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Mechanistic modeling of landscape fire patterns

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Introduction

Fire as a landscape process is of broad interest to ecologists and land managers. Fires alter forest age-distributions (Heinselman, 1973; Van Wagner, 1978), are sensitive to climate (Balling *et al.*, 1992, Swetnam and Bettancourt, 1990; Swetnam, 1993; Timoney and Wein, 1991), can be manipulated by fire suppression (Baker, 1992; Barrett, 1994), and affect directions for land management policy (Hunter, 1993; Lesica, 1996; Huff *et al.*, 1995; Johnson *et al.*, 1995; Omi, 1996). Fire models are used for ecological research into spatial disturbance and recovery patterns (Turner *et al.*, 1989; Green, 1989; Ratz, 1996; Boychuk *et al.*, 1997), forest landscape dynamics (Keane *et al.*, 1996; Mladenoff *et al.*, 1996; Boychuk and Perera, 1997; Li *et al.*, 1997), and fire planning (Kessell, 1976; Methven and Feuenkes, 1988; Beer, 1990). For ecological modeling, fire or disturbance patterns have usually been simulated by directly applying stochastic algorithms to modify spread directions and rates (Turner *et al.*, 1989; Green, 1989; Baker *et al.*, 1991; Mladenoff *et al.*, 1996; Gardner *et al.*, 1996), or to burn a proportion of the landscape area (Ratz, 1996; Li *et al.*, 1997). Another approach is to focus on simulating the fire processes so that the cause-and-effect relationships for a given pattern can be studied. There is great interest in analyzing landscape patterns that result from fire to determine how those patterns relate to ecological theories (Romme, 1982; Baker, 1992; Suffling *et al.*, 1988). Because many landscape patterns are produced by variation in fire behavior, a mechanistic simulation of fire behavior and fire growth is useful for explaining how, why, and when such patterns can form.

Mechanistic simulation models (e.g., process models) try to represent a system as a set of fundamental processes that each describe cause and effect relationships between physical variables. Often, empirical relationships must substitute for individual processes that are not understood well enough for a more detailed description. The general mechanistic approach is useful for studying fire patterns because it allows an evaluation of: (i) the role of specific environmental factors in creating patterns of fire behavior and effects, (ii) the effects of each component process on the simulated fire pattern, and (iii) how spatial and temporal dependencies affect fire patterns.

A mechanistic simulation of fire growth must contain components that describe specifically how fuels, weather, and topography affect fire behavior. Wildland fire research over the past several decades has led to the development of numerous models for different fire behaviors (Rothermel, 1972; Albini, 1976, 1979; Van Wagner, 1977; Forestry Canada Fire Danger Group, 1992). Systems such as BEHAVE in the US (Burgan and Rothermel, 1984; Andrews, 1986) and the Canadian Fire Behavior Prediction System (Forestry Canada Fire Danger Group, 1992) have incorporated these models as tools for fire management applications. For mechanistically simulating fire as an ecological process, these models represent the crucial link between the largely independent environmental variables and the fire behavior that produces those ecological effects.

Recent advances in mathematics (Richards, 1990, 1995) as well as computing have provided a means of linking separate models of fire behavior into a practical spatial simulation of two-dimensional wildland fire growth (Finney, 1998). In the US, the simulation model *FARSITE* (Fire Area Simulator) integrates component models for surface fire, crown fire, fire acceleration, spotting, and fuel moisture (Finney, 1994, 1998). *FARSITE* was originally developed as a tool for making long-range projections of prescribed natural fires in large wilderness areas of the western US (Finney, 1994; Finney and Ryan, 1995). In has since been applied to other problems including planning for fire management activities (Van Wagtendonk, 1996) and ecological modeling of landscape fire patterns as a component of spatial forest succession models (Keane *et al.*, 1996*a*, *b*).

The mechanistic structure of *FARSITE* has allowed some insight into the causes of variable fire behavior across a landscape. Simulated fire behavior patterns can be related to their causative factors that change both spatially and temporally. As the fire front expands across a landscape, it encounters different fuels and topography under particular weather conditions that may be unique to that place and time. Spatial heterogeneity in fire behavior results because of the interdependent combinations of variables that drive fire behavior. Weather is obviously the most variable influence on fire behavior in space and time. Changing temperature and humidity affects fuel moisture throughout the day, and differentially by elevation, slope, and aspect. Winds change speed and direction and strongly influence the fire spread rate, direction, and intensity. Fuel structure and topography vary with space but are constant in time (at least during a single fire). The ignition location establishes the context for relative fire spread direction on that landscape (backing, flanking, or heading) that strongly affects fire behavior for a given set of environmental conditions. The ignition location also establishes the possible routes that fire can travel to other points on the landscape.

Variable fire behavior causes variable fire effects. This variation occurs at all spatial scales but is especially noticeable, for example, within large burns in forests affected by crown fire. Here, the wide range in potential fire behavior makes differences in fire effects more obvious. The different behavior of surface fires and crown fires causes a wide range in tree mortality and crown damage that is highly visible (Agee and Huff, 1980; Despain *et al.*, 1989; Morrison and Swanson, 1990; Turner and Romme, 1994). Causes of this variation can be difficult to interpret after the fire, sometimes prompting descriptions of these patterns as "random" or "stochastic", especially if the fire's progress was not observed. Explanations of such spatial patterns can often be found, however, once the time domain for fire travel has been established and the pre-fire landscape conditions have been mapped. Such analysis requires detailed temporal data on weather and winds as well as spatial information on fuels, vegetation, topography, and fire growth (Wade and Ward, 1973; Anderson, 1968; Simard *et al.*, 1983; Alexander, 1991; Rothermel, 1993; Butler and Reynolds, 1997). Although fire will not be completely predictable, it is likely to be understandable in mechanistic terms as a time- and space-dependent physical and ecological phenomenon.

This chapter presents a review of fire growth simulation, describes the constituent fire behavior models incorporated into *FARSITE*, and demonstrates the spatial consequences of this approach to fire behavior variation across the landscape.

