Chapter 9: Landscape Fire Simulation and Fuel Treatment Optimization

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Abstract

Fuel treatment effects on the growth and behavior of large wildland fires depend on the spatial arrangements of individual treatment units. Evidence of this is found in burn patterns of wildland fires. During planning stages, fire simulation is most often used to anticipate effects of fuel treatment units. Theoretical modeling shows that random patterns are inefficient in changing large-fire growth rates compared to strategic designs. For complex landscapes, computational methods are being developed to identify optimal placement of fuel treatment units that collectively disrupt fire growth similarly to the strategic patterns. By combining these algorithms with forest simulations over long periods (say 50 years), the long-term effects of various treatment strategies can be compared.

Keywords: Fire simulation, fire modeling, fuel treatments.

Introduction

Large wildland fires are archetypal landscape phenomena. Landscapes are large land areas that encompass properties that vary at scales finer than the landscape as a whole (e.g., vegetation and topography). Wildland fires often encompass spatial and temporal domains that are large compared to the landscape properties critical to their behavior (fuels, weather, and topography). As fires advance across the landscape, they encounter fine-scale variability in fuels, topography, and weather that produces complex patterns of behavior and effects (see review by Finney 1999). Simulation models can accommodate such high-frequency variation in the fire environment and thereby help us understand movement and behavior of individual fires in complex conditions (Finney 1998). Simulation models are the main tools used to anticipate the effects management of vegetation and forests has on large fire growth and behavior. Fire simulations, however, must be coupled with vegetation or forest growth simulations if long-term consequences of wildland fires and management are to be addressed (Johnson et al. 1998, Keane et al. 1996, Sessions et al. 1999). This paper will first summarize fire modeling and fuel management techniques and then discuss methods for incorporating fire growth simulations and fuel management optimization into landscape forest simulations.

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Fire Simulations and Their Requirements

Wildland fire behavior has long been known to be a function of fuels, weather, and topography (Brown and Davis 1973). Fire behavior programs in use today, e.g., the fire behavior (BEHAVE) prediction and fuel modeling system (Andrews 1986), accept inputs for these factors and predict fire behavior characteristics. Fire behavior refers to the gross characteristics of fire, e.g., fireline intensity (kW/m, or power per unit length of the flaming front), spread rate (m/min^{-1}), spotting distance, fuel consumption (kg/m), and whether the fire is a surface or crown fire. These quantities are important to managing wildland fire fighting operations, to estimating ecological effects of fires, and to designing fuel treatments that change fire behavior. The BEHAVE program applies fire behavior models to a given point on the ground or in one dimension.

The Fire Area Simulator (FARSITE) program extends these models to calculate fire behavior in two dimensions or across an area of land. As a result, data on fuels, weather, and topography must be provided spatially, with weather and fuel moisture allowed to change with time. Fire behavior across two spatial dimensions varies by the relative direction of fire spread, e.g., heading with the wind or slope, or flanking normal or backing counter to the heading direction. Relative fire spread direction is important in determining the variability of behaviors and effects that occur as large wildland fires move across landscapes (Catchpole et al. 1982). Many techniques have been applied to the problem of two-dimensional fire growth (see reviews by Finney 1998, 1999). Techniques that represent the growth and behavior of the fire edge as a vector or wave front (Finney 2002a, Richards 1990, Sanderlin and Van Gelder 1977) produce less distortion of fire shape and response to temporally varying conditions than techniques that model fire growth from cell-to-cell on a gridded landscape. They are thus preferable for performing fire simulations for supporting fire management operations because they can realistically reflect changes in fire behavior resulting from suppression, fuel, and weather changes.

Fuel Management Activities and Changes to Fire Effects and Behavior at the Stand Level

Fuel management activities are designed to change the structure of wildland vegetation and biomass distribution for the purpose of altering potential fire behavior. The prescriptions and objectives for fuel management depend on the characteristics of the vegetation and fire regime. For forest ecosystems with low- and mixed-severity fire regimes (Agee 1998), fuel management prescriptions can be designed to improve survivability of trees following wildland fires, restore forest structure, and improve the success of fire suppression efforts. For high-severity fire regimes in brushland and forest ecosystems, fuel management objectives can change fire behavior, slowing overall fire growth and improving fire suppression. Fuel management techniques that have proven effective in changing wildland fire behavior and effects consist of prescribed burning (Davis and Cooper 1963, Deeming 1990, Helms 1979, Koehler 1993, Martin et al. 1989, Pollet and Omi 2002), thinning (Hirsch and Pengelly 1999, Keyes and O'Hara 2002), and other mechanical manipulation of living or dead vegetation (Brown and Davis 1973, Pyne et al. 1996). Forest fuel treatments that reduce canopy fuels must often be accompanied by surface fuel treatment; otherwise the surface fuel hazard can be increased (Alexander and Yancik 1977, van Wagtendonk 1996). There are three main targets of fuel management prescriptions that contribute to changes in discrete kinds of fire behavior (table 7).

