Differences among the slopes are significant at $P<0.0001$.

clusters and the decrease in the size of the largest cluster (from 15 370 ha to less than 2000 ha from wetter to drier conditions). The area-weighted cluster size (Saw, Table 9.7) further illustrates the effect of fire on forest fragmentation, showing a 20-fold decline in Saw from the wetter to drier conditions.

Table 9.6 *Forest*
each of three weat

Forest cover (ha)	
LP0 mean/year	
CV[a]	
LP1 mean/year	
CV[a]	
LP2 mean/year	
CV[a]	
LP3 mean/year	
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[a]CV is coefficient

Discussion

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Table 9.6 *Forest cover at the end of 10 sets of 1000 year simulations of EMBYR for each of three weather scenarios*

	Weather scenario		
Forest cover (ha)	Wetter	Nominal	Drier
LP0 mean/year	8738	9486	10 440
CV[a]	87.9%	82.1%	73.6%
LP1 mean/year	14 568	16 066	17 304
CV[a]	35.5%	33.1%	29.5%
LP2 mean/year	24 832	26 715	27 872
CV[a]	16.6%	16.5%	16.5%
LP3 mean/year	30 251	26 073	22 642
CV[a]	22.5%	23.9%	23.4%

[a]CV is coefficient of variation defined as the standard deviation/mean × 100

Discussion and conclusions

Small changes in climate, and the subsequent climatically induced changes in fire regime (Clark, 1989), can result in rapid shifts in pattern and process at landscape scales (Clark, 1990; Baker, Egbert & Frazier, 1991). Although many terrestrial systems may be fire-adapted, the complex interaction between weather, fuel characteristics, history of fire suppression, and the landscape pattern of fuels make landscape-scale effects of altered regimes difficult to predict. The simulations reported here explored the long-term effects of climate-altered fire regimes on the pattern of forested areas within Yellowstone National Park. The results showed that small changes in weather parameters can produce significant shifts in the age structure and spatial arrangement of the forest. The 'drier climate' scenario had more frequent fires (Table 9.3), burned a larger area in a shorter time (Table 9.4), but had fewer extreme fire events (Table 9.3). The result was a reduction in the amount and an increase in the fragmentation of mature forest (Table 9.7). The 'wetter climate' scenario had fewer fires with a longer period required to burn the area being studied (Table 9.4). However, because wetter conditions allowed larger areas of contiguous patches of mature forest to form (Table 9.7), the risk of larger fires increased under wetter climates. These results are remarkably similar to those of Swetnam (1993) whose 2000 year fire records in giant sequoia stands showed that frequent small fires occurred during warm periods but more widespread fires occurred during cooler climate conditions.

Climate projections from global climate models do not clearly indicate if

Table 9.7. *Spatial pattern of forest cover of LP3 stands at the end of 10 sets of 1000 year simulations of EMBYR for each of three weather scenarios*

	Weather scenario		
Spatial pattern[a]	Wetter	Nominal	Drier
Total number	9560	9783	13 329
CV[b]	38.9%	33.5%	15.9%
Largest cluster (ha)	15 370	12 245	1997
CV[b]	84.3%	90.6%	52.0%
Saw (ha)	10 204	7552	490
CV[b]	115%	139.7%	79.9%

[a]'Total number' refers to the total number of clusters of LP3 sites. 'Largest cluster' is the single largest number of connected sites for each simulation. Saw, the area-weighted average cluster size of all fires, is calculated as: Saw $=\Sigma S_i^2/\Sigma S_i$, where S_i is the cluster size of burned sites. Clusters were identified as LP3 sites connected by the next-nearest neighbour rule.

[b]CV is coefficient of variation defined as the standard deviation/mean × 100.

increasing levels of atmospheric CO_2 will create wetter or drier conditions in the Yellowstone region. However, it does appear that warm conditions in Yellowstone are more likely, with the probability of summer and autumn drought increasing, making weather conditions for large fires more probable (Overpeck *et al.*, 1990; Flannigan & Van Wagner, 1991). A recent analysis of 1895–1989 weather records for Yellowstone (Balling, Meyer & Wells, 1992) revealed such a trend: summer temperatures generally have increased, spring precipitation has declined, and variations in burn area within YNP have been significantly related to these changes. However, projecting the long-term biotic response to these changes is directly dependent on the adequacy of the methods used to generate daily weather records of sufficient length and detail to simulate the long-term response of vegetation. The adequacy of the weather generator for fire modelling is especially important because 'weather, as it controls fuel moisture, is more important than differences in elevation and vegetation composition within the subalpine forest in determining the rate of spread, intensity and fuel consumption' (Fryer & Johnson, 1988). Care must also be taken to observe subtle relationships among weather variables: for instance, temporal and spatial patterns of rainfall can be more important in explaining burned area than cumulative precipitation (Flannigan & Harrington, 1988). The advantages of the methods we have used are (1) temporal correlations in weather are maintained (Fig. 9.4); (2) the instrumental record preserves important relationships among weather variables; and (3) parameters controlling the weather

