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# Design of Regular Landscape Fuel Treatment Patterns for Modifying Fire Growth and Behavior

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**ABSTRACT.** Patterns of disconnected fuel treatment patches that overlap in the heading fire spread direction are theoretically effective in changing forward fire spread rate. The analysis presented here sought to find the unit shape and pattern for a given level of treatment that has the maximum effect on forward spread rate. This occurs when the treatment units cause the fire to spread through them at the same rate as it spreads around them. Simulations suggested that these treatment patterns reduce the spread rate or fireline intensity over much of the area burned, even outside the treatment units where the fire was forced to flank. The ideal patterns are theoretically scale independent, allowing for flexible application across heterogeneous landscapes. The topology of these patterns has implications for designing landscape-level fuel treatment patterns and for understanding spatial dynamics of fuel patterns across landscapes. *FOR. SCI.* 47(2):219–228.

**Key Words:** Fuels, fuel treatments, fire behavior, landscape patterns, fire modeling.

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**T**HE GOAL OF FUEL MANAGEMENT IS to preemptively modify wildfire behavior through changes to the fuel complex. Fuel management has received increasing interest for mitigating fuel hazards (U.S. Department of the Interior and Department of Agriculture 1996, U.S. General Accounting Office 1999), some of which were created by nearly a century of fire suppression on millions of acres in the western United States (Arno and Brown 1991). Fuel treatments are intended to help limit wildland fire sizes and severity by directly mitigating fire behavior and indirectly by facilitating suppression. Prescribed burning and mechanical thinning can lower fire spread rates and intensities within the treated area (van Wagtenonk 1996, Helms 1979), at least until fuels and vegetation reaccumulate. Fireline construction can be faster and more effective (fewer escapes) when heavy concentrations of brush and logs are removed, and spotting from torching trees is limited.

Treating all fuels across an entire landscape is practically impossible, however. Limited funding, inadequate road ac-

cess, variable land ownership, and regulations often restrict prescribed burning, smoke production, or timber harvesting. Fuel management on a landscape scale tends to be limited in the amount of a given treatment, location of treatments, and the kinds of treatments permitted. Priorities for treatment are often based on local hazards, ecological objectives, convenience, cost, land ownership, or accessibility. These priorities are not necessarily topological or spatial as is fire growth and behavior and they do not prioritize the layout of treatment units with an explicit consideration of fire growth among adjacent units. With all the limitations on treatment location and continuity of treatments across a landscape, it is logical to address how the spatial arrangement of treatment units affects fire growth.

Two basic strategies for landscape-level fuel management are to contain fires and to modify fire behavior. Linear fuel breaks (Agee et al. 2000, Weatherspoon and Skinner 1996) have been proposed to help contain fires. Fuel breaks are intended to reinforce defensible locations and facilitate sup-

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pression action by indirect tactics including backfiring (Green 1977, Omi 1996). It is assumed that undesirable fire effects are limited by reducing fire sizes. The fuel breaks themselves are only burned along the zone of suppression, not by the fire. By contrast, a spatial arrangement of treatments that primarily modifies fire behavior would involve area-based or dispersed patterns (Martin et al. 1989). Fire effects and behaviors are modified wherever the fire encounters the treatment units. Suppression is facilitated by allowing any tactic (direct, indirect, or parallel attacks) to adapt to changes in collective fire behavior.

For fire modification, it is clear that the greatest reduction in fire size and severity occurs when fuel treatment units limit fire spread in the heading direction. The heading portion of a fire (moving with the wind or slope) has the fastest spread rate and highest intensity compared to flanking and backing portions (Catchpole et al. 1982). The heading fire also holds the most potential for initiating crown fire and spotting, which makes suppression much more difficult.

To disrupt the spread of the heading fire, there are three basic geometric treatment patterns offering varying degrees of overlap: complete, none, or partial (Figure 1). The case of complete overlap by multiple treatments (Figure 1a) has the effect of producing a harmonic mean spread rate among multiple fuel types as the fire burns sequentially through the strips (Fujioka 1985, Martin 1988):

$$h = \frac{1}{f_1/r_1 + f_2/r_2 + \dots} \quad (1)$$

where  $f_i$  is the fraction of the total distance across the  $i$ th fuel type having a characteristic spread rate  $r_i$ . Here the effective heading spread rate  $h$  is proportional to the time spent in each fuel type; the fire must spread through the treatment strips perpendicular to their orientation (e.g., no flanking). This arrangement would rarely be practical for treating large and variable landscapes. It would require extensive area to be treated and continuous land ownership and access. By contrast, a treatment pattern with no overlap of the treatment units (Figure 1b) may not change the forward spread rate across the landscape; fire can burn unfettered through the corridors between treatment blocks. A random or arbitrary arrangement of treatments would closely resemble this pattern because it has no requirement for producing overlap. It would, however, be expected to yield increasing overlap in a given direction as the treatment area or number of treatment units increased. The effect of partial overlap (Figure 1c) on fire growth is more complex because the fire must progress through the pattern with a combination of forward and lateral spread. This means that unit size, shape, orientation, and

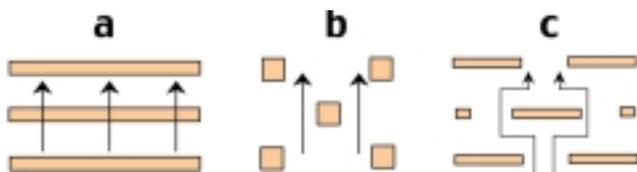


Figure 1. Three basic fuel treatment patterns characterized by (a) complete overlap in the heading direction, (b) no overlap, and (c) partial overlap. The arrows show the general paths of fire travel.

juxtaposition to other units will strongly affect fire growth. The topology will be general to heterogeneous landscapes where fire is forced to progress among multiple fuel types. Since a large number of unit configurations is possible, the following analysis was directed to find a regular pattern of treatments that produces the greatest reduction in overall fire spread rate with a minimum of treated area.