Fire growth modeling

Fire growth models originated with the need to calculate fire size and perimeter length for fire-fighting operations. The earliest research efforts were directed toward determining the shape of fires burning under relatively uniform environmental conditions (Hornby, 1936; Fons, 1946). Using a constant fire shape, the relative location of the ignition point, and an estimate of the forward spread rate, changes in fire size and perimeter could be calculated as a function of time. The fire shape most commonly used has been the ellipse (Van Wagner, 1969; Alexander, 1985; Andrews, 1986). It is mathematically simple and apparently fits well to most empirical data on fire shapes (Green *et al.*, 1983). Fire shapes vary from circular without wind on flat terrain to highly elongated or eccentric ellipses produced by high winds and steep slopes (Alexander, 1985). Some evidence suggests that fires may be better described as egg-shaped, ovoid, or double ellipsed (Peet, 1967; Albini, 1976; Anderson, 1983). The practical importance of using one of these more exotic shapes over a simple ellipse may be negligible, however. The differences occur largely in the backing or rearward flanking directions that constitute a low proportion of spread and intensity compared to the forward flanks and head. Furthermore, if environmental conditions are constant, the simple ellipse can be easily used for all fire growth modeling without a computer (Van Wagner, 1969), even for producing spatially explicit intensities and spread rates (Catchpole *et al.*, 1982, 1992).

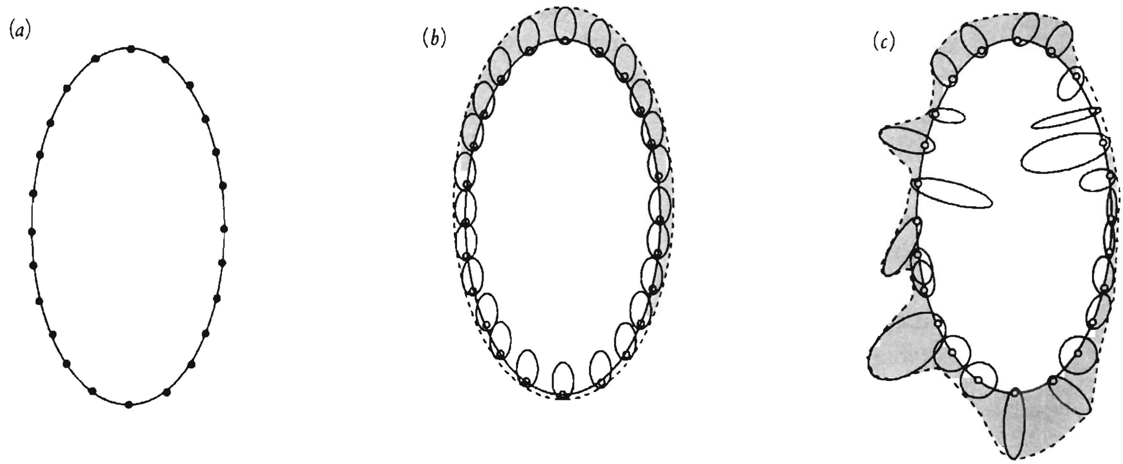
Environmental conditions do not remain constant throughout the duration of most fires. As the fire gets larger, it encounters different topography and fuel types. The longer it burns, the more likely it will be subjected to changing weather.

This environmental heterogeneity requires more complex simulation methods to produce the proper effect on spatial patterns of fire growth and behavior.

Simulation of two-dimensional fire growth since the 1970s can be classified into one of two approaches: cellular or vector. The difference lies in how space and time variables are used. Cellular models use the fixed distances between regularly spaced grid cells to solve for fire's arrival time from one cell to the next. Vector models use a specified time interval to solve for the distance fire would travel in a calculated direction. Although the differences appear as simple inverses, their ramifications are far-reaching, and have limited the ability of cellular models to simulate expected fire shapes under heterogeneous environmental conditions (French, 1992). This has compromised their utility as operational tools in fire management and their accuracy in implementing fire behavior models in two dimensions.

The cellular approach involves a discrete process of "ignitions" within the regular structure of a gridded landscape. The earliest implementation of this by Kourtz and O'Regan (1972) showed how fire could travel along a fixed number of radii between cells under homogenous conditions of fuels, weather, and topography. Model iterations update the arrival time from burning cells to each unburned cell connected to it within some radial distance. The radius determines the number of cells involved in each iteration and consequently the number of angular sides acquired by the fire (O'Regan *et al.*, 1976; Feunekes, 1991; French, 1992). This angular distortion to fire shape is a serious problem for practical uses. Distortion results when fire travel is constrained to a fixed set of pathways between cells when more direct routes, and shorter arrival times, are possible. The distortion can be minimized under homogeneous environmental conditions by increasing the radius for each iteration (O'Regan *et al.*, 1976; French, 1992; Xu and Lathrop, 1994). While increasing the demand on computing power, this also produces a legacy or holdover effect that influences fire growth long after a temporal change occurs (i.e., wind direction or speed). Cells not ignited before the change still contain arrival times that were reduced during earlier conditions; the legacy arrival times in these cells continue to influence the sequence of ignitions long after new conditions begin affecting the fire. Resetting all unburned cells to an initial state merely removes the benefit of greater precision intended originally by increasing the radius. Many workers have experimented with this and related cellular techniques (see Green, 1983; Feunekes and Methven, 1987; Vasconcelos *et al.*, 1990; Ball and Guertin, 1992). Other techniques for modeling fire growth as cellular automata include the transfer of fractional burned area (Richards, 1988; Karafyllidis and Thanailakis, 1997), probability-driven models (Von Niessen and Blumen, 1988; Beer and Enting, 1990; French, 1992; Gardner *et al.*, 1996; Ratz, 1996), or fractal models (Clarke *et al.*, 1994). Under uniform conditions, almost any technique can probably reproduce idealized fire shapes (ellipsoids). They can also be used to create spatial patterns of burned cells. Cellular models in general, however, have not been able to produce the expected responses under test conditions that intro-

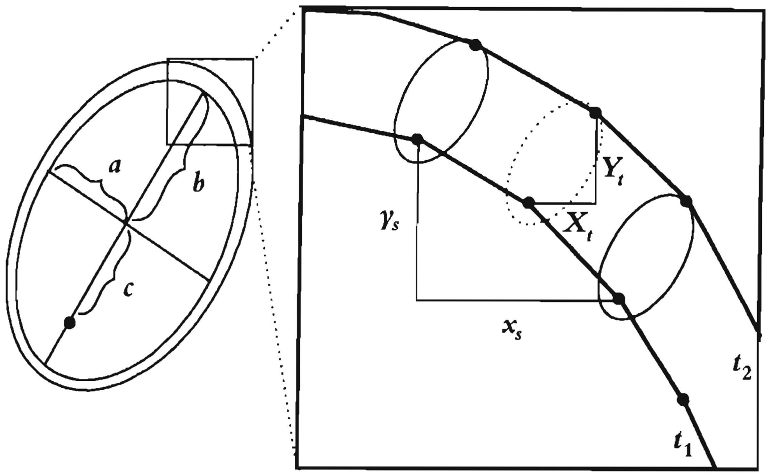
Fig. 8.1. Schematic of Huygens' principle for fire front expansion. (a) *The fire front is defined by vertices,* (b) *Uniform conditions at each vertex allow constant shapes and sizes of elliptical wavelets and produces elliptical fire growth* (gray) *over a finite time step, and* (c) *non-uniform conditions where the local fuels, weather and topography at each vertex determine different shapes, sizes, and orientation of wavelets, resulting in complex fire growth patterns.*



duce spatial and temporal heterogeneity (French, 1992). For this reason, the vector approach was chosen for use in developing the *FARSITE* simulation.