The changes in potential fire behavior are produced at the stand level, or within the treated area. Fire behaviors before and after treatment can be modeled by using fire behavior prediction systems such as BEHAVE (Andrews 1986) and Nexus (Scott and Reinhardt 2001) to compare fire spread rates, intensities, and propensity for crown fire.

Although fuel management tends to produce immediate changes in fire behavior, fuel treatment effects are only temporary. Fuel conditions change over time as a result of fuel accretion, regrowth of understory vegetation, and ingrowth of young trees. More research

Table 7—General relationships among fuels, prescriptions, and intended changes to fire behavior from fuel treatments

Fuel target	Prescription	Change in fire behavior
Surface fuels (live grass and brush, and dead and downed woody material)	Prescribed burning, mechanical treatments remove, compact, or reduce continuity of surface fuels	Reduced spread rate and intensity, and limit ignition of tree crowns and other aerial fuels
Ladder fuels (small trees, brush, low limbs)	Thinning (small-diameter trees) and prescribed burning (scorching and killing small trees and brush) to decrease vertical continuity between surface and crown fuels	Limit ability for fire to transition from surface to crown fire by separating surface fuels from crown fuels
Canopy fuels (fine fuels like needles, and small twigs in tree crowns)	Thinning to reduce horizontal continuity of crowns (e.g., overstory thin)	Limit spread of crown fire

is required to understand the long-term efficacy of fuel treatments on fuel conditions and fire behavior so that scheduling of future management activities and maintenance can be determined.

Landscape Effects of Fuel Management

Landscape strategies for fuel treatments can be distinguished in terms of their intention to (1) contain fires or (2) to modify fire behavior. Fire containment has been attempted by arranging fuel treatments as fuel breaks (Agee et al. 2000, Green 1977, Omi 1996, Weatherspoon and Skinner 1996). Fuel breaks are designed to facilitate active fire suppression at predetermined locations by indirect tactics (e.g., burnout). An alternative is to modify fire behavior and fire progress across landscapes through strategic placement of treatments and patterns of treatments (Brackebusch 1973; Finney 2001a, 2001b; Hirsch et al. 2001). The latter strategy affords flexibility for integration into land management planning and does not rely on uncertainties of success in fire suppression to mitigate fire effects. The remainder of this paper will focus on strategic treatments.

Although behavior and effects of wildland fires can be changed within a particular treatment unit or stand, the behavior and progress of a much larger fire may not be affected by small treatment units. Fire progression maps often reveal that small units are circumvented by large wildland fires (Dunn 1989, Salazar and Gonzalez-Caban 1987) with little net effect on the overall growth of the fire (fig. 27). Instead, the progress of large wildland fires is only affected by treatments that are (1) comparable to the size of the fire or (2) by treatments that collectively disrupt the growth of fires (Brackebusch 1973, Finney 2001a, Gill and Bradstock 1998). Examples of landscape-scale effects of fuel management are evidenced in large national parks (e.g., Yosemite, Sequoia, and Kings Canyon) where fire management policies have allowed free-burning fires for nearly three decades (Parsons and van Wagtendonk 1996, van Wagtendonk 1995) and in Baja, California, chaparral where little fire suppression exists (Minnich and Chou 1997). Because large fires are of primary concern to fire and forest managers, the most important effects of fuel treatments can only be achieved if landscape-scale considerations are incorporated into