## Analysis

Fire shapes formed the basis for analyzing how flanking and heading spread affected the progress of fire within a mixture of fuel types. Shapes of wildland fires are known to be ellipsoidal under homogeneous conditions of fuels, weather, and topography (Van Wagner 1969, Anderson 1983, Alexander 1985). The simple ellipse is the most common shape used in modeling fire growth, and its dimensions are assumed to depend mainly on wind and slope (Alexander 1985). For an elliptical fire, the rectangular expansion rates ( $\partial x/\partial t, \partial y/\partial t$ ) in a given direction  $\theta$  ( $0 \leq \theta \leq 2\pi$ ) from the center (Figure 2) can be obtained using spread rate components ( $a, b, c$ ) for the dimensions of length and breadth (Anderson et al. 1982, Richards 1990):

$$\partial x/\partial t = a \sin \theta \quad (2)$$

$$\partial y/\partial t = b \cos \theta + c \quad (3)$$

The heading spread rate  $r$  is the sum  $b + c$  ( $\theta = 0$ ) because  $c$  is the offset from the center of the ellipse to the ignition point. The dimensions are parallel to the ground slope. Stronger winds and steeper slopes produce more eccentric fire shapes as described by the length to breadth ratio (Figure 2). The spread rates and intensities around the fire edge (Catchpole et al. 1982) and their distributions within the

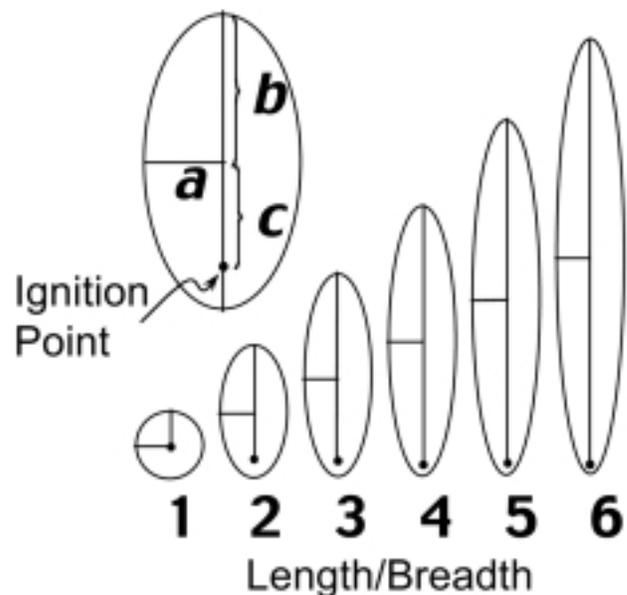


Figure 2. Elliptical fire shapes described by length to breadth ratio and by spread rate dimensions  $a, b$ , and  $c$ . Dimension  $a$  is the flanking spread rate,  $b + c$  is the forward spread rate, and  $c$  is the offset from the center of the ellipse to the ignition point along the major axis. Length to breadth ratio is  $b/a$ .

burned area (Catchpole et al. 1992) depend on fire shape. Fuel type is often assumed to play little role in the shape of fires (Anderson 1983) but greatly affects fire size because of different intrinsic spread rates for given environmental conditions. Thus, fuel treatments that only affect surface fuels would mainly change fire spread rates and sizes but not shapes. On forested lands, treatments often remove some of the overstory trees to decrease horizontal and vertical crown fuel continuity. This could produce faster windspeeds in the understory as a result of a sparser canopy and thereby elongate the fire spread pattern and increase spread rate to some degree.

A main assumption of the following analysis is that treatments effectively slow the fire spread rate. This is expected, under most weather conditions, during the period that forest and brush fuels are reduced after prescribed fire and mechanical treatment. Burning reduces fuel loading, depth, and continuity, and thus fire spread and intensity. Thinning can limit the potential for fast-spreading crown fires. This analysis assumes no spotting or acceleration of the fire when spreading between fuel types and that fire shape is the same in treated and untreated areas.

### Shape of a Single Treatment Unit

A single treatment unit that reduces spread rate most efficiently for the amount of area treated is one that will just be burned completely as the fire simultaneously burns through and circumvents the unit. Consider an elliptical fire with dimensions  $a$ ,  $b$ ,  $c$  that spreads from a point at a rate  $r_m$  for a distance  $D$  in homogeneous fuels (Figure 3);

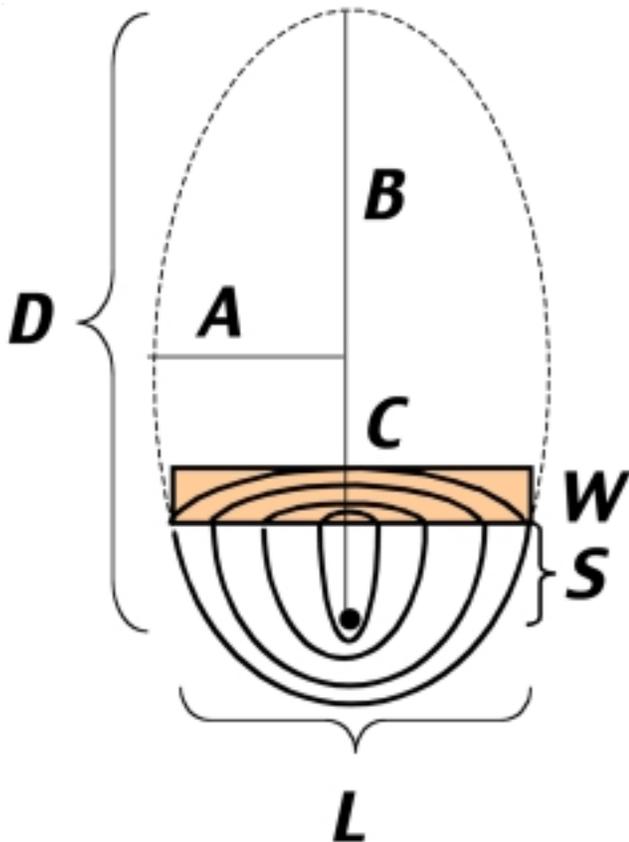


Figure 3. Treatment unit dimensions  $W$  and  $L$  are a function of fire shape and spread rates according to Equations (4)(5)(6)(7) and (8).