The vector or wave-type models avoid the problems encountered by cellular models in dealing with spatial and temporal heterogeneity. With vector models, both the direction and distance of fire travel are determined independently of the resolution of the spatial input data. Here, the fire front is represented as a series of vertices (Fig. 8.1*a*) that collectively define the edge of a spreading fire at a particular instant in time (Sanderlin and Sunderson, 1975; Anderson *et al.*, 1982). The environmental conditions local to each vertex are used to compute the forward fire spread rate and its direction. The fire is propagated from each vertex assuming "Huygens' principle" applies to a fire front as it was originally intended for light waves. Huygens' principle states that a wave front can be propagated using any point on its edge as an independent source of a new "wavelet" (Anderson *et al.*, 1982). The wavelets refer to elliptical fires of a size determined by a fixed time step and the fire spread rate local to each vertex. The orientation of these elliptical wavelets is determined by the maximum fire spread direction θ, calculated as the resultant vector of local wind and slope (Finney, 1998). The shape of each wavelet is a function of the midflame wind-slope vector (U, m s^{-1}, expressed as an effective windspeed) that determines the eccentricity of an ellipse (length-to-breadth ratio LB) under locally uniform conditions. Several LB equations have been developed (Alexander, 1985; Andrews, 1986; Rothermel, 1991). *FARSITE* uses one modified from Anderson (1983):

Fig. 8.2. Elliptical dimensions and parameters used by Richards (1990) equations for fire growth (Eqs. 3 and 4).



$$LB = 0.936\ e^{(0.2566U)} + 0.461\ e^{(-0.1548U)} - 0.397 \qquad (1)$$

For surface fires, the windspeed used is reduced for canopy cover (%) and tree height (*m*) (Albini and Baughman, 1979) but for crown fires the overstory wind conditions are used. The rear focus of the ellipse is assumed to be the ignition point (Alexander, 1985), such that the heading-to-backing ratio *HB* is:

$$HB = (LB + (LB^2 - 1)^{0.5})/(LB - (LB^2 - 1)^{0.5}) \qquad (2)$$

Conceptually, the fire front is expanded over each time step by aggregating the individual wavelets into an "envelope" around the previous fire front (Fig. 8.1(*b*)). Because the conditions at each vertex produce independent elliptical wavelets of potentially different shapes and sizes, this technique is flexible in representing highly heterogeneous conditions encountered by a fire in both space and time (Fig. 8.1(*c*)).

A number of mathematical methods have been developed for propagating wavelets with this technique (Richards, 1990, 1995; Knight and Coleman, 1993; Wallace, 1993; and Dorrer, 1993). *FARSITE* uses equations from Richards (1990) with modifications for sloping terrain:

$$X_t = \frac{a^2 \cos\theta\ (x \sin\theta + y_s \cos\theta) - b^2 \sin\theta\ (x_s \cos\theta - y_s \sin\theta)}{(b^2\ (x_s \cos\theta + y_s \sin\theta)^2 - a^2\ (x_s \sin\theta - y_s \cos\theta)^2)^{1/2}} + c \sin\theta \qquad (3)$$

$$Y_t = \frac{-a^2 \sin\theta\ (x_s \sin\theta + y_s \cos\theta) - b^2 \cos\theta\ (x_s \cos\theta - y_s \sin\theta)}{(b^2\ (x_s \cos\theta + y_s \sin\theta)^2 - a^2\ (x_s \sin\theta - y_s \cos\theta)^2)^{1/2}} + c \cos\theta \qquad (4)$$

where X_t and Y_t are the spread rate components of fire growth at each vertex, the a, b, and c parameters describe the elliptical dimensions (Fig. 8.2), x_s and y_s are the directional components that determine the orientation angle of the vertex on the fire front ($x_{i-1}-x_{i+1}$, $y_{i-1}-y_{i+1}$), and θ is the direction of maximum fire spread (resultant wind slope vector). It is critical to recognize that on sloping topography, all inputs and outputs from these equations relate to the local surface plane not to the horizontal plane. Storage and display of fire growth, however, must be on the horizontal plane. This requires all input parameters to be transformed first to terrain-following coordinates for use in Eqns. (3) and (4) and the outputs then transformed back to horizontal coordinates (see Finney, 1998).

FARSITE description

FARSITE (Fire Area Simulator) is a stand-alone fire growth model that incorporates fire behavior models for surface fire, crown fire, fire acceleration, spotting, and fuel moisture using the vector modeling technique of Huygens' principle. The data inputs to *FARSITE* consist of eight raster GIS themes (Table 8.1) that describe the terrain, surface fuels, and crown fuels (Fig. 8.3: see color section), and two data streams for wind and weather (Table 8.2 and Table 8.3). Other inputs are fuel-specific initial fuel moistures and spread rate adjustment factors used for calibrating the model's output with observed fire progression.

The weather stream contains precipitation, temperature, and humidity patterns on a daily basis (Table 8.2). The temperature and humidity values are maxima and minima that allow cosine interpolation of their values for any time of the day. The wind stream (Table 8.3) contains event-driven temporal changes in horizontal wind speed and direction at the US standard reference height (6.1m or 20 ft). It also specifies cloud cover (percentages) that decrease solar radiation reaching the top of the vegetation.

Fire behavior is assumed to follow a typical sequence of activity. First, the behavior or a surface fire is calculated (Rothermel, 1972). If the environmental conditions permit, this fire may transition to some form of crown fire (Van Wagner, 1977, 1993) that can initiate spotting (Albini, 1979). When environmental conditions change to produce faster spread rates at each time step, the fire is accelerated toward the new spread rate (Forest Canada Fire Danger Group, 1992) rather than jumping immediately to the faster rate.

Fuel moisture

Dead and live fuel moistures greatly affect fire behavior. Moisture content of fine dead fuels varies throughout the day according to temperature, humidity, solar irradiance, wind speed, and fuel size. The user provides an initial suite of fuel moisture conditions by surface fuel model for dead and live fuels. *FARSITE* then calculates moisture content (percentage of dry weight) of dead woody fuels in the

[1] *FARSITE* is available free of charge (www.montana.com/sem) and requires an IBM compatible computer (Pentium-class CPU or better) with Microsoft Windows 95 (16MB+RAM) or Windows NT (32MB).