generation process (Table 9.1) can be empirically estimated. The disadvantages of this method are those imposed by the limitations of the available instrumental records and the possible importance of inter-annual trends and cycles in weather (Yeakley *et al.*, 1994). No matter what method is used to produce long sequences of weather records, many uncertainties remain. For instance, climate induced changes in wind will be particularly important, but it is not currently known if winds will increase or decrease as a result of climate change (Flannigan & Van Wagner, 1991). The inclusion of methods for accurately simulating wind fields (e.g. Zack & Minnich, 1991) will be an important improvement.

Fire-dominated landscapes are never truly in an equilibrium state (Pickett & White, 1985; Picket *et al.*, 1989; Baker *et al.*, 1991; Turner *et al.*, 1993). However, the spatial patterns of stand-replacing fires showed a recurring pattern (Fig. 9.5) that is affected by climate and which, in turn, is likely to affect the process of plant reestablishment, landscape-scale changes in species abundance and diversity, and ecosystem fluxes of matter and energy (Davis & Burrows, 1993; Turner & Romme, 1994). The non-equilibrium conditions produced by the continual build-up and combustion of fuels illustrates the self-organized criticality of the Yellowstone landscape that is similar to that predicted from consideration of very simple fire models (Bak, Tang & Wisenfeld, 1988; Bak, Chen & Tang, 1990). These self-organized systems are unpredictable over short time intervals, but long-term dynamics are driven by the rate of fuel accumulation and the frequency of weather conditions that allow fires to occur. Therefore, the effect of climate change on fire regimes (Table 9.5; Turner & Romme, 1994), combined with the build-up of fuels during long periods without fire (Romme & Despain, 1989), may result in rapid loss of large areas of mature forest (Flannigan & Van Wagner, 1991). If drier weather conditions prevail, then more frequent but predictable fire events should occur after the initial loss of large areas of mature forest. The effect on species diversity of rapid shifts in the age structure and spatial arrangement of forests have not yet been fully explored (Suffling, Lihou & Morand, 1988; Romme & Turner, 1991). However, present knowledge suggests that species associated with older forest successional stages (LP_3) may be strongly influenced by the size and spatial arrangement of LP_3 patches. Our results showed that these patches are likely to become substantially smaller under drier climatic conditions, and suggest that these species may be vulnerable to reduced population sizes, genetic changes, and local extinctions.

Results of a number of studies indicated that climatically induced changes in the fire regime may lead to substantial changes in the frequency and extent of disturbance (Suffling *et al.*, 1988; Clark, 1990; Graham,