the smallest rectangular treatment unit with slower spread rate  $r_t$  that could block its path at a distance  $S$  from the ignition point would allow the fire to spread forward a distance  $W$  and laterally a distance  $L$  such that:

$$\frac{L}{2} = A \sin\left(\cos^{-1}\left(\frac{C-S}{B}\right)\right) = \frac{A}{B} \sqrt{B^2 - (C-S)^2} \quad (4)$$

$A$ ,  $B$ , and  $C$  are distances scaled from the spread rate dimensions ( $a$ ,  $b$ ,  $c$ ) of an elliptical fire in the untreated fuels using known distances  $S$  and  $W$ :

$$A = B \frac{a}{b} \quad (5)$$

$$B = D \frac{b}{(b+c)} \quad (6)$$

$$C = D \frac{c}{(b+c)} \quad (7)$$

and  $D$  is the forward spread distance from the ignition point assuming only untreated fuels:

$$D = S + W \frac{r_m}{r_t} \quad (8)$$

The length  $D$  is critical to the  $A$ ,  $B$ ,  $C$  dimensions of the fire and thus, the  $L$  and  $W$  of the treatment units.

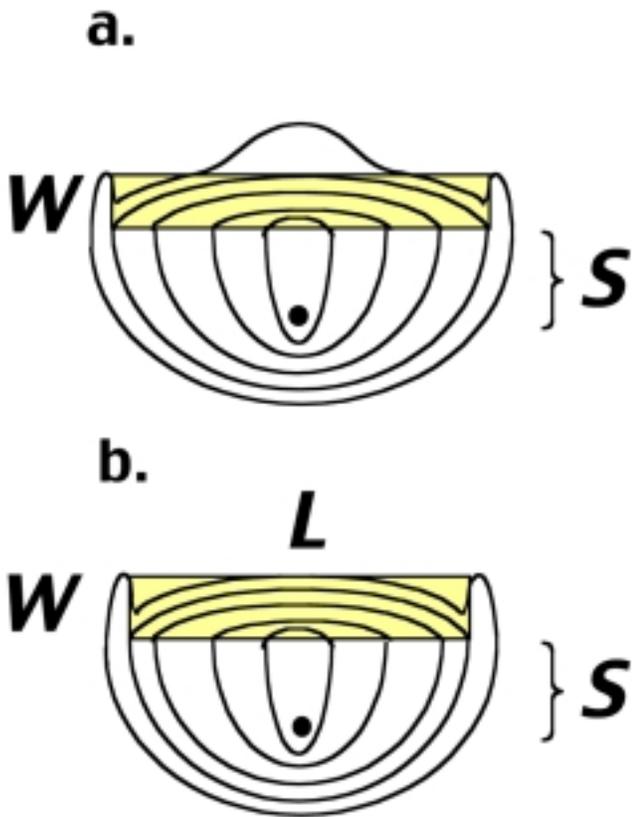
If this fire were to continue growing under constant environmental conditions, it would flank to the left and right edges of the treatment, turn the corners, and resume spreading as two separate heading fires (Figure 4a). At the same time, the fire would exit the lee side of the treatment and also resume heading through the matrix. The fire burning through the unit maintains a distance  $W$  ahead of the fires that have flanked from around each side and thus, a faster overall spread rate. The most efficient treatment unit width  $W$  occurs when the fire exiting the lee of the unit synchronously arrives at the same forward position as the fires moving around the ends (Figure 4b) making the spread rates equal. This was obtained by modifying Equation (8) to reduce the influence of  $W$  on  $L/2$  in Equation (4):

$$D = S + W \left(1 - \frac{r_t}{r_m}\right) \frac{r_m}{r_t} = S + W \left(\frac{r_m}{r_t} - 1\right) \quad (9)$$

Together, Equations (4)–(7) and (9) describe a rectangular treatment unit that provides the maximum delay of forward fire spread per unit area treated for a single point-source fire igniting at a specific location outside the unit. A wider unit does not stem the forward spread of the fire because the fire flanks around it. A narrower unit burns through before the fire flanks to its edges.

### Regular Pattern of Overlapping Units

With slight modification, the analysis for a single treatment unit [Equations (4)–(9)] can be extended to address fire growth through a repeating regular pattern of identical

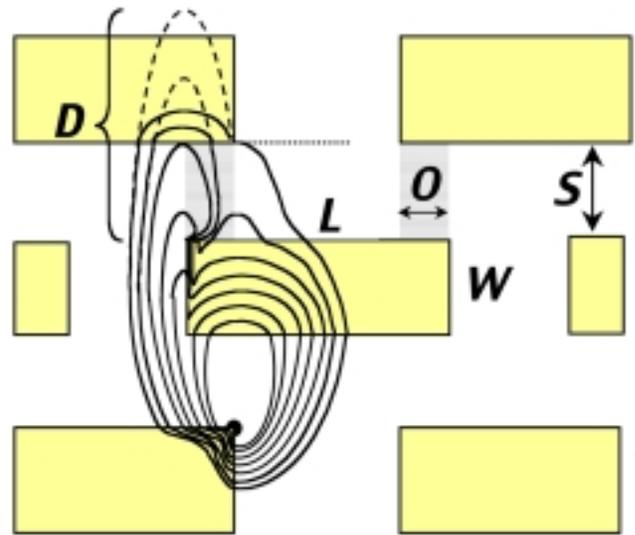


**Figure 4.** Fire spread rates through and around treatment units will be (a) different using Equation (8), or (b) equal with Equation (9).

rectangular units across a landscape (e.g., the partial overlap pattern). Assuming that the fire burns steadily under constant environmental conditions, the pattern consists of parallel rows of units that overlap normal to the direction of heading fire spread by a constant amount (Figure 1c). The embedding of a single treatment unit in a regular pattern of units changes the interpretation of the ignition point in Equations (4)–(9) to a virtual point located at the leeward corners of the previous units (Figure 5). These corners become virtual point source ignitions because the fire can make no lateral progress into the units that could affect fire growth outside the units. Although a small amount of flanking spread within the units does take place before the heading fire reaching these corners (Figure 4a,b), it is irrelevant to fire shape or growth after fire reaches these corners because of the faster flanking spread in the matrix.