Table 8.1. *Raster inputs to FARSITE and their usage in the simulation*

Raster theme	Units	Usage
Elevation	m, ft	Adiabatic adjustment of temperature and humidity from the reference elevation input with the weather stream
Slope	%, deg	Used for computing direct effects on fire spread, and along with Aspect, for determining the angle of incident solar radiation (along with latitude, date, and time of day) and transforming spread rates and directions from the surface to horizontal coordinates
Aspect	deg Az	(see Slope)
Fuel model		Provides the physical description of the surface fuel complex that is used to determine surface fire behavior (see Anderson, 1982). Included here are loadings (weight) by size class and dead or live categories, ratios of surface area to volume, and bulk depth
Canopy cover	%	Used to determine an average shading of the surface fuels (Rothermel *et al.*, 1986) that affects fuel moisture calculations. It also helps determine the wind reduction factor that decreases windspeed from the reference velocity of the input stream (6.1 m above the vegetation) to a level that affects the surface fire (Albini and Baughman, 1979)
Crown height	m, ft	Affects the relative positioning of a logarithmic wind profile that is extended above the terrain. Along with canopy cover, this influences the wind reduction factor (Albini and Baughman, 1979), the starting position of embers lofted by torching trees, and the trajectory of embers descending through the wind profile (Albini, 1979)
Crown base Height	m, ft	Used along with the surface fire intensity and foliar moisture content to determine the threshold for transition to crown fire (Van Wagner, 1977; Alexander, 1988)
Crown bulk density	kg m^{-3} lb ft^{-3}	Used to determine the threshold for achieving active crown fire (Van Wagner, 1977, 1993)

1 h and 10 h timelag categories using the models from BEHAVE (Rothermel *et al.*, 1986; Hartford and Rothermel, 1991). The 100-h timelag fuel moisture is computed using the National Fire Danger Rating System (Bradshaw *et al.*, 1984). Moisture content of live fuels (shrubs, green grass, etc.) are input by the user but are not modified by the simulation. The environmental inputs required by the dead fuel moisture models are provided by the weather stream, wind stream, and

Table 8.2. *Sample of weather stream format*

Month	Day	Precip. (mm)	Hour (am)	Hour (pm)	Temp. (°C min)	Temp. (°C max)	Humid. (% max)	Humid. (% min)	Elevation (m)
7	31	0	0500	1500	7	29	65	25	915
8	1	0	0500	1500	7	29	65	25	915
8	2	0	0500	1500	13	28	55	18	915
8	3	2	0500	1500	13	25	55	18	915
8	4	0	0500	1500	7	26	66	25	915
8	5	0	0500	1500	14	31	56	25	915
8	6	0	0500	1500	16	32	45	24	915
8	7	0	0500	1500	16	32	45	24	915

The weather stream specifies precipitation, and maximum and minimum temperature, and humidity for each day at a particular reference elevation.

the spatial GIS data on terrain and forest cover. Solar irradiance influences the rate of fuel drying and is computed for a given pixel from the latitude, time of day, cloud cover, slope, aspect, and canopy structure (Rothermel *et al.*, 1986). The air temperature, relative humidity, and windspeed are then used to compute moisture contents on an hourly basis for fuels in the 1 h and 10 h categories and daily for the 100-h fuels. For each fire behavior calculation, the current fuel moisture contents at a given time are computed from their initial conditions. This technique produces moisture data for only those locations that are involved in a calculation. It has proven faster than progressively calculating moisture contents for all cells across the landscape at each time step, regardless of their involvement in subsequent computations.

Surface fire

A *surface fire* burns in the grass, shrubs, or downed woody material lying in contact with the ground surface. *FARSITE* uses the Rothermel (1972) fire spread equation to compute the steady-state spread rate R (m min^{-1}) and fireline intensity I_b (kW m^{-1}) of a surface fire. Surface fuels are described by their loading (dry weight per unit area) by size class and live/dead category, the surface-area-to-volume ratios for each size class, and the bulk depth of the fuel complex. These parameters are combined to form a fuel model (Anderson, 1982). To calculate fire behavior for a given fuel model, the Rothermel (1972) equation requires data on the environmental conditions, including moisture content by size class for live and dead fuels (% dry weight), midflame wind speed, and topographic slope.

Crown fire

Crown fire describes fire burning in the foliage and fine branches of trees. *FARSITE* uses the crown fire criteria developed by Van Wagner (1977, 1993) to determine

Table 8.3. *Sample portion of the wind stream format*

Month	Day	Hour	Wind speed (6.1m, km/h)	Wind dir (Azimuth)	Cloud cover (%)
7	31	2000	20	234	0
7	31	2200	8	90	0
8	1	0000	6	90	0
8	1	0200	17	258	0
8	1	0400	18	271	0
8	1	0610	15	267	0
8	1	0800	13	260	0
8	1	1000	16	275	0
8	1	1200	14	230	0
8	1	1400	12	181	0
8	1	1600	9	182	0
8	1	1800	3	164	0
8	1	2000	2	174	0
8	1	2200	6	176	0
8	2	0000	5	189	0
8	2	0200	11	181	0
8	2	0400	5	176	0
8	2	0600	6	250	0
8	2	0800	9	250	0
8	2	1000	11	260	0
8	2	1200	31	270	0
8	2	1400	39	270	0
8	2	1600	42	270	0
8	2	1800	40	260	0
8	2	2000	29	200	0
8	2	2200	13	211	0
8	3	0000	5	190	0
8	3	0200	2	195	0
8	3	0400	5	200	0
8	3	0600	6	196	0
8	3	0800	9	200	0
8	3	1000	5	234	0
8	3	1200	6	240	0
8	3	1400	7	220	0

The wind stream contains wind speed and direction changes to the nearest minute along with cloud cover.

if a surface fire makes the transition to some form of crown fire and then if that crown fire achieves a faster spread rate typical of "active" crown fires. Van Wagner (1977) suggested that the crown is ignited if the surface fire intensity I_b exceeded a threshold value I_o determined by the availability of crown fuels (e.g., proximity to the surface fire) and the ignition energy required to ignite them:

$$I_o = (0.010\ CBH\ (460 + 25.9M))^{3/2} \quad (5)$$

where CBH is the crown base height (m), M is moisture content (%). If I_b meets or exceeds I_o, then at least some of the crown fuels become ignited. These burning crown fuels increase the intensity but not the spread rate unless a crown fire threshold (RAC m min^{-1}) is surpassed that determines the critical mass flow rate through the crown fuels:

$$RAC = 3.0/CBD \quad (6)$$

where CBD is the crown bulk density, a stand-level crown fuel descriptor. Higher CBD facilates active crown fires. Beyond this threshold, the fire is an active crown fire and burns with a faster heading crown fire spread rate. The crown fire spread rate was based on Rothermel's (1991) correlation of 3.34 times the surface fire spread rate for a timber understory fuel model (US fire behavior fuel model 10, with wind reduction factor of 0.4). The crown fire spread rate at each vertex depends on its orientation on the fire front relative to the direction of maximum spread using the elliptical dimensions for a crown fire (Eq. 1).