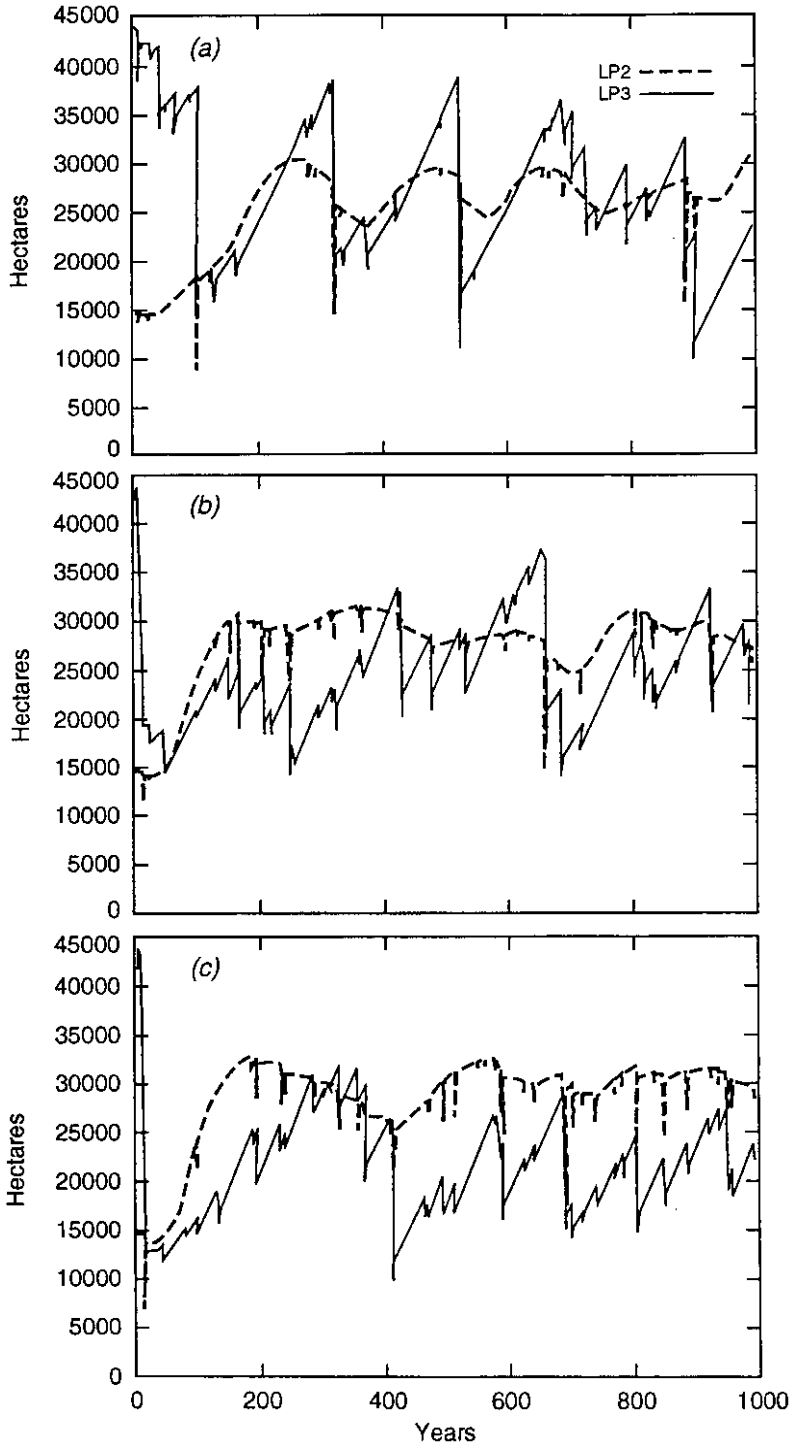

Figure 9.5 *An example 1000-year simulation of EMBYR showing the changes in LP2 and LP3 for (a) the wetter, (b) nominal, and (c) drier weather scenarios.*

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Turner & Dale, 1990; Johnson *et al.*, 1990; Romme & Turner, 1991; Balling *et al.*, 1992; Davis & Burrows, 1993). These changes may affect landscapes in two ways. First, as suggested by our long-term simulations, the characteristic mosaic of successional stages across the landscape may be altered from that which has characterized the landscape during the past few centuries. Change in the abundance and distribution of old and young forest stands has implications for the rest of the biota, including changes in herbaceous species composition, an increased probability of invasion of new species, and shifts in the distribution and abundance of fauna. Field data we collected following the 1988 fires indicate widespread establishment of seedlings of aspen (*Populus tremuloides*) across burned areas of the Yellowstone Plateau, far from the previous range of aspen (W. H. Romme *et al.*, unpublished data). Second, other ecological processes, such as nutrient losses and changes in nutrient cycling (Kauffman, Cummings & Ward, 1994; Trabaud, 1994), soil erosion and hydrological dynamics (Meyer *et al.*, 1992) may be dramatically changed as a consequence of more frequent fires. Our simulations have not accounted for these changes, but studies of other ecosystems suggest that mature plants might survive short-term climate fluctuations (Malanson *et al.*, 1992) with species that are better adapted to a changed climate becoming established following fire (Dunwiddie, 1986). The linkage of a model of post-fire forest re-establishment that incorporates the climatic requirements for germination and growth of potential dominant tree species with EMBYR would permit potential community shifts to be explored.