Once embedded in a repeating pattern, the width of each unit serves a double purpose: it delays the head of the fire while it flanks along the overlap formed with the unit of the previous row, and then (in the opposite direction) along the overlap with the units in the next row. Thus, with two rows of overlap surrounding each unit, the effect of  $W$  on  $O$  needs to be only half that described by Equation (9) to produce the maximum delay of the fire:

$$D = S + \frac{W}{2} \left( \frac{r_m}{r_t} - 1 \right) \quad (10)$$



**Figure 5.** By embedding a single treatment unit in a regular pattern of identical units,  $W$  delays fire growth during flanking around two sides of the unit. The spread rate of the fire moving around the units is, therefore, equivalent to the spread rate through the units only if the effect of  $W$  on  $O$  is reduced by one-half [Equation (10)]. Dashed lines indicate the hypothetical forward spread distance  $D$  with no treatment.

With this modification, Equation (4) relates only to the portion of the treatment unit causing the fire to flank (e.g., the overlap  $O$ ) not  $L/2$ .

$$O = \frac{A}{B} \sqrt{B^2 - (C - S)^2} \quad (11)$$

Equations (5), (6), (7), (10), and (11) can now be used to calculate  $O$  for a pattern of treatment units given the separation  $S$  from neighboring units,  $W$  of the unit itself, the fire shape outside the unit, and spread rates inside and outside the treatments. Equation (10) could also be rearranged to yield  $W$  for inputs of  $S$  and  $O$ :

$$W = 2(D - S) \left/ \left( \frac{r_m}{r_t} - 1 \right) \right. \quad (12)$$

but requires iteration to estimate  $D$ . The distance  $D$  is interpreted as the hypothetical forward spread distance of the fire burning only in untreated fuels (Figure 5) having a lateral spread distance of  $O$  at a distance  $S$  from the ignition point and can be estimated as:

$$D = O \frac{r_m}{a \sin \theta} \quad (13)$$

where

$$0 < \theta \leq \pi \quad \left| \quad \frac{O}{S} = \frac{a \sin \theta}{c + b \cos \theta} \quad (14)$$

Together, Equations (5), (6), (7), (10), and (11) [or (12) and (13)] describe the maximum reduction of forward fire spread by rectangular treatment units per unit area treated. In other words, these equations regulate fire growth so that the fire spreads through the units in the pattern at the same rate as

it flanks around them. The equations do not depend on the fire shape in the treatment, only the forward spread rate because spread rate in the treatment is assumed slower.

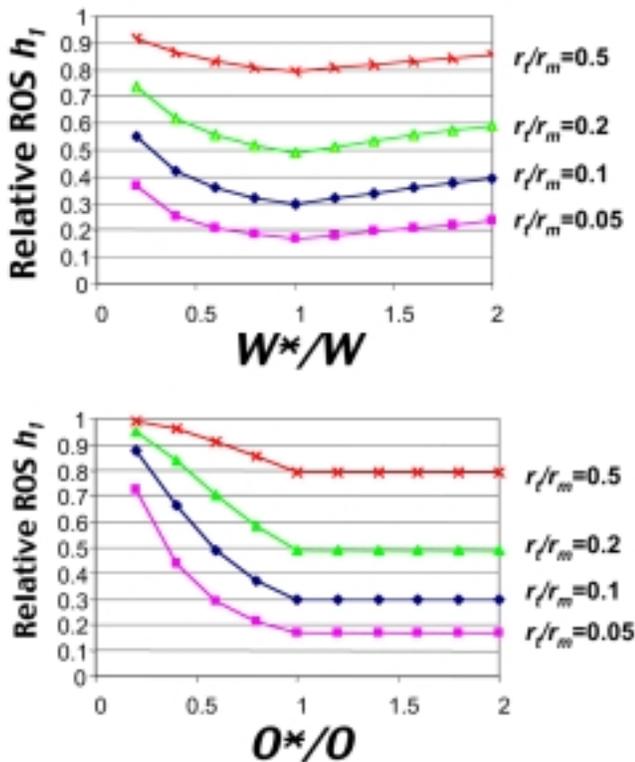
The aggregate forward spread rate through the partial overlap pattern is identical to a harmonic mean spread rate  $h_1$  calculated through the “thin” part of the pattern (e.g., not through the overlapping portion of the treatments):

$$h_1 = \frac{2(S+W)}{(2S+W)/r_m + W/r_t} \quad [15]$$

It is faster but closely related to a harmonic mean calculated through the thick part of the pattern (e.g., through the overlapping treatments):

$$h_2 = \frac{S+W}{S/r_m + W/r_t} \quad (16)$$

As intended, the aggregate spread rate  $h_1$  in this regular pattern is at a minimum when units are dimensioned per Equations (5), (6), (7), (10), and (11) (Figure 6). It seems counterintuitive, but increases or decreases in the width of the units (holding constant all other dimensions) only increases the aggregate spread rate through the pattern. A thicker  $W$



**Figure 6.** Independent changes to (a) the width of the treatments (indicated by  $W^*$ ) or (b) the overlap of the treatments (indicated by  $O^*$ ) relative to ideal dimensions [Equations (5), (6), (7), (10), (11)] generally result in increased spread rates when  $S$  is held constant. Thinner units ( $W^*/W < 1.0$ ) allow the fire to burn through the units first. Thicker units ( $W^*/W > 1.0$ ) allow the fire to first flank around the unit and head for a larger forward distance through the faster matrix fuels. Smaller overlap ( $O^*/O < 1.0$ ) produces faster spread rate  $h$  as the fire burns around the units before it burns through them.<sup>1</sup> No change in spread rate is produced for larger overlap ( $O^*/O > 1.0$ ) because it doesn't change the forward dimension of the treatment units (the amount of matrix fuels burned in heading spread doesn't change).

[than indicated by Equation (12)] allows the fire to flank around the units before they burn through and increases the proportion of heading spread through the matrix fuels (because of the larger cross section of each unit). A thinner  $W$  or smaller  $O$  [compared to Equation (11)] each permits the fire to burn through before it is forced to flank around the units, increasing the aggregate spread rate. Larger  $O$  produces no change in  $h_1$  because the forward dimension of the pattern remains the same (Figure 6), meaning no change in the amount of heading spread within the pattern.