Fire acceleration

Fire acceleration defines the rate of increase in fire spread rate for a given ignition source (e.g., point fire or line fire) assuming environmental conditions remain constant. Point source fires may take 20 minutes or more to accelerate to an equilibrium spread rate (McAlpine and Wakimoto, 1991) whereas than line-source fires accelerate faster (Johansen, 1987). *FARSITE* uses the logarithmic model developed for the CFBPS (Forestry Canada Fire Danger Group, 1992) to calculate the spread rate R (m min^{-1}) after time t (min) for both line and point source fires:

$$R = R_e(1 - e^{-at}) \quad (7)$$

where the a is the acceleration constant and R_e (m min^{-1}) is the new equilibrium spread rate. Point and line source fires are differentiated by the length of the fire perimeter set by the user. At the start of a new time step, the fire spread rate is accelerated from its previous value toward the new equilibrium spread rate calculated from current conditions. The acceleration constants can be set by fuel type to allow, for example, fire to accelerate faster in grass fuels than in timber or heavy slash fuels. Over relatively short time domains, fire acceleration is important to determining the fire spread rate and intensity where environmental conditions change rapidly.

Spotting

Spotting describes the lofting and transport of burning embers downwind of the main fire front where they may serve as new ignition sources. Once some form of crown fire is initiated ember transport from torching trees is simulated using the model of Albini (1979). This model was originally designed only for individual trees and groups of trees and will thus underestimate spotting distances for active crown fires. Spotting is modeled in terms of: (i) flame characteristics of the torching tree or group of trees, (ii) lofting of embers of different size classes, (iii) downwind travel of embers over the landscape, and (iv) ignition of new fires.

Flame structure and duration are determined for a given tree species and tree diameter based on their relationship to crown weight (Albini, 1979). The number of trees torching in a group is modeled as increasing with canopy cover and crown fraction burned. Little is known on ember production or size class distributions. Thus, a fixed number of embers between 0.1 cm and 2.5 cm are lofted from the tree top to their maximum heights determined by the flames from the torching tree.

The trajectory of each ember is then iterated during its descent and lateral movement across uneven terrain (Albini, 1979). The vertical windspeed profile is modeled as logarithmic, based on the reference velocity input at 6.1 m above the vegetation (Albini and Baughman, 1979). During its flight the combustion time of the ember is computed; small embers may burnout before they contact the ground. The objective of the spotting model is to use embers of different sizes to find areas where embers can ignite new fires. If a burning ember contacts fuel, it may start a new fire if it hasn't fallen within an existing fire front. Ignition itself is modeled stochastically because many important factors cannot be modeled at the relatively coarse scale of the spatial inputs, including the spatial distributions of receptive fuel (e.g., rotten wood) and fine-scale variability of the fuel bed.

Spatial and temporal simulation control

Three parameters are used to control the space and time resolution of the calculations made during a simulation: *time step*, *distance resolution*, and *perimeter resolution*. All three parameters are crucial to controlling the amount of data used in the simulation and thus, how much detail is present. The time step is the maximum amount of simulation time allowed between fire behavior calculations. Fuel moisture and winds are constantly changing over time, and the time step controls for the maximum time interval between accesses to temporal data used for computing fire behavior. The distance resolution is the farthest distance the fire is allowed to spread between successive fire behavior calculations. It ensures that the simulation uses a minimum density of spatial data in calculating fire behavior as it progresses across a landscape. The perimeter resolution is the maximum distance between perimeter vertices on the fire front. As convex portions of the fire front expand, the vertices become separated. The separation distances are checked at least once in a time step and new points are inserted at mid-span if the perimeter resolution is exceeded.

Fire growth is either limited by the time step or the distance resolution as set by the user. Time is limiting if the fire spread rate is slow enough that the spread distance from any vertex is less than the distance resolution at the end of the time step. The time step then forces additional data to be used for fire behavior calculation. Distance becomes limiting when fire spread is greater than the specified distance resolution within a given time step. The original time step is then partitioned into sub time steps, determined as the minimum time required for the fire to spread the length of the distance resolution. In this way, multiple steps are used to achieve fire growth for the original time step. At each sub time step, the perimeter resolution is checked and crossovers along the fire front are processed. Obviously, larger time steps, distance resolutions, and perimeter resolutions permit coarser approximations of simulated fire growth because data used in computations are more sparse.

Crossovers and mergers

The perimeter expansion technique used for fire growth modeling is not inherently capable of differentiating areas already burned from those not yet burned. As a result, fire fronts will cross over themselves along locally concave regions and, if multiple fires exist, "reburn" areas already burned by other fires. Specialized computational methods are required to eliminate the influence of crossing segments, to merge fire fronts that overlap, and to identify and preserve enclaves that are produced by these crosses and mergers. Enclaves are essentially new fire fronts that burn inward, eventually extinguishing themselves.

Richards and Bryce (1995) neutralize vertices that fall within already burned areas, leaving them in place but allowing no further activity at those points. Richards (1990), Knight and Coleman (1993), and Wallace (1993) describe techniques that eliminate the overlapping portions from the list of vertices that comprise a given fire. The algorithm developed for *FARSITE* is similar to the latter type, where vertices are removed when they fall inside existing fire polygons. The algorithm processes a given fire perimeter by first comparing every segment for intersection with every other segment, producing an ordered list of crossing segments. The outer edge of the main fire perimeter is then extracted by tracing the outside edge between intersecting segments. Subsequent processing uses the list of intersections to identify and preserve enclaves that are sometimes formed by the crossing. These enclaves must be preserved as separate fire fronts.

With more than one fire being simulated (for example, with spotting), the numbers of comparisons becomes factorial, requiring a search for overlap between each fire and every other fire. If bounding rectangles for two fires overlap, a more detailed procedure compares each segment on one fire with all segments on the other fire. The merger then identifies the main fire front as well as enclaves that have formed by the merger. Merging can occur between two outward burning fire fronts, and between an outward and an inward fire front. The latter situation occurs when spot fires ignite within an enclave.