Many issues must be resolved before the effects of climate change and disturbance regimes can be effectively linked. Changes in weather patterns due to increased levels of atmospheric CO_2 may have a positive feedback effect on climate change (Auclair & Carter, 1993), and increases in erosion are likely to affect soil moisture and fertility levels (Meyer *et al.*, 1992). If large areas of forests continue to burn (as occurred again in 1994 in the west and northwest United States) then the effect of altered albedo will be an important factor in local and regional weather patterns (Pielke & Avisser, 1990). These changes may, in turn, alter the pattern of species that can quickly repopulate disturbed areas. Although species composition after large fires in YNP largely reflects the species present before the fires occurred (Anderson & Romme, 1991), the long-term effect of large fires on local edaphic factors suggests that succession in some areas may be dominated by the ability of plants to migrate to suitable germination sites (Prentice, 1986).

The YNP landscape has undergone major changes in climate and vegetative composition in prehistoric times. For example, during the most recent glacial period (*c.* 20 000–16 000 BP) the upper timberline in the Yellowstone

region was 600–1200 m lower than it is today (Barnosky *et al.*, 1987). Yellowstone was considerably warmer than present during the early Holocene (*c.* 10 000–14 000 BP), and Douglas fir (*Pseudotsuga menziesii*) apparently grew at higher elevations (Barnosky *et al.*, 1987). Future climate changes are uncertain, but tools such as EMBYR permit scientists and land managers to explore the implications of alternative climate scenarios and rates of climate change.

It is the goal of Focus 2 of GCTE to model the complex suite of impacts and responses of vegetation that result from climate change (Steffen *et al.*, 1992). The challenge is to develop and identify appropriate models that can handle the suite of ecosystem effects of repeated impacts (Smith, Leemans & Shugart, 1994), and link vegetation changes with animal population dynamics and socio-economic development. New methods and extensive data are rapidly being developed to address a variety of global change issues. The linkage of models and data in such a fashion that they address processes at many scales will be necessary before the implications of climate change on disturbance regimes can be understood.

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References

Albinet, G., Serby, G. & Stauffer, D. (1986). Fire propagation in a 2-D random medium. *Journal de Physique*, 47, 1–7.

Ales, R. F., Martin, A., Ortega, F. & Ales, E. E. (1992). Recent changes in landscape structure and function in a mediterranean region of SW Spain (1950–1984). *Landscape Ecology*, 7, 3–18.

Anderson, J. E. & Romme, W. H. (1991). Initial floristics of lodgepole pine (*Pinus contorta*) forests following the 1988 Yellowstone fires. *International Journal of Wildland Fire*, 1, 119–24.

Antonovski, M. Ya., Ter-Mikaelian, M. T.

& Furyaev, V. V.
model of long-ter
and its application
Siberia. *A Systems*
Boreal Forest, ed.
Leemans & G. B.
Cambridge Univer

Auclair, A. N. D. &
Forest wildfires as
CO_2 at northern l
Journal of Forest F

Bak, P., Chen, K. &
forest-fire model a
turbulence. *Physic*
297–300.

Bak, P., Tang, C. &
Self-organized crit
Review A, 38, 364

Baker, W. L. (1992).
ecology of large di
design and manage
reserves. *Landscap*

Baker, W. L. (1993).
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scapes to fire supp
66–71.

Baker, W. L., Egbert,
G. F. (1991). A sp
studying the effect
on the structure of
large disturbances.
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Balling, R. C., Meyer
S. G. (1992). Clim
stone National Par
related risk of wild
Climatic Change, 2

Barnosky, C. W., An
Bartlein, P. J. (198
western US during
tional history and
implications. In *N*
Adjacent Oceans du
ation. The Geology
vol. K-3, ed. W. F
Wright Jr, pp. 289
Colorado: Geologic
America.

Barnsley, M. F., Deva
Mandelbrot, B. B.,

& Furyaev, V. V. (1992). A spatial model of long-term forest fire dynamics and its application to forests in Western Siberia. *A Systems Analysis of the Global Boreal Forest*, ed. H. H. Shugart, R. Leemans & G. B. Bonan. Cambridge: Cambridge University Press.

Auclair, A. N. D. & Carter, T. B. (1993). Forest wildfires as a recent source of CO_2 at northern latitudes. *Canadian Journal of Forest Research*, **23**, 1528–36.

Bak, P., Chen, K. & Tang, C. (1990). A forest-fire model and some thoughts on turbulence. *Physics Letters A*, **147**, 297–300.

Bak, P., Tang, C. & Wiesenfeld, K. (1988). Self-organized criticality. *Physical Review A*, **38**, 364–74.