Both spread rates  $h_1$  and  $h_2$  converge on the harmonic mean  $h$  calculated from Equation [1] using the fraction of area treated  $T$  within the overlap pattern:

$$T = r_m \frac{S+W}{D+W} = \frac{LW}{2(L-O)(S+W)} \quad (17)$$

As  $S$  shrinks toward zero or  $O$  goes to  $L/2$  the partial overlap pattern approaches a series of parallel strips (Figure 1a) with a harmonic mean spread rate  $h$  [Equation (1)]. This reinforces the interpretation that the harmonic mean (Fujioka 1985, Martin 1988) assumes fire spreads only in a single direction. The proportions used in Equation (1) are nonspatial, referring to both area and distance fractions of each fuel type.

It is clear that the separation distance  $S$  is critical to both  $W$  and  $O$ . Increasing  $S$  raises the effective spread rate  $h_1$ ; it also raises the treatment fraction  $T$  because  $W$  changes with  $S$  [Equation (12)]. The choice of  $S$  is somewhat arbitrary, however, within the range defined by the dimensions of the treatment units. Its influence on  $O$  means that  $S$  must be greater than zero but not so large that  $O$  becomes longer than  $L/2$ .

#### Extension to Two Directions

With the parallel-linear arrangement of treatment units above,  $S$  affects the treatment fraction (of the total landscape) as well as the angles that gaps between the treatment units align to make the pattern porous. A wind shift to these angles would allow the fire to head through the gaps (pores) without interruption by the treatment units. Obviously the pattern is completely porous to heading fire spreading at an angle  $\alpha = \pi/2$  relative to the direction normal to the treatments. But the pattern is also porous to heading fire moving at specific angles:

$$\alpha = \tan^{-1}\left(\frac{n(L-O)}{S+W}\right) \quad (18)$$

where  $n$  is any odd integer. Thus, the pattern will still overlap at wider angles as  $L$  increases or  $S$  decreases, meaning a greater tolerance for varying wind and fire spread directions. Heading spread is blocked by the pattern for fires moving at intervening angles (when  $n$  is even) and when

$$\alpha \geq \tan^{-1}\left(\frac{L-2O}{W}\right) \quad (19)$$

It is probably not possible to produce a treatment pattern that has equal effects on fire growth in all directions because

spread rates vary elliptically with direction. However, it is possible to modify the parallel-linear treatment pattern to eliminate porosity at all angles while keeping spread rate reduced in a single heading direction according to Equations (5)–(13). The modification involves slanting the treatments by row, like louvered window blinds, in alternating directions by an angle  $\beta$  (Figure 7). This changes the dimensions of the treatment units and how fire interacts with them.

The angle  $\beta$  determines the angle of an elliptical fire front (as measured from the heading direction) that first contacts, enters, and burns through a slanted treatment unit. The spread rate of the fire in the slanted unit at that point (Catchpole et al. 1982) is slower than  $r_i$ :

$$r'_i = c \cos \beta + \sqrt{b^2 \cos^2 \beta + a^2 \sin^2 \beta} \quad (20)$$

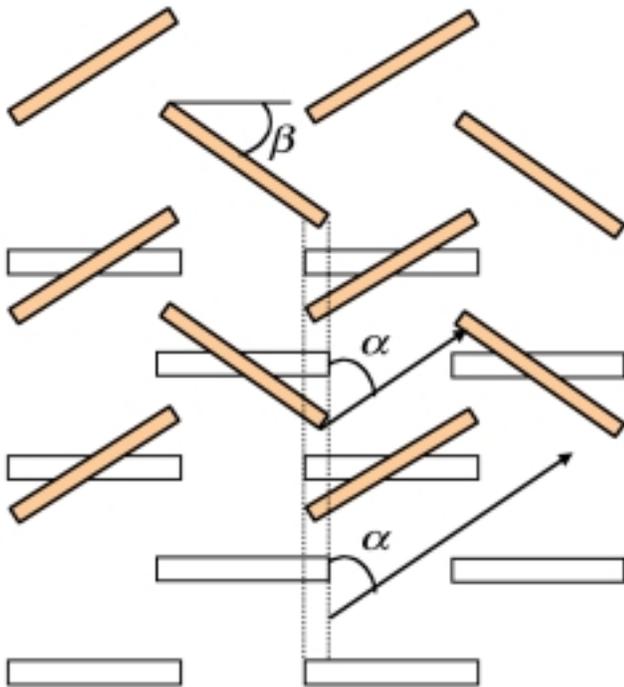
This slower  $r'_i$  can be accommodated by the treatment pattern in various ways. The easiest is to keep the cross-section  $W$  of the units constant and allow  $r'_i$  to increase the overlap  $O$  of the slanted units [Equation (10)]. The actual width of the slanted units  $W'$  however, must be reduced:

$$W' = W \cos \beta \quad (21)$$

and their length  $L'$  modified (Figure 7):

$$L' = \frac{L}{\cos \beta} - W' \tan \beta \quad (22)$$

This keeps the lateral dimension of the treatment units equal to  $L$  and accounts for the rotation of the right-angled corners. Steeper slant angles  $\beta$  reduce the treatment fraction  $T$  of the pattern because the treatment unit width  $W'$  contributes a



**Figure 7.** The parallel treatment pattern (open rectangles) can be louvered (shaded rectangles) at an angle  $\beta$  to block porous angles  $\alpha$  through the pattern. The dimensions  $O$  and  $L$  must be increased and  $W$  decreased to keep fire spread through the slanted units at the same rate as it spreads around them [Equations (20)–(22)].

greater amount to the lateral dimension of the units [Equation (22)] and because the width of the units decreases. These modifications also result in slight increases in the forward spread rate  $h_1$  compared to the parallel arrangement.