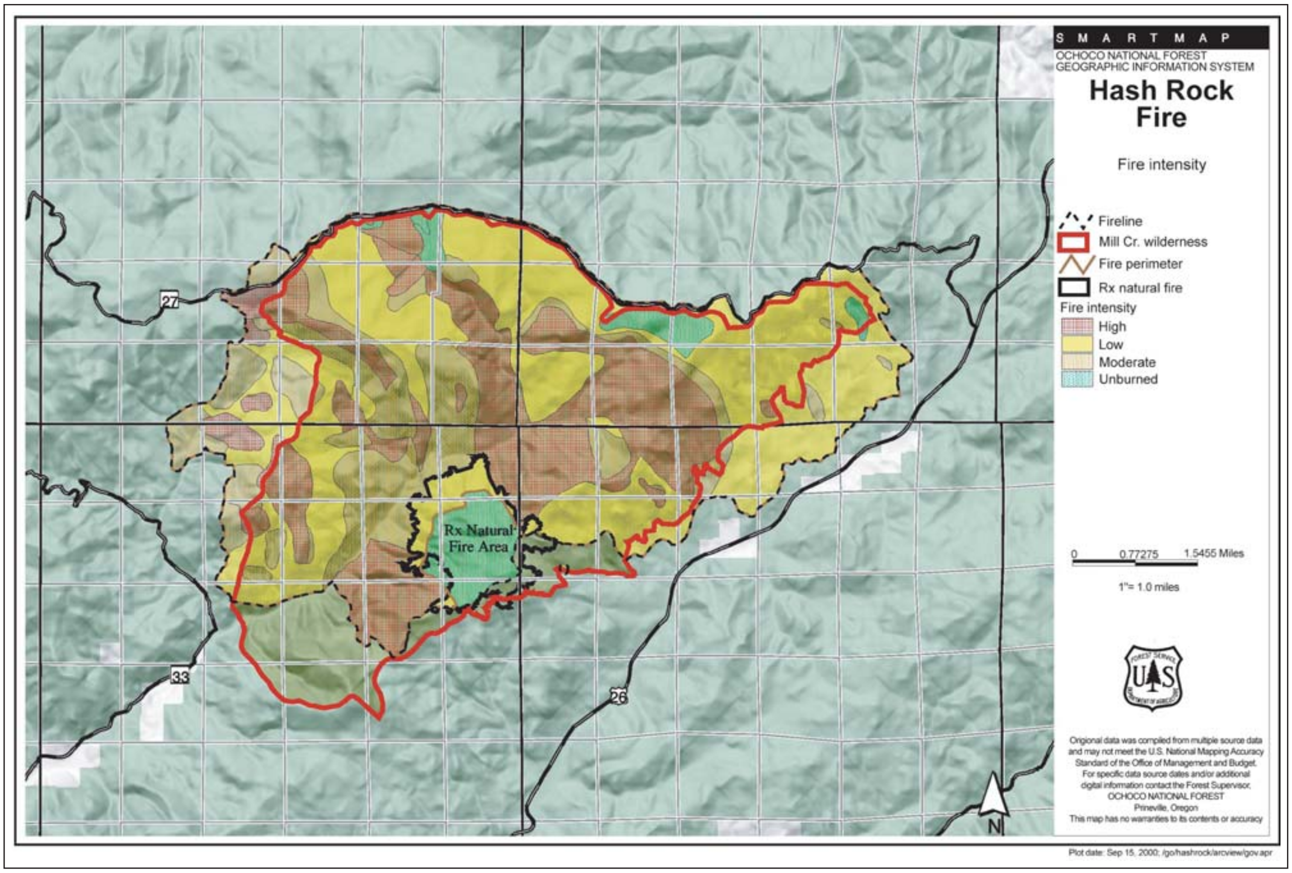

Figure 27—Fire severity at the Hash Rock fire (August 2000) near Prineville, Oregon. A prescribed natural fire (i.e., fire use for resource benefit) that occurred in 1995 produced important localized changes in fire behavior but had little effect on the progress of the Hash Rock Fire as a whole.

the design and positioning of fuel treatments (Brackebusch 1973, Deeming 1990, Omi 1996, Omi and Kalabokidis 1998).

The effects of individual fuel treatment units on large fires must be modeled through simulation. Aside from the minimally managed fire regimes in a few national parks and wilderness areas, no full-scale landscape fuel management activities have been attempted. Thus, our only indications as to the effectiveness of treatments and patterns come from theoretical and modeling activities, and occasional experience of using forest harvest patterns for fire suppression (Bunnell 1998). Brackebusch (1973) advocated a mosaic pattern of managed fuel patches to disrupt fire growth. Gill and Bradstock (1998) discussed the amount of randomly arranged prescribed burns needed to disrupt fire growth. Hirsch et al. (2001) proposed strategically locating fuel treatment units in a "smart forest" approach to harvest scheduling and location. Theoretical work on fuel patterns (Finney 2001a, 2001b) indicates that spatial patterns of fuel treatments are critical to fire growth rates (i.e., the rate of spread of large fires) (fig. 28). Here, random fuel treatments are very inefficient in changing overall fire growth rates. Compared to the partially overlapped pattern, randomly arranged treatments permit fire to easily move laterally around treatments unless large portions of the landscape are treated. This is further illustrated by a comparison of large fire growth rates across the entire range of treatments (fig. 29). If fire spread rate is reduced to one-fifth within the treatment unit compared to the untreated surrounding landscape (as a direct effect of the treatment