Baker, W. L. (1992). The landscape ecology of large disturbances in the design and management of nature reserves. *Landscape Ecology*, **7**, 181–94.

Baker, W. L. (1993). Spatially heterogeneous multi-scale response of landscapes to fire suppression. *Oikos*, **66**, 66–71.

Baker, W. L., Egbert, S. L. & Frazier, G. F. (1991). A spatial model for studying the effects of climatic change on the structure of landscapes subject to large disturbances. *Ecological Modelling*, **56**, 109–25.

Balling, R. C., Meyer, G. A. & Wells, S. G. (1992). Climate change in Yellowstone National Park: is the drought-related risk of wildfires increasing? *Climatic Change*, **22**, 35–45.

Barnosky, C. W., Anderson, P. M. & Bartlein, P. J. (1987). The Northwestern US during deglaciation: vegetational history and paleoclimatic implications. In *North America and Adjacent Oceans during the Last Glaciation. The Geology of North America*, vol. K-3, ed. W. F. Rudiman & H. E. Wright Jr, pp. 289–321. Boulder, Colorado: Geological Society of America.

Barnsley, M. F., Devaney, R. L., Mandelbrot, B. B., Peitgen, H.-O., Saupe, D. & Voss, R. F. (1988). *The Science of Fractal Images*. New York: Springer.

Bonan, G. B., Shugart, H. H. & Urban, D. L. (1990). The sensitivity of some high-latitude boreal forests to climatic parameters. *Climatic Change*, **16**, 9–29.

Clark, J. S. (1989). Ecological disturbance as a renewal process: theory and application to fire history. *Oikos*, **56**, 17–30.

Clark, J. S. (1990). Fire and climate change during the last 750 years in northwestern Minnesota. *Ecological Monographs*, **60**, 135–59.

Clarke, K. C., Olsen, G. & Brass, J. A. (1993). Refining a cellular automaton model of wildfire propagation and extinction. In Proceedings, Second International Conference on the Integration of Geographic Information Systems and Environmental Modeling, Breckenridge, CO, USA.

Davis, F. W. & Burrows, D. A. (1993). Spatial simulation of fire regime in mediterranean-climate landscapes. In *The Role of Fire in Mediterranean-type Ecosystems*, ed. M. C. Talens, W. C. Oechel & J. M. Moreno. New York: Springer.

Deeming, J. E., Burgan, R. E. & Cohen, J. D. (1978). *The National Fire-Danger Rating System*. USDA Forest Service General Technical Report INT-39.

Despain, D. G. (1987). The two climates of Yellowstone National Park. *Proceedings of the Montana Academy of Science*, **47**, 11–19.

Despain, D. G. (1990). *Yellowstone's Vegetation: The Consequences of History and Environment in a Natural Setting*. New York: Roberts Rinehart, Inc.

Dirks, R. A. & Martner, B. E. (1982). *The Climate of Yellowstone and Grand Teton National Parks*. US Department of the Interior, National Park Service Occasional Paper no. 6, pp. 1–26.

Dunwiddie, P. W. (1986). A 6000-year record of forest history on Mount Rainier, Washington. *Ecology*, **67**, 58–68.

Feder, J. (1988). *Fractals*. New York: Plenum Press.

Flannigan, M. D. & Harrington, J. B. (1988). A study of the relation of meteorology variables to monthly provincial area burned by wildfire in Canada 1953–80. *Journal of Applied Meteorology*, **27**, 441–52.

Flannigan, M. D. & Van Wagner, C. E. (1991). Climate change and wildfire in Canada. *Canadian Journal of Forest Research*, **21**, 66–72.

Fryer, G. I. & Johnson, E. A. (1988). Reconstructing fire behaviour and effects in a subalpine forest. *Journal of Applied Ecology*, **25**, 1063–72.

Graham, R. L., Turner, M. G. & Dale, V. H. (1990). How increasing atmospheric CO_2 and climate change affects forests. *BioScience*, **40**, 575–87.

Green, D. G. (1983). Shapes of simulated fires in discrete fuels. *Ecological Modelling*, **20**, 21–32.

Green, D. G., Tridgell, A. & Gill, A. M. (1990). Interactive simulation of bushfires in heterogeneous fuels. *Mathematical and Computer Modelling*, **12**(12), 57–66.

Hargrove, W. W., Gardner, R. H., Turner, M. G., Romme, W. H. & Despain, D. G. (manuscript). Simulating fire patterns in heterogeneous landscapes.