As long as  $S < L$ , it will be possible to block the porous angles by slanting the pattern alternately at some  $\beta$ . The porosity of the pattern at  $\alpha = \pi/2$  becomes completely blocked when:

$$S = L \tan \beta - \frac{W'}{\cos \beta} + 2W' \cos \beta - W \quad (23)$$

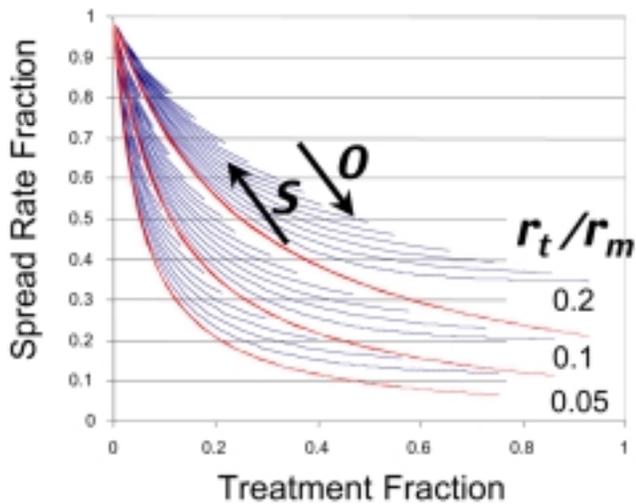
Simulations of fire growth through the various fuel patterns were performed using the *FARSITE* model (Finney 1998) to examine their effects on fire growth and behavior. The *FARSITE* model (Finney 1998) simulates fire growth for complex conditions of terrain, fuels, and weather. *FARSITE* assumes a perfect elliptical fire under uniform conditions with the ignition located at the rear focus of the ellipse (Alexander 1985). It was therefore suited to testing the relationships developed here. The simulations were simplified to maintain constant weather, fuel moistures, and wind direction with the only variation coming from fuel patterns and types. For each simulation, two ignition points were located at the lee corners of the treatment units to form symmetric fire growth patterns and to meet the assumptions that the fire is growing steadily among the units.

## Results

By relating the dimensions of the treatment units ( $L$  and  $W$ ) to their juxtaposition on the landscape ( $S$  and  $O$ ), the concept of fuel treatments is expanded topologically to address arrangement and efficiency of treatment area. It links the effect of one treatment to its neighbors through the dimensions of fire shape and spread rate. Thus, for a specified amount or fraction of treatment area and fire dimensions, there will be an arrangement of identical fuel treatment units that satisfies the above conditions for unit shape, separation, and overlap and produces the maximum spread rate reduction for the area treated.

These relationships permit a depiction of tradeoffs between intensive and extensive treatment strategies (Figure 8). As the relative spread rate due to treatment ( $r_i/r_m$ ) decreases, the fraction of the landscape requiring treatment decreases (at a given spread rate  $h_1$  through the pattern). For example, at a constant  $S$  for a fire with a length to breadth ratio of 2.0, an effective spread rate of 60% of the untreated condition could be achieved by treating 20%, 10%, or 7% of the landscape depending on spread rate in the treatments of 1/5th, 1/10th, or 1/20th of the matrix. A comparison of spread rates for a constant treatment level, say 20% of the landscape, reveals effective spread rates of 60%, 40%, and 25% of the untreated condition depending on the relative spread rate in the treated areas.

The treatment patterns tested with *FARSITE* simulations each had about 19% of the area treated and produced spread rates that were consistent with Equations (1) and (15) with  $r_i/r_m = 0.1$  (Figure 9). Spread rate maps from the simulations



**Figure 8. Relative fire spread rate in relation to the fraction of landscape treated for fires with a length to breadth ratio of 2.0. Three levels of treatment are defined by the spread rate in the treatment ( $r_t$ ) relative to the matrix ( $r_m$ ). Thick lines are the harmonic mean spread rate [ $h$ ; Equation (1)]. Thin lines are the spread rate  $h_1$  [Equation (15)] of the overlapped pattern with variation due to  $S$ . Smaller  $S$  produces lower relative spread rates and treatment fractions. Greater overlap  $O$  increases the treatment fraction and lowers the relative spread rate.**

showed that the partial overlap patterns split the regions of heading spread rates (Figure 9a) into multiple smaller regions (Figure 9c, 9d). The frequency distribution of spread rates or fireline intensities for elliptical fires burning under homogeneous conditions varies by fire shape (Catchpole et al. 1992). The simulations showed that the complete and partial overlap patterns shifted the mode of this spread rate distribution from the right side of the range to the left side of the range (Figure 10). These slower spread rates occurred directly within the treated areas and in the matrix fuels between the overlapping regions of the treatments where the fire was forced to flank. The overlapping regions occur outside the actual treatment unit as a lee-side effect of the overlap between treatments (Figure 10), meaning reduced spread rates and intensities for more of the landscape than was physically treated.

## Discussion

The analysis presented here showed that there is an ideal pattern of overlapping units that efficiently reduces the aggregated fire spread rate per area treated. Simulations suggested that the spread rates within the burned areas should also be reduced, even outside the treatments, where the fire is forced to flank around the units within the regions of overlap  $O$ . This implies that fire effects on a landscape basis such as crown scorch and tree mortality which depend on fireline intensity could be ameliorated by these patterns to a greater extent than the immediate areas receiving treatment. Fireline intensity is proportional to spread rate for a given fuel type (Byram 1959). Furthermore, the overlapping treatment patterns would fragment the most extreme fire effects into smaller patches because the heading fire is split by the treatment units. To increase the area burned by flanking fire, the amount of overlap  $O$  must be increased, which requires a larger fraction of the landscape to be treated. Further analysis