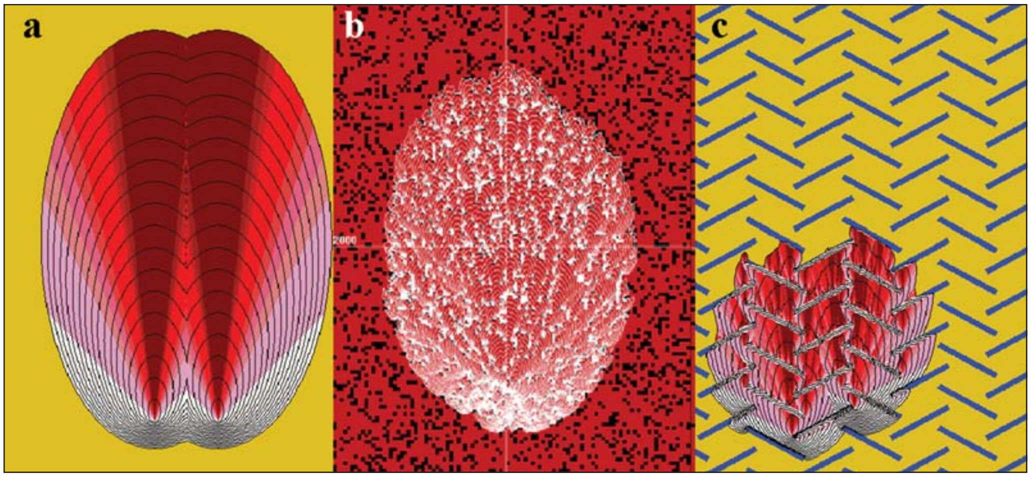

Figure 28—Simulations of fire growth on different theoretical fuel patterns. Compared to (a) no treatment, (b) random 20-percent treatment produces little effect on overall fire growth compared to (c) a theoretical partial-overlap treatment. Random arrangements are ineffective because the fire can circumvent treatment areas.

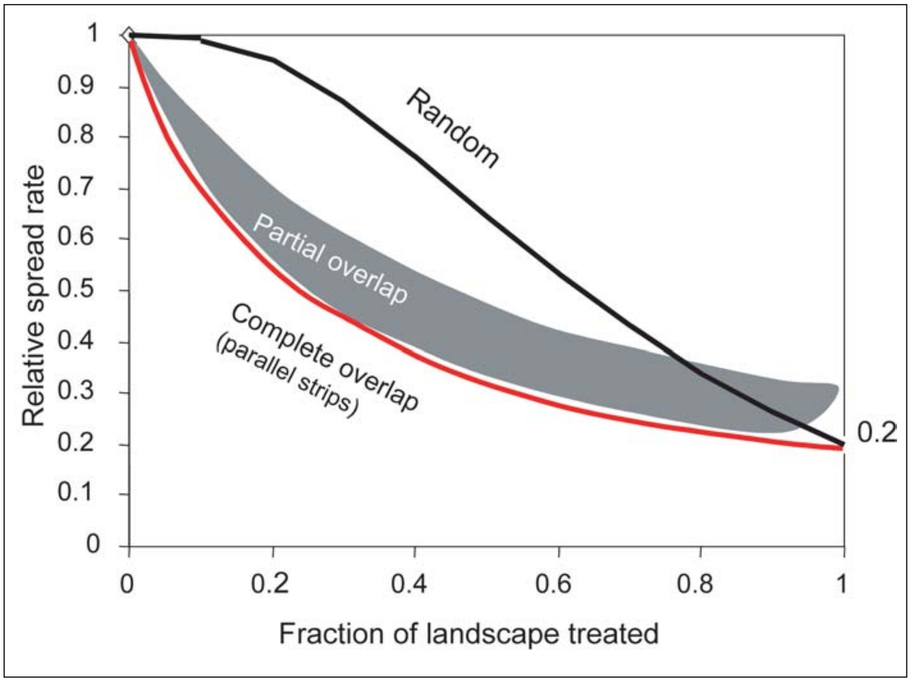

Figure 29—Overall fire spread rate as a function of treatment fraction for different spatial patterns of treatment units (from Finney 2001a, 2003) reduces relative spread rate to 0.2. Compared to patterns that require overlap among treatments, the random treatment pattern produces little reduction in overall fire spread rate until relatively large proportions of the landscape are treated (because fire goes around the treated patches).