Johnson, E. A. & Van Wagner, C. E. (1985). The theory and use of two fire history models. *Canadian Journal of Forest Research*, **15**, 214–20.

Johnson, E. A. & Wowchuk, D. R. (1993). Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Canadian Journal of Forest Research*, **23** 1213–22.

Kauffman, J. B., Cummings, D. L. & Ward, D. E. (1994). Relationships of fire, biomass and nutrient dynamics along a vegetation gradient in the Brazilian cerrado. *Journal of Ecology*, **82**, 519–31.

Kessell, S. R. (1976). Gradient modeling: a new approach to fire modeling and wilderness resource management. *Environmental Management*, **1**, 39–48.

Kessell, S. R. (1979). *Gradient Modelling: Resource and Fire Management*. New York: Springer.

Levin, S. A. (1992). The problem of pattern and scale in ecology. *Ecology*, **73**, 1943–67.

Lewis, W. M. Jr. (1986). Nitrogen and phosphorus runoff losses from a nutrient-poor tropical moist forest. *Ecology*, **67**, 1275–82.

Malanson, G. P., Westman, W. E. & Yan, Y.-L. (1992). Realized versus fundamental niche functions in a model of chaparral response to climatic change. *Ecological Modelling*, **64**, 261–77.

Mandelbrot, B. B. (1983). *The Fractal Geometry of Nature*. San Francisco: W. H. Freeman.

Meyer, G. A., Wells, S. G., Balling, R. C. Jr. & Tull, A. J. T. (1992). Response of alluvial systems to fire and climate change in Yellowstone National Park. *Nature*, **357**, 147–50.

Mitas, L. & Mitasova, H. (1988). General variational approach to the interpolation problem. *Computers and Mathematics with Applications*, **16**, 983–92.

Mitasova, H. & Mitas, L. (1993). Interpolation by regularized spline with tension. I. Theory and implementation. *Mathematical Geology*, **25**, 641–55.

Moreno, J. M. & Oechel, W. C. (eds.). (1994). *The Role of Fire in Mediterranean-type Ecosystems*. New York: Springer.

Neilson, R. P. (1993). Transient ecotone response to climatic change: some conceptual and modelling approaches. *Ecological Applications*, **2**, 385–95.

Ohtsuki, T. & Keyes, T. (1986). Biased percolation: forest fires with wind. *Journal of Physics A. Mathematical and General*, **19**, L281–7.

Overpeck, J. T., Bartlein, P. J. & Webb, III, T. (1991). Potential magnitude of future vegetation change in Eastern North America: Comparisons with the past. *Science*, **254**, 692–5.

Overpeck, J. T., Rind
(1990). Climate-inc
forest disturbance
Nature, **343**, 51–3.

Pickett, S. T. A., Kol
& Collins, S. L. (1
disturbance and its
various hierarchical
129–36.

Pickett, S. T. A. & Wh
(1985). *The Ecology*
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Academic Press.

Pielke, R. A. & Avissar
ence of landscape st
regional climate. *La*
133–55.

Plotnick, R. E. & Prest
Fractal analysis of g
In *Fractals in Geogr*
L. DeCola, pp. 207–
Cliffs, NJ: Prentice-

Prentice, I. C. (1986). V
to past climatic varia
131–41.

Renkin, R. A. & Despai
Fuel moisture, forest
ning-caused fire in Y
Park. *Canadian Journ*
Research, **22**, 37–45.

Romme, W. H. (1982).
diversity in subalpine
stone National Park.
graphs, **52**, 199–221.

Romme, W. H. & Despa
Historical perspective
stone fires of 1988. *B*
695–9.

Romme, W. H. & Turne
Implications of global
for biogeographic patt
Yellowstone ecosysten
Biology, **5**, 373–86.

Rothermel, R. C. (1972).
Model for Predicting F
land Fuels. USDA Fo
Intermountain Forest
ment Station Research
INT-115, Ogden, Ut

SAS Institute (1990). *SA*

Overpeck, J. T., Rind, D. & Goldberg, R. (1990). Climate-induced changes in forest disturbance and vegetation. *Nature*, **343**, 51–3.

Pickett, S. T. A., Kolasa, J., Armesto, J. J. & Collins, S. L. (1989). The concept of disturbance and its expression at various hierarchical levels. *Oikos*, **54**, 129–36.