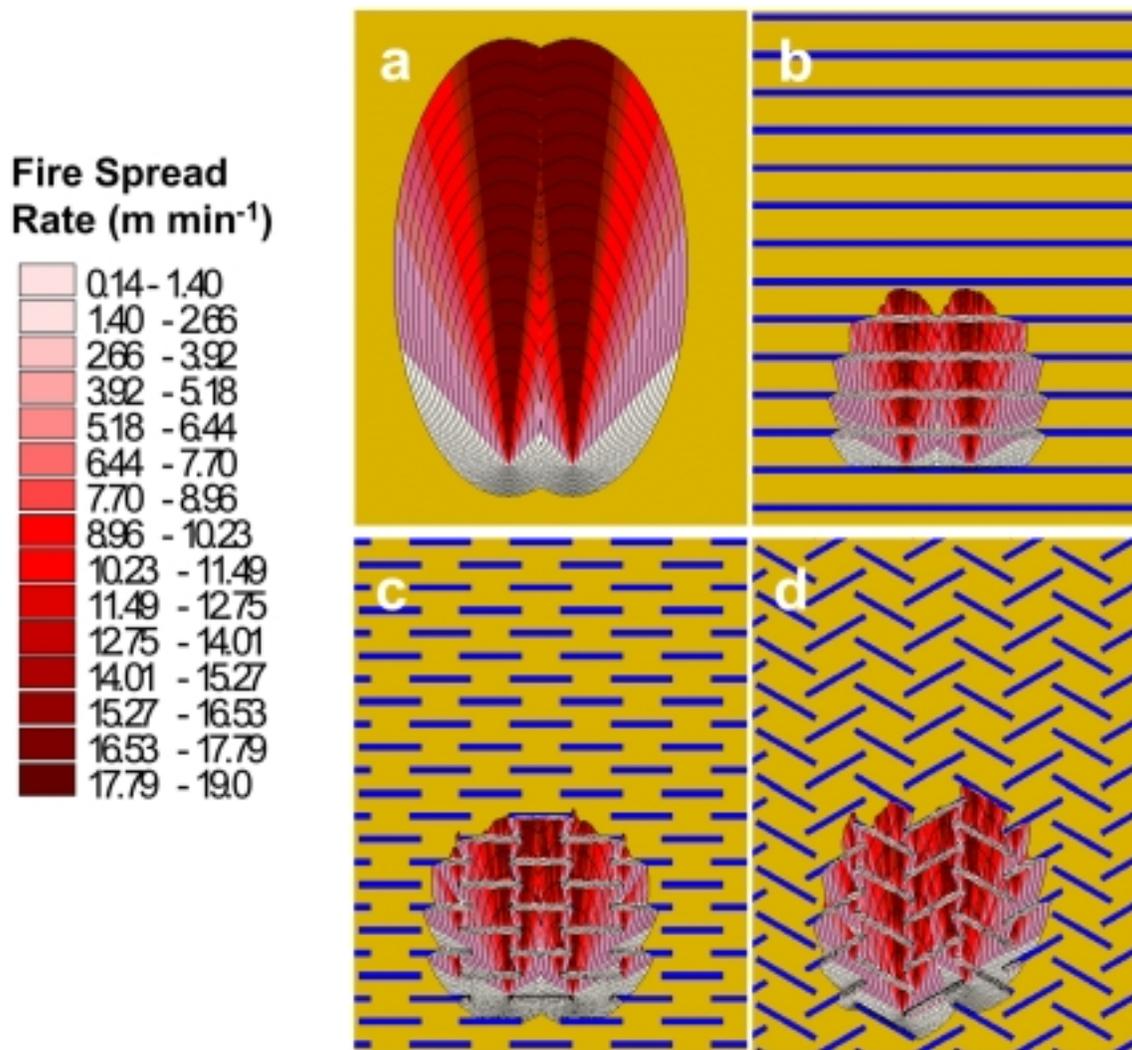
of these patterns may suggest ways to specifically improve these benefits.

The assumptions for this analysis suppose a restrictive set of conditions that are unlikely to be completely met for a given fire or landscape. Treatments in some vegetation types can actually produce increases in fire spread rates over time if burning and harvesting encourage the growth of fine fuels and understory vegetation. Nevertheless, much evidence from natural fire regimes suggests that spread rates after treatment do decrease until fuels accumulate and vegetation regrows. Wildfires burning into treated areas exhibited decreased intensities and spread rates (Helms 1979, Martin et al. 1989) and caused less mortality (Wagle and Eakle 1979, Martin et al. 1989). The patchwork of free-burning fires at Yosemite National Park and Sequoia and Kings Canyon National Parks showed fire slowing and stopping along boundaries of previously burned areas (van Wagtenonk 1995, Parsons and van Wagtenonk 1996). Frequent chaparral fires in Baja California were kept small by the fine-scale pattern of recent burns, but infrequent large fires burned across more homogeneous chaparral landscapes in the United States (Minnich and Chou 1997). Weight of fine dead fuels were found to accumulate to preburn levels within 7 yr of prescribed burning (van Wagtenonk and Sydoriak 1987). Even with faster spread rates, the benefits of fuel management would be seen in reduced fire damage to the forest and improved controllability (i.e., grass fires are easier to control than crown fires in timber types because of lower intensity and reduced spotting).

Spotting was excluded from this analysis but would likely result in large fires, independently of any landscape fuel pattern except wholesale treatment. Assuming that the treatment pattern is extensive, each spot fire would be subjected to the same maze of slow burning treatments that impedes the growth of the main fire. Also, treatments designed to restrict the availability of crown fuels would locally limit the production of new embers from the treated areas, probably reducing spotting. Spotting amidst this kind of treatment pattern would likely produce “intensity shadows” on the lee side of the treatments similar to those observed by (Heinselman 1996) in the Boundary Waters Canoe Area. There, natural lakes disrupted fire growth so that fire reached the windward shores only by spotting; spot fires produced lower intensities until they coalesced and resumed burning as a broad fire front.

Fire suppression was excluded from the analysis but could certainly be expected to benefit from the influences of slower fire growth rate and the frequent presence of treatment units near the fire that both speed line construction and moderate fire behavior. For any fire suppression activity to directly use the treatments, the tactics would need to be adjusted to reflect an awareness of unit locations and their consequences to fire behavior and safety.