prescription) 35-percent reduction in large fire growth rates is achieved by treating about 10 percent of the landscape in the strategic pattern compared to 50 percent in a random pattern (fig. 29). The strategic pattern is clearly more efficient (per area treated) than a random spatial arrangement of treatments. In nature, fire patterns created by free-burning fires in the large national parks and Baja (Minnich and Chou 1997, Parsons and van Wagtendonk 1996, van Wagtendonk 1995) obstruct fire growth because large percentages of the landscape are maintained by previous fires, despite the random locations of those fires and previously burned areas.

The effects of fuel and forest management activities on fire behavior are not restricted to the stand that is treated. Behavior characteristics of large wildland fires can be altered outside the treated area because of the way fire behavior changes depending on the relative fire spread direction. These constitute an “off-site” effect of treatments that are seen as changes in overall fire growth rate (fig. 28), flanking and backing fire burning with lower fireline intensity on the lee-side of treatment units (fig. 30), and in moderated fire effects on the lee-side of fuel changes (fig. 31). Such landscape-scale effects on large fires become important to the patch sizes and proportions of areas burned with different severities.

Effects of Spatial Locations and Patterns of Landscape Fuel Treatments

Despite the potential benefits of fuel management at the stand and landscape levels, limitations on the amounts and locations of treatment suggest that these activities must be carefully chosen to achieve the greatest effect and benefit. The problem might be approached as an optimization of effects given constraints on locations, amounts, and prescriptions that can be applied. Application of spatial optimization and strategies in forest management (Baskent 1999, Baskent and Jordan 1996, Snyder and ReVelle 1996) and fire management (Finney 2001a, Hirsch et al. 2001, Hof et al. 2000, Wilson and Baker 1998) is becoming more common. For a simple theoretical landscape consisting of two fuel types on flat terrain, a pattern of rectangular fuel treatment units can be optimized for size and placement (Finney 2001a). Such patterns are optimal in terms of efficiency and effectiveness in reducing large-fire growth rates compared to random fuel patterns (Finney 2001b, 2003). However, there are no analytical solutions to the optimization of fuel treatment locations on real landscapes that are complex in terms of fuels, topography, and weather. For real landscapes, where fuels, topography, and weather all differ, an optimization of this kind is complicated by the spatial and temporal nature of fire and its movement through a pattern of fuel treatments.

An optimization algorithm is under development for helping choose the placement of fuel treatments on real landscapes (Finney 2002b). One process now being considered consists of two steps: (1) use fire growth algorithms to identify the fastest travel routes across a landscape, and (2) use heuristic algorithms to optimize the locations and sizes of fuel treatments to block these routes. The fastest travel routes produced by fire growth algorithms suggest initial places for optimal placement of fuel treatments for delaying fire growth. The procedure requires the construction of a gridded landscape containing information on fuels and topography (fig. 32a). Specific weather conditions associated with the conditions targeted for fuel treatment performance, including wind direction, windspeed, humidity, and temperature are used to compute the fire behavior at each cell. Each cell contains fire spread rates in all directions assuming an elliptical fire shape (Finney 2002a) so that fire growth across the landscape can be computed from a generic ignition source. The fire growth algorithm is based on minimum fire travel time methods from graph theory (Finney 2002a, Moser 1991) that efficiently calculate fire growth and behavior for each cell (node) on the landscape. The paths producing the minimum fire travel time can then be processed to identify the “influence paths” or routes of fire travel