Pickett, S. T. A. & White, P. S. (eds.) (1985). *The Ecology of Natural Disturbance and Patch Dynamics*. New York: Academic Press.

Pielke, R. A. & Avissar, R. (1990). Influence of landscape structure on local and regional climate. *Landscape Ecology*, **4**, 133–55.

Plotnick, R. E. & Prestegaard, K. (1993). Fractal analysis of geologic time series. In *Fractals in Geography*, ed. N. Lam & L. DeCola, pp. 207–22. Englewood Cliffs, NJ: Prentice-Hall.

Prentice, I. C. (1986). Vegetation responses to past climatic variation. *Vegetatio*, **67**, 131–41.

Renkin, R. A. & Despain, D. G. (1992). Fuel moisture, forest type, and lightning-caused fire in Yellowstone Naional Park. *Canadian Journal of Forest Research*, **22**, 37–45.

Romme, W. H. (1982). Fire and landscape diversity in subalpine forests of Yellowstone National Park. *Ecological Monographs*, **52**, 199–221.

Romme, W. H. & Despain, D. G. (1989). Historical perspectives on the Yellowstone fires of 1988. *BioScience*, **39**, 695–9.

Romme, W. H. & Turner, M. G. (1991). Implications of global climate change for biogeographic patterns in the greater Yellowstone ecosystem. *Conservation Biology*, **5**, 373–86.

Rothermel, R. C. (1972). *A Mathematical Model for Predicting Fire Spread in Wildland Fuels*. USDA Forest Service, Intermountain Forest and Range Experiment Station Research Paper, INT-115, Ogden, Utah, USA.

SAS Institute (1990). *SAS User's Guide: Statistics*. Cary, NC: SAS Institute Inc.

Smith, T. M., Leemans, R. & Shugart, H. H. (1994). *The Application of Patch Models of Vegetation Dynamics to Global Change Issues*. Proceedings of a workshop, Apeldoorn, Netherlands 28 March–1 April, 1994. Amsterdam: Kluwer.

Steffen, W. L., Walker, B. H., Ingram, J. S. I. & Koch, G. W. (1992). *Global Change and Terrestrial Ecosystems: The Operational Plan*. IGBP Report 21. Stockholm: The International Geosphere-Biosphere Programme, International Council of Scientific Unions.

Suffling, R., Lihou, C. & Morand, Y. (1988). Control of landscape diversity by catastrophic disturbance: a theory and a case study of fire in a Canadian boreal forest. *Environmental Management*, **12**, 73–8.

Swetnam, T. W. (1993). Fire history and climate change in giant sequoia groves. *Science*, **262**, 885–9.

Swetnam, T. W. & Betancourt, J. L. (1990). Fire–Southern Oscillation relations in southwestern United States. *Science*, **249**, 1017–20.

Trabaud, L. (1994). The effect of fire on nutrient losses and cycling in a *Quercus coccifera* garrigue (southern France). *Oecologia*, **99**, 379–86.

Turner, M. G., Gardner, R. H., Dale, V. H. & O'Neill, R. V. (1989). Predicting the spread of disturbance across heterogeneous landscapes. *Oikos*, **55**, 121–9.

Turner, M. G. & Romme, W. H. (1994). Landscape dynamics in crown fire ecosystems. *Landscape Ecology*, **9**, 59–77.

Turner, M. G., Romme, W. H., Gardner, R. H., O'Neill, R. V. & Kratz, T. K. (1993). A revised concept of landscape equilibrium: Disturbance and stability on scaled landscapes. *Landscape Ecology*, **8**, 213–27.

Urban, D. L., O'Neill, R. V., & Shugart,

H. H. (1987). Landscape ecology. *BioScience*, **37**, 119–27.

Vasconcelos, M. J. & Guertin, D. P. (1992). FIREMAP – Simulation of fire growth with a geographic information system. *International Journal of Wildland Fire*, **2**, 87–96.

von Niessen, W. & Blumen, A. (1988). Dynamic simulation of forest fires. *Canadian Journal of Forest Research*, **18**, 805–12.

Yeakley, A. A., Moen, R. A., Breshears, D. D. & Nungesser, K. (1994). Response of North American ecosystem models to multi-annual periodicities in temperature and precipitation. *Landscape Ecology*, **9**, 249–60.

Zack, J. A. & Minnich, R. A. (1991). Integration of geographic information systems with a diagnostic wind field model for fire management. *Forest Science*, **37**, 560–73.

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