Model performance

The *FARSITE* model was written in C++ and has been compiled to run under 32-bit Windows™ and several UNIX operating systems. The most common form of the model runs under Windows™ 95 or NT and has a graphical Windows interface. On a given computer, performance varies by the number of fires being simulated, the size of the fires (i.e., number of vertices), the time and space resolutions specified for the simulation, and the kinds of outputs selected. In general, the simulations are completed quickly, with those shown in Figs. 8.5 and 8.6 taking no more than about 5 minutes on an Intel Pentium Pro 200. The vector technique is computationally efficient because it requires calculations only for those vertices involved in the active fire front.

Model applications

The application of Huygens' principle to vector modeling of fire growth has been demonstrated for surface fires. Sanderlin and Sunderson (1975) found reasonable agreement between their predicted and observed growth of a Southern California chaparral fire. Anderson *et al.* (1982) and French (1992) used observed growth rates to parameterize their elliptical wavelets and found that grass fires with varying wind were well modeled with the technique. Finney (1994) reported several initial comparisons of *FARSITE* output with prescribed natural fires in forest and brush fuels in the Southern Sierra Nevada mountains. Coleman and Sullivan (1996) also described a comparison of predicted and observed spread patterns. One of the most interesting results of the validations is the apparently consistent overprediction of fire spread rates for surface fires (Finney, 1994; Finney and Ryan, 1995). Potential sources of overprediction include varying topographic sheltering of surface fuels to winds and inaccurate fuel maps. The causes of overprediction have not yet been determined conclusively, but an explanation may involve scale differences that are independent of any data or model inadequacy.

It is recognized that the scale of input data to the simulation is coarse compared to the frequency of variation in real environmental conditions affecting a fire. Winds are input at intervals of an hour or half hour (at best) and fuels and topography are typically resolved to a spatial resolution of about 30 meters. In nature, winds are more variable (on the order of seconds to minutes) as are fuels and topography (order of 10^{-1} m to 10^{1} m). The disparity in scales means the models tend to calculate equilibrium conditions from the homogenized input data compared to variable fire spread rates that are really accelerating and decelerating over time and space (Albini, 1982*a*,*b*). The application of the modeled spread rate to large space and time scales of the simulation may not equal the cumulative spread produced by a variable environment because of lag times and non-linear spread rate responses to changing conditions. This does not imply that the fire spread rate and behavior calculations for a given suite of conditions are necessarily wrong (they may be exactly right), only that the calculated fire spread rate cannot be applied over large distances for long times without some adjustment.

Simulations of fire behavior under simple conditions

Simplified conditions are useful for understanding how individual environmental factors affect fire growth and behavior that, in turn, produces fire effects. The shapes of fires simulated under constant environmental conditions are perfect ellipses, as demanded by the wavelets used with Huygens' principle (Fig. 8.4: see color section). Larger and more eccentric fires are produced by higher winds in a given time period. Fireline intensity (kW m^{-1}) displays a radial pattern, illustrating the potential for variable spatial effects due entirely to relative fire spread direction. The heading portion of each fire, burning with the wind and slope, has the highest intensity. Intensity diminishes as the relative spread direction rotates toward the backing side of the fire. Faster winds or stronger slopes increase the absolute and relative variability of fireline intensity within a given fire (Catchpole *et al.*, 1992).

When slope changes, but fuels and winds are uniform, both the spread direction and intensity change. In this example, fire spreading in grass fuels across a flat plane encounters a conical hill (Fig. 8.5: see color section). Fire progression rate as seen from above (Fig. 8.5*a*) often appears different when viewed obliquely because of the projection to horizontal (Fig. 8.5*b*). This simulation occurs over a period of about 5 hours. During this time, fireline intensity varies with changing fuel moisture and the different topography of the cone. The changing aspect around the cone produces variation in the vectoring of slope and wind that changes fire spread direction and rate; this adds obvious complexity to the patterns of fireline intensity.

These simulations illustrate that fire growth and intensity patterns can exhibit a high degree of variability, even under simple environmental conditions. It is easily demonstrated that more heterogeneity in the environment, either spatially or temporally or both, will result in more complex fire behavior patterns on a landscape. Realistic combinations of time- and space-dependent environmental conditions can produce widely heterogeneous patterns of fire behavior.

Simulations of fire behavior and effects on real landscapes

FARSITE is used as a modeling component of landscape-level ecological simulations (Keane *et al.*, 1996*a*,*b*). These simulations are designed to model forest dynamics over hundreds of years as spatially explicit processes across topographically and ecologically variable landscapes. The weather inputs needed to drive forest growth and decomposition are at monthly time scales. When a fire occurs, however, its behavior is determined temporally by weather and wind changes at a sub-hourly time scale. The varying weather and spatially varying fuels and topography result in very heterogeneous fire behavior. The fire behavior, in turn, is used to drive fire effects, such as tree mortality and fuel consumption, that consequently promulgate changes in forest dynamics in succeeding years.

The linkage between the environmental inputs, fire growth, fire behavior, and fire effects, is shown for an example fire simulation (Fig. 8.6: see color section) using data developed for the Selway Bitterroot Wilderness of Idaho and Montana (Keane *et al.*, 1998). All of the fuel layers shown in Fig. 8.3 were developed by a combination of satellite imagery, ecological modeling, and ground-based inventories. For this simulation, a point-source ignition, such as lightning, was started under a typical August weather scenario (August 1st). The following day consisted of high afternoon winds followed by several days of less extreme conditions (Table 8.1(*a*), (*b*)).

Because the *FARSITE* simulation was constructed mechanistically, the effects of these input factors can be directly interpreted at any place or time in terms of the resulting fire behavior and effects. In this example simulation, the moderate winds caused the fire initially to spread at a modest rate through an open ridgetop meadow (Fig. 8.6*a*). Higher winds during the following afternoon caused some torching, isolated patches of active crown fire, and consequent spotting (Fig. 8.6*a*). Areas of faster fire spread and higher intensity (longer flames) generally occurred in the heading directions (upslope and downwind) and during the afternoons when fuel moistures were lower and winds were stronger (Fig. 8.6*b*). Slower spread and lower intensities occurred in the flanking and backing directions, during the night and mornings, in patches of more compact surface fuel types, and where heavy forest cover and tall overstory trees diminished understory windspeeds.