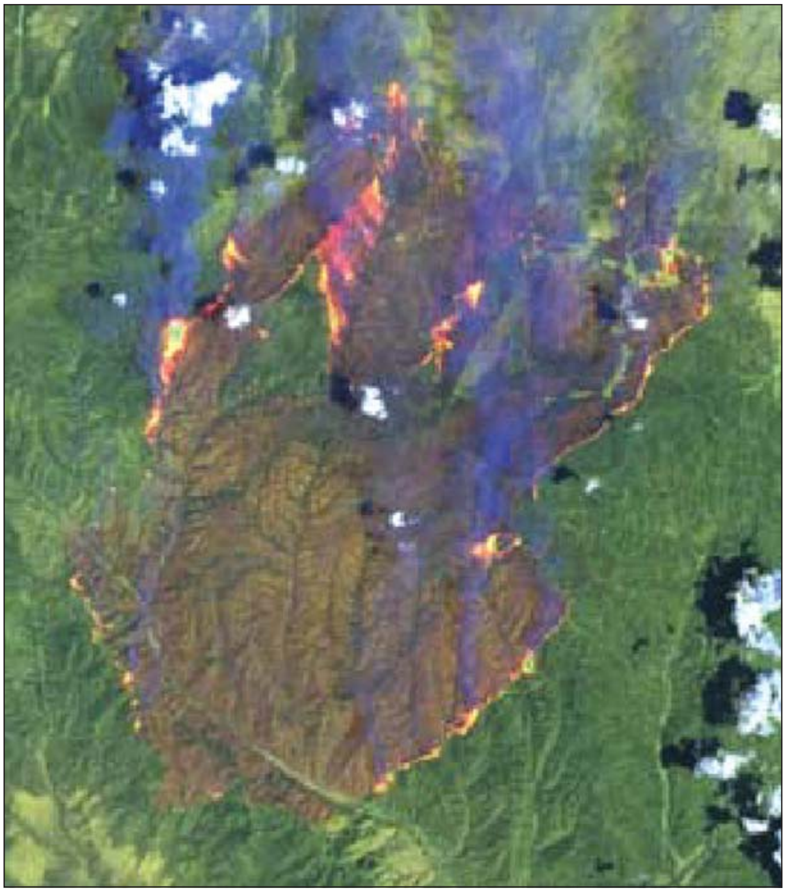

Figure 30—Landsat 7 image of the Rodeo fire in Arizona (June 21, 2002) showing interior fire fronts around arrow-shaped islands within the main fire. These occur where fire fronts join after circumventing the islands and are a landscape-scale effect of varying fuels and fire behavior.

Figure 31—A ridge within the Alder Creek fire (Montana 2000) showing offsite effect of rocky areas (arrows) on fire effects and behavior. Crown fire moved from lower left to upper right and could not burn areas on lee side of rocky patches (photo by Colin Hardy, USDA FS, Missoula Fire Sciences Lab).

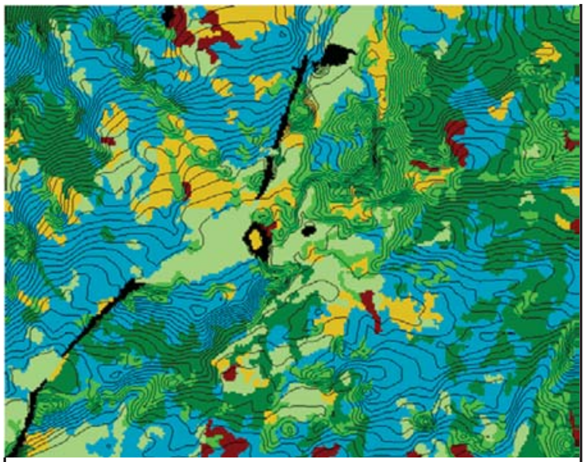

Figure 32a—Fuels and terrain data showing fire growth contours (progression in 1-hour time step from north to south).

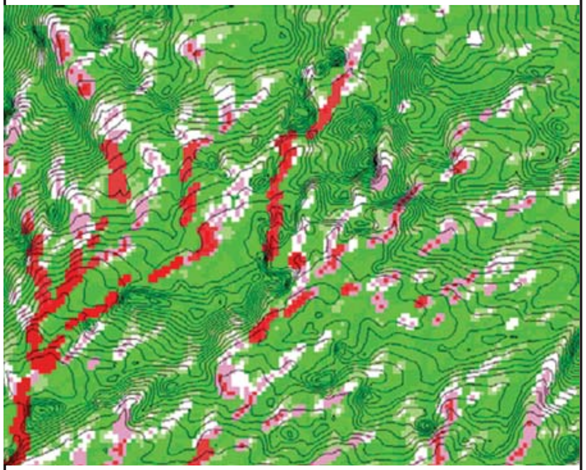

Figure 32b—Fire influence paths calculated from fire growth algorithm. Given the ignition configuration (bottom of landscape), fire burning through paths of high influence (red) ultimately burns more land area than areas around them. These suggest places to place fuel treatment units because a large effect would be achieved by slowing fire spread through those areas compared to surrounding areas.