Although treatments would not be as visually apparent as illustrated here unless the overstory was heavily thinned, the idealized and artificial treatment patterns would probably never be achievable or even desirable in practice. Management activities on a landscape are typically arranged to satisfy other more compelling needs such as timber harvest volume, water quality,



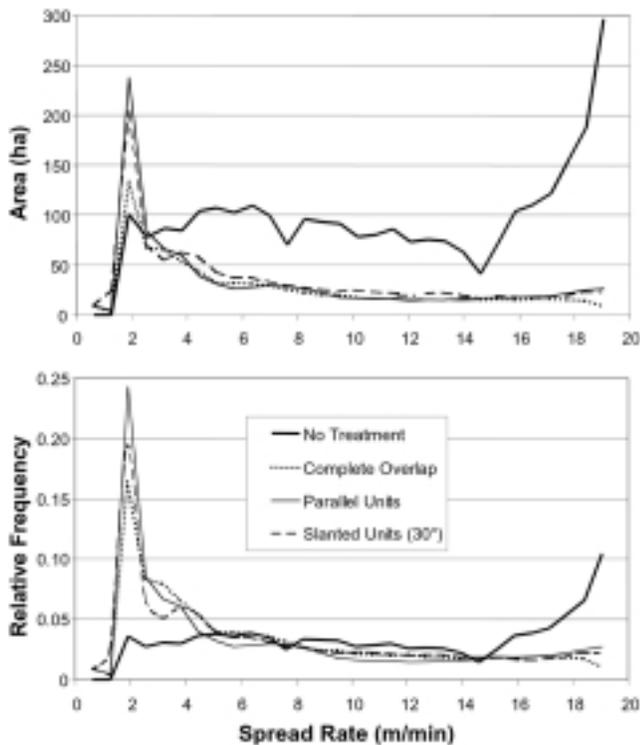
**Figure 9.** Fire growth and spread rate patterns simulated using *FARSITE* with various treatment patterns. The relative spread rate in the treated areas (blue) is 1/10th of that in the matrix (yellow). All treatments occupy about 19% of the area. Homogeneous conditions (a) produce a relative forward spread rate of 1.0 for comparison with (b) complete overlap of treatment strips that produce a harmonic mean  $h$  of 0.41 [Equation (1)], (c) partial overlap with mean spread rate  $h_1$  of 0.43, and (d) slanted partial overlap with harmonic mean  $h_1$  of 0.49. See Figure 10 for distributions of spread rates within the burned areas.

wildlife issues, and so on. However, a number of the relationships developed here have the potential for practical application to strategic planning of landscape-level fuel management programs. It is possible that some of the topological considerations of this analysis could be incorporated into the planning and layout of actual treatments without upsetting the existing priorities. This could produce a value-added modification of wildland fire growth and behavior for little extra effort. The primary considerations are:

- Treatment units need to overlap in an anticipated heading spread direction.
- The pattern should target fires burning under specific weather and fuel moisture conditions because of their characteristic sizes and spread rates under that environment.
- The relationship between separation and overlap must consider the expected fire shape and relative spread rates in the treated areas.

- Separation must be small compared to the fire sizes.
- There is a tradeoff in the amount of treatment and the intensity of the treatment prescription.

The size of the treatment pattern is theoretically scale-independent. That is, the actual sizes of the treatment units (and dimensions  $O$ ,  $S$ ) are only relative to each other. The pattern can thus be adapted to localized spatial constraints and variability across a landscape. In practice, the scale of the pattern could not be coarser than the size of fires for the pattern to have any effect on a real fire. The distance of  $S$  would need to be considerably shorter than the forward dimension of the fire. Coarse patterns with long  $S$  could allow a fire to burn mostly without influence of the treatments (e.g., within the untreated space between treatment units). Pattern dimensions would probably need to be between  $10^1$  and  $10^3$  m to be involved in most fires. The expected spotting distance for the targeted weather conditions would also be an important consideration for unit width ( $W$ ).



**Figure 10.** Spread rate distributions for the different treatment patterns show that the complete, parallel, and slanted overlap patterns all shift the spread rates to the lower part of the range. The distribution is dominated by slower spread rates within the treated area as well as areas outside the treatments burned by flanking ( $r_t/r_m = 0.1$ ,  $LB = 2.0$ ).

The dependency on fire sizes and shapes indicates that the patterns would need to target fires that burn under a specific set of weather conditions. For example, fuel moisture and wind conditions associated with the historical 90th percentile level of fire danger indices (Andrews and Bradshaw 1997) provide information on the relative spread rates in different fuel types and fire shapes. Very often, large fires in a given area are oriented along a particular axis (e.g., generally west to east) determined by the direction of episodic wind events, like cold fronts. Fires burning under more mild weather conditions are less affected by the spatial treatment pattern because fires are smaller, and because the relative spread rates in the treated and untreated fuels become more similar as burning conditions moderate. The pattern of fuel treatments would have less utility to suppression under moderate conditions because suppression efforts are already effective, and under “worst case” conditions because suppression efforts are largely ineffective anyway. Individual treatment units would be expected to mitigate fire effects within the units under a broad range of weather.

The uncertainty and variability in burning conditions associated with a fire or fire weather suggests that some dimensions of the treatment pattern would probably need to be larger to afford greater latitude in effectiveness than determined strictly by the theory. The sensitivity analysis [Figure (6)] suggests that overall spread rate ( $h_1$ ) is not penalized by increasing the overlap of the treatment units. Although larger area must be treated, larger overlap pro-

vides some buffer against the variability in fire shape and changing wind direction. Treatment width would also need to account for anticipated changes in fuel structure of treated areas over time.

The effects of fuel treatments on fire behavior are only temporary. More research is needed on fuel accumulation and long-term changes in fuel-bed structure. This will influence the longevity of individual treatments that would dictate both the schedule for creating the initial pattern and the cycle of maintaining existing units. It would also determine the scheduling of new patches that could be inserted into an existing pattern. The problem of how to maintain the topology of a landscape-level effect on fire as fuel patches age across both space and time is very challenging. Perhaps some pattern can be devised that accounts for the temporal changes in local spread rates by adjusting both the treatment dimensions and the timing and location of new treatments within the pattern.

This analysis was developed for the simplest of conditions, namely having only two fuel types and a single wind direction. However, because the above relationships are essentially scale independent, they should also apply to heterogeneous conditions where spread rates and maximum spread directions all vary. This will be the subject of continuing work but might be approached by reducing the complexity of the landscape to several maps. The main maps would need to be horizontal fire spread rate in the direction of interest, elliptical dimensions of the fire, and direction of maximum spread. Areas with homogeneous characteristics (within some tolerance) can then be delineated and analyzed separately. Some modification of the existing equations would then be needed to dimension the pattern along the boundaries of homogeneous areas. Understanding the role that treatment unit size, shape, and placement play in modifying fire growth and behavior will allow managers to employ fuel treatments in an efficient and effective manner.

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