This pattern of variable fire behavior translated to additional heterogeneity in terms of fire effects. The patchwork of species assemblages and tree size- or age-classes across the landscape differentially affects tree mortality for given fireline intensity. The most obvious effect of fire is the level of crown damage induced by convection of hot air and gasses from the fire upward into the tree crowns (Van Wagner, 1973). A map of crown scorch fraction (% of stand height) combines the scorch height from fireline intensity with the forest stand height to suggest a general level of fire effect that would be visible across the landscape (Fig. 8.6*c*). Furthermore, the percentage of crown kill is a strong predictor of tree mortality and can be calculated with the fireline intensity and crown dimensions of individual trees. Along with bark thickness and tree size, the probability of tree mortality can be calculated (Peterson and Ryan, 1986; Ryan and Reinhardt, 1988). Of course, tree mortality within a given pixel must be determined by the simulation for each tree species by size-class within the stand. This is too complex, however, to easily display on a single map.

Implications and conclusions

By simulating fire growth and behavior as a mechanistic process, it can be seen how complex spatial patterns of fire and effects can form because of the spatial and temporal linkage between elements of the fire environment. Although often described as random, many fire patterns are produced by processes that are reasonably well described by fire phenomenology in general, and the available fire behavior models in particular (e.g., Andrews, 1986; Forestry Canada Fire Danger Group, 1992). Fire patterns are not determined solely by spatial properties of the landscape (e.g., topography, fuels, or vegetation structure). Tremendous variation is caused by the weather and winds at the time the fire burns each part of that landscape; weather changes that follow diurnal and synoptic patterns that can be modeled, although not necessarily predicted into the future. The relative fire spread direction (e.g., heading, flanking, backing) can also play an important role in determining the fire behavior and consequent effects. The area burned by flanking and backing spread is usually small compared to the heading direction on fast moving and short-duration fires. Areas burned by the different relative spread directions are more evenly distributed on slow-moving fires or those that last for many weeks or months.

Mechanistic simulations are particularly useful for investigating or reconstructing the causes of patterns within a single fire. Visible crown damage patterns such as tree-crown streets (Haines, 1982) or stringers (Foster, 1983) can be simulated in *FARSITE* by varying wind direction and speed (Finney, 1998). The winds change fire spread rates around the fire front relative to the thresholds for crown fire activity (Eqns. 5 and 6). Other patterns, such as the formation of unburned islands within large burns (Eberhart and Woodard, 1987; Foster, 1983; Van Wagner, 1983) may also be investigated by simulation. The example fire in Fig. 8.6 showed unburned islands that began as large gaps between the main fire front and spot fires. The slow closure of these islands was afforded by locally unfavorable topography, fuels, or barriers that kept the heading portion of the main fire from burning rapidly into the gaps. The fire was slowly backing into these areas against wind or slope, and would have eventually burned the entire enclave if this simulation had continued. To have remain unburned, the fire surrounding the enclaves would need to have: (i) experienced a change in weather conditions (becoming more probable with longer burn times) and/or (ii) be slowed to a smolder by the absence of wind or slope assistance. Studies suggest that flaming spread may not be sustained under certain combinations of moisture content and fuel structure (packing ratio, surface-area-to-volume ratio) unless the fire is spreading with the wind (Beer, 1995) or up slope (Martin and Sapsis, 1987). These limits of sustainability would probably preclude flaming spread in backing and flanking spread directions but are not yet modeled for fires in general or for that matter, in *FARSITE* which uses only the Rothermel (1972) equation for surface fires (wind and slope modify spread rate that occurs under calm and flat conditions). Fire spread by smoldering is so slow (about 3 cm h^{-1}; Frandsen, 1991) that changing weather would likely extinguish the fire before larger enclaves could be entirely burned. Shifting wind directions could, however, rekindle smoldering sections and resume the burning of enclaves with heading fire spread.

Mechanistic simulations can be used to explore the repeatability of fire effects on different sites within a landscape or the equability of fire behavior and effects due to topography or productivity. For example, more variable fire effects might be expected where topographic position and productivity do not limit the fuel production, fire behavior, or direction from which fires can arrive from adjacent lands. Some topographic positions, like ridges or steep slopes, may be predisposed to the extreme fire behavior and effects (Geldenhuys, 1994; Kushla and Ripple, 1997; Minnich, 1988; Minnich and Chou, 1997) given wind patterns and limited productivity. By integrating fire models with forest simulators (e.g., Keane *et al.*, 1996*a*) the role of site productivity in determining repeated fire patterns and fire regimes on large landscapes can be further explored.

The future of mechanistic fire simulation will likely involve better component models for all processes such as fuel moisture, surface fire, crown fire, and three-dimensional winds. Coupling of fire and atmospheric models (e.g., Clark *et al.*, 1996; Linn and Harlow, 1998) offers a way to explore fire – environment interactions that are not possible with the two-dimensional techniques as used in *FARSITE*. Fire whorls, mass fires, plume-dominated fires are some of the many fire behaviors that are not well understood. Once modeled, these behaviors might also help to explain some fire patterns that remain mysterious today.

Notwithstanding, mechanistic models are known for their rapacious data requirements. As models are improved by adding more detailed component processes, the data required to run the models increases as well. *FARSITE* was developed for practical use by fire managers in simulating active fires and planning for potential fires. The remote sensing and computer technology necessary for generating and managing data for large landscapes are reasonable and attainable today but were not practical even a decade ago. Recognizing data limitations is the first step toward new efforts to gather data to run the models; making the data available then stimulates the development of new models. The result of this process is a steadily advancing ability to understand and predict phenomena that would not be possible if we remained sated by current technology and information.