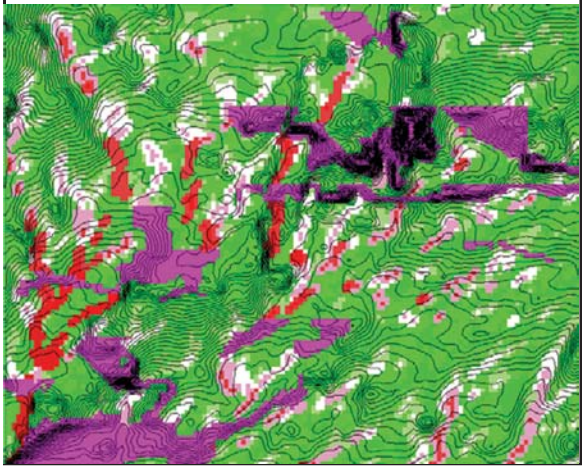

Figure 32c—Fuel treatments (fuchsia color) optimized by using a genetic algorithm for this landscape. Treatments cause fire growth to take twice as long as it would without treatments to cross this landscape while occupying about 15 percent of the total land area.

that account for the most area burned later in time (fig. 32b). These paths are the starting locations for treatment units because of the large influence that blocking those paths has on area burned. The exact number, sizes, and patterns of those treatments, however, must be obtained through the use of a heuristic algorithm (fig. 32c).

Heuristic algorithms are used to find spatially optimal fuel treatment unit sizes and locations. At present, a genetic algorithm (Goldberg 1989) is being developed for evaluating collections of fuel treatment units to determine their effectiveness and efficiency at changing overall fire growth rates. The challenging part of this problem is the sequential nature of fire movement. Fuel treatment units located upwind divert fire growth and change the priorities for fuel treatments downwind (sizes and locations). Furthermore, the optimal spatial pattern is not necessarily composed of locally optimal treatment units. In other words, the importance of each unit is only realized in context of the entire pattern. An approach to this problem involves the use of recursion, starting the algorithm at downwind locations and allowing it to recurse toward the ignition location. At each location, a population of “best” treatment units is selected based on the best populations from previous locations (i.e., upwind or closer to the ignition). The performance of individual treatment patterns is assessed by using the fire growth algorithm to compare fire travel times among treatment alternatives. The genetic algorithm (GA) is used to refine the population of individual treatment units within a horizontal strip, where each treatment unit has characteristics of vertical location and size. Ultimately, the optimal solution is selected from the treatments that produce the overall best effect. The algorithm consists of the following steps:

- Evaluate the fire growth by using the minimum travel time algorithm for the landscape without treatment.
- Divide the landscape into a series of strips of random width running perpendicular to the main fire spread direction.
- Starting with the downwind strip (i.e., farthest from the ignition), use GA to optimize the fuel treatment locations and unit sizes for each of the fuel treatment configurations obtained from the GA on previous strips. Applying the GA to each strip requires recursion into preceding strips to find the optimal treatment locations and sizes. Each treatment configuration in each strip is evaluated by using the minimum travel time algorithm.
- Within each strip, create populations of treatment locations and sizes to evaluate and improve by using the GA. Treatment unit sizes are obtained by infilling the fire growth contours from a starting point (e.g., an influence path) by using the differential spread rate owing to treatment.
- Pick the best overall treatment pattern from all strips that maximize the fire travel time across the landscape as a whole.

The above algorithm is being developed for handling spatial constraints on treatment area and local treatment effectiveness (i.e., within a given stand and stand type). So far, the algorithm appears to identify fuel treatment units that efficiently retard overall fire growth (fig. 32c).

Integration of Fire and Landscape Simulations

Long-term consequences of forest and fuel management activities on wildland fire behavior can only be understood by either large-scale experimentation or through simulation modeling. Until experimental or operational treatment areas have been established on the ground and monitored, simulation modeling will be the only method available.

Many landscape simulation approaches are currently used for spatially modeling fire and long-term future forest development (Johnson et al. 1998, Jones and Chew 1999, Keane et al. 1997, Mladenoff and He 1999, Sessons et al. 1996, Thompson et al. 2000). Some of these have been proposed for modeling effects of treatments and for optimizing the scheduling of fuel treatments. At present, these simulations do not permit control for fuel treatment spatial patterns. As the above analysis of simple landscape patterns suggests, however, fuel treatments at the landscape scale have topological effects that are critical to changing fire growth. Improvements to landscape simulations include the prescription, scheduling, and location of treatments dynamically in response to unpredicted disturbances (fire, insects, etc.). Furthermore, the simulation must have fine-scale resolution of landscape units, as either grids (raster) or small polygons, to retain the fine resolution of spatially variable fire effects (Finney 1999).

The intent of a new modeling effort is to modify the simulation approach (Simulation and Analysis of Forests with Episodic Disturbances [SafeD]) described by Sessions et al. (1999) and Johnson et al. (1998) to incorporate a spatial optimization for fuel treatments (Finney 2002b). The SafeD model has been used previously to examine how fuelbreaks performed in the presence of wildfire and forest change (Johnson et al. 1998, Sessions et al. 1999). Currently, SafeD (Graetz 2000) is a spatially explicit simulation/optimization tool that features a stand prescription generator (Wedin 1999), forest growth-and-yield modeling by using the Forest Vegetation Simulator (FVS), a heuristic method of allocating activities across a landscape with multiple constraints, and a spatially explicit fire growth model FARSITE (Finney 1998). Together, these models allow for scheduling of fuel and harvesting treatments, simulation of wildfire events and effects, growth and mortality of vegetation, surface and crown fuel development, and specification of stand- and landscape-level objectives. The landscape goal-seeking component of SafeD couples heuristic techniques with goal programming to find near-optimal sets of stand and landscape prescriptions. Multiple stand management objectives can be specified for the simulations. Mechanical and prescribed fire treatment effects are modeled in SafeD by manipulation of tree lists (lists of density by size and species of trees) and surface fuel components. Wildfire effects are created by fireline intensity maps created by FARSITE simulations that are activated by the SafeD model.

Several additions to the SafeD model will be required to permit spatial optimization of fuel treatments. Optimal fuel treatment locations will be determined by inclusion of a spatial treatment algorithm (e.g., Finney 2002b).

Research Applications

A project funded by the Joint Fire Science Program (http://www.nifc.gov/joint_fire_sci/jointfiresci.html) will make use of the SafeD simulation system to address landscape fuel treatment scheduling and potential effects for several study areas. These study areas are located in the Blue Mountains in eastern Oregon (one of the INLAS study sites), Sanders County in western Montana, the Sierra National Forest in California, and southern Utah. The landscapes were chosen as samples of different ecosystems, fire regimes, mixtures of landownership, and fuel and forest management issues and constraints to examine, in a practical sense, how the outcomes of landscape fuel treatment programs can be expected to differ. A series of simulations for these landscapes will be performed to address the following questions:

- How important is fuel treatment topology to the potential effects of treatments on real landscapes?
- For different fuel treatment amounts and patterns, what fuel treatment effects (e.g., fire sizes, burned area, severity) can be expected with no constraint on treatment location or prescription?
- What fuel treatment effects are possible given current restrictions on fuel and forest management activities?
- What are the tradeoffs in fuel treatment effectiveness possible by relaxing some of the constraints?

The results of this project are intended to lead to practical methods for guiding fuel treatment planning across landscapes and for helping identify constraints on needed management activities through cooperation among the many competing interests in wildland management.

Conclusions

The fire behavior models presently available can be used to simulate fire growth, behavior, and effects at the landscape scale. Effects of fuel treatments on changes in fire behavior can be modeled for a variety of prescriptions and environmental conditions. The fire simulations also have been used to examine spatial effects of fuel treatment patterns, suggesting that fuel treatment topology can be important to effects on fire growth and behavior. Fire growth simulation and heuristic algorithms are being combined as a means to find optimal patterns of treatments in highly variable conditions found on real landscapes. These optimizations are to be combined with landscape simulation and scheduling programs to examine likely effects of spatial fuel treatment programs on wildland fire behaviors and effects at the landscape scale.

Acknowledgments

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English Equivalents

When you know:	Multiply by:	To find:
Meters (m)	3.28	Feet
Kilograms (kg)	2.205	Pounds
Kilowatts per meter (kW/m)	0.2889	British thermal unit per foot per second

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