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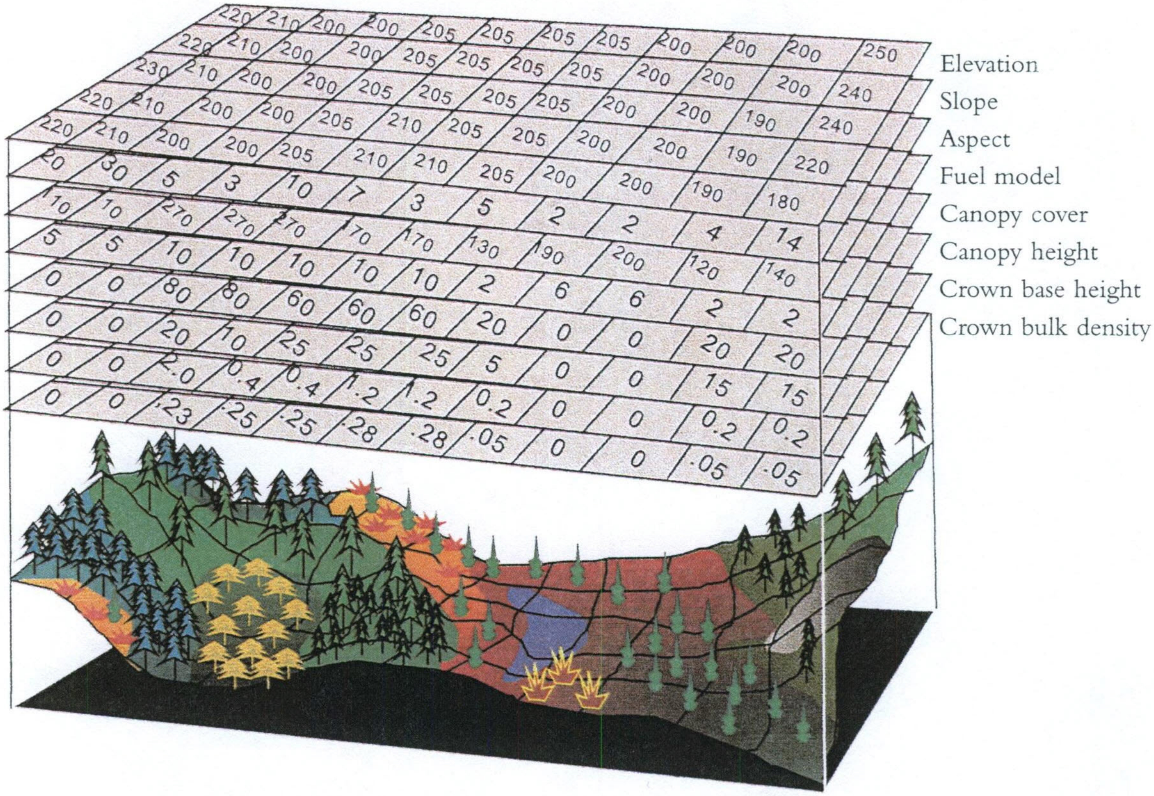
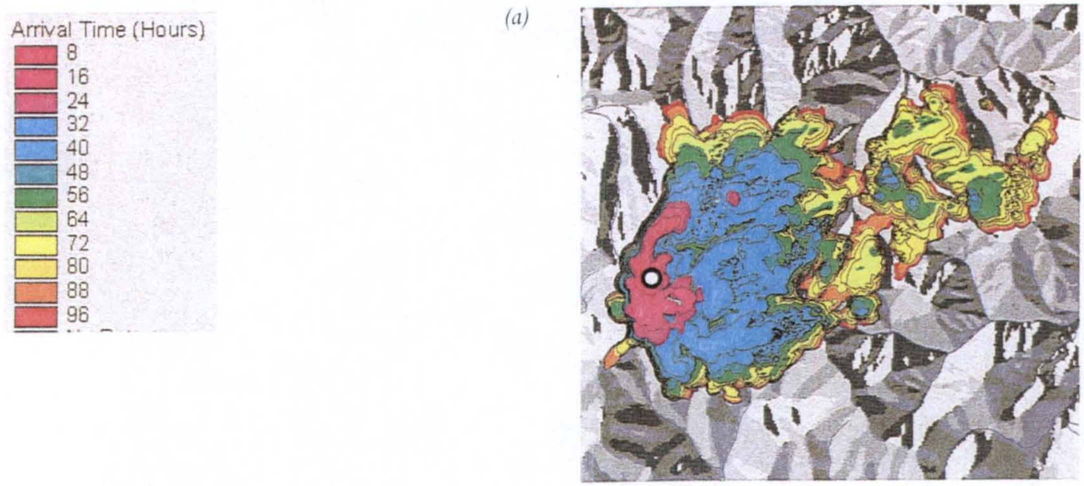
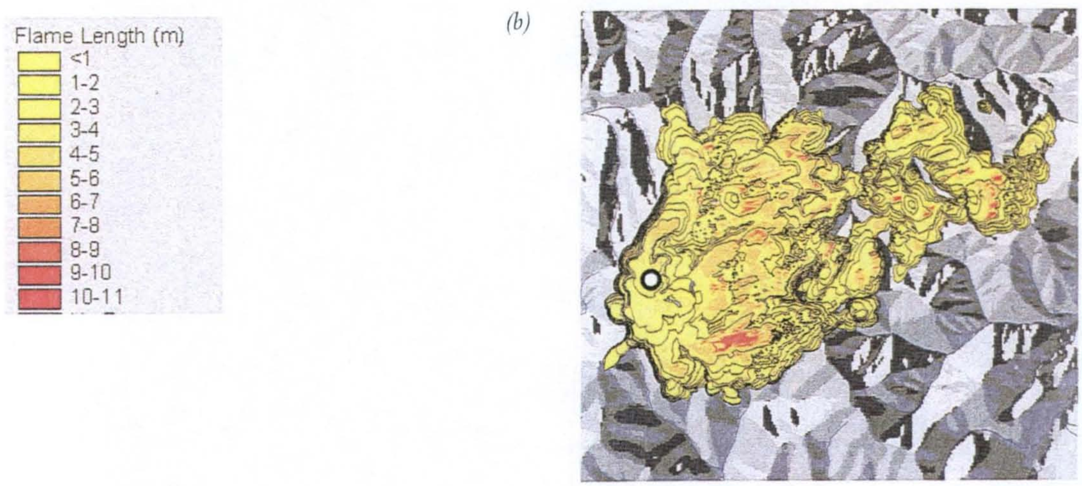


Fig. 8.3. Raster GIS themes used for spatial input data to FARSITE.





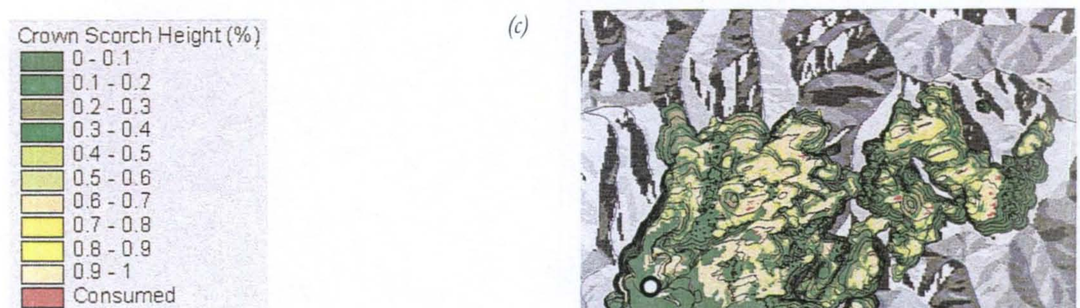


Fig. 8.6. Four-day fire simulation in the Selway-Bitterroot Wilderness, Idaho. (a) *Fire progression,* (b) *flame length, and* (c) *percentage crown scorch. Higher intensities and crown scorch occurred in the afternoons, during passage of a cold front, and with uphill fire runs. Lower intensities occurred at night and from backing and flanking spread.*