SPATIAL PATTERNS OF FUEL TREATMENTS AND SOME EFFECTS OF FIRE GROWTH AND BEHAVIOR

Mark A. Finney
Systems for Environmental Management
PO BOX 8868, Missoula, MT 59801
Phone: (406) 329-4832
E-mail: mfinney@montana.com

ABSTRACT

Patterns of disconnected fuel treatment patches that produce overlaps 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. The topology of these patterns has implications for designing landscape-level fuel treatment patterns and for understanding spatial dynamics of fuel patterns across landscapes.

INTRODUCTION

The goal of fuel management is to preemptively modify wildfire behavior through changes to the fuel complex. These changes, referred to generally as fuel treatments, can help limit wildfire sizes and severity directly by mitigating fire behavior, and indirectly by facilitating suppression. Prescribed burning and mechanical methods can lower fire spread rates and intensities within the treated area (Van Wagtendonk 1996, Weatherspoon and Skinner 1996), at least until fuels and vegetation re-accumulate. Fireline construction and can be faster and more effective (fewer escapes) when heavy accumulations of brush and logs are removed and spotting from torching trees is limited.

Treating fuels across an entire landscape is often impossible, however. Limited funding, inadequate road access, variable land ownership, and regulations often restrict the amount of 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; they don't 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, is it logical to wonder 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. A spatial arrangement used for containing fires has involved the use of linear fuel breaks. Fuel breaks are intended to reinforce defensible locations and facilitate suppression action by indirect tactics and backfiring (Green 1977, Omi 1996, Agee *et al*. 1999). Undesirable fire effects are limited by reducing fire sizes; the fuel breaks themselves are only burned along the zone of suppression, not by the wildfire. By contrast, a spatial arrangement of treatments that primarily modifies fire behavior would involve area-based or dispersed patterns. Fire effects and behaviors are modified wherever the fire encounters the treatment units. These facilitate suppression by allowing any tactic (direct, indirect, or parallel attacks) to adapt to changes in collective fire behavior.

For the "fire modification" strategy, it is clear that treatment units would achieve the greatest reduction in fire size and severity if they limited 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. These behaviors also make suppression more difficult.

To disrupt the spread of the heading fire, there are three basic geometric treatment patterns offering varying degrees of interception: complete, none, or partial (Figure 1). The case of complete interception, or overlap by multiple treatments, (Figure 1a) has the effect of producing a harmonic mean spread rate among multiple fuel types (Fujioka 1985, Martin 1987):

$$h = \frac{1}{f_1/r_1 + f_2/r_2} \qquad [1]$$

where f_i is the fractional distance with a given spread rate r_i. Here the effective heading spread rate is proportional to the time spent in each fuel type; the fire must spread through the treatment strips normal 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 treat-

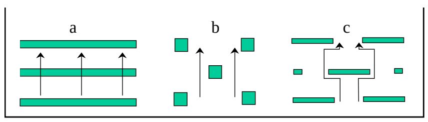


Figure 1. Three basic fuel treatment patterns characterized by a) complete overlap in the heading direction, b) no overlap, and c) partial overlap. The arrows show the path of fire travel.

ments 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 juxtaposition to other units will strongly affect fire growth. Consequently, this topology will be of general relevance to heterogeneous landscapes where fire is forced to progress across and around multiple fuel types. It is the subject of the following analysis.

ANALYSIS

Fire shapes form the basis for analyzing how flanking and heading spread affects 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, Alexander 1985, Anderson 1983). The simple ellipse is the most common shape used, and its dimensions depend on wind and slope (Alexander 1985). Its shape (Figure 2) is described in rectangular coordinates by spread rate components (a, b, c) for the dimensions of length and breadth, (LB) $(0 \leq \theta \leq 2\pi)$:

$$x = a \sin\theta \qquad [2]$$

$$y = b \cos\theta + c \qquad [3]$$

The heading spread rate r is the sum $b+c$. The dimensions are parallel to the ground slope. Stronger winds and steeper slopes produce more eccentric fire shapes (Figure 2). The spread rates and intensities round the

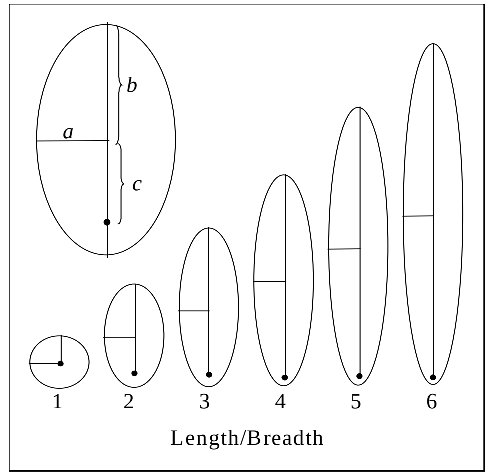


Figure 2. Elliptical fire shapes are described by Length/Breadth and by spread rate dimensions *a*, *b*, and *c*.

fire edge, and their distributions within the burned area, depend on fire shape (Catchpole *et al.* 1992, Catchpole *et al.* 1992). 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 would 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 recovering after prescribed fire and mechanical treatment; burning reduces fire spread and intensity, and thinning can limit the potential for fast-spreading crown fires. The analysis also assumed no spotting or acceleration of the fire when spreading between fuel types.

Shape of a Single Treatment Unit

A single treatment unit that reduces spread rate most efficiently for the amount of area treated will just be burned completely as the fire exits or 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); 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:

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

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.

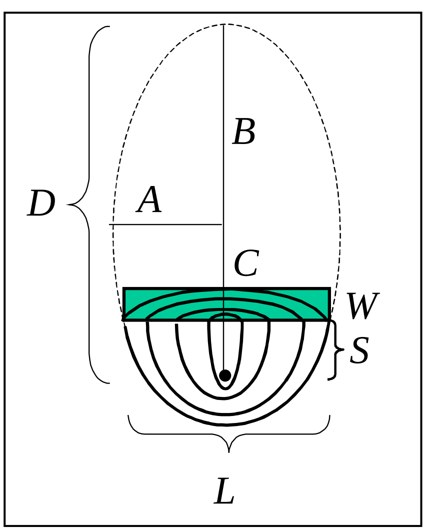


Figure 3. Treatment unit dimensions *W* and *L* are a function of fire shape and spread rates according to equations [4][5][6][7][8].

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 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, maintaining a distance *W* ahead of the fires that flanked around each side (Figure 4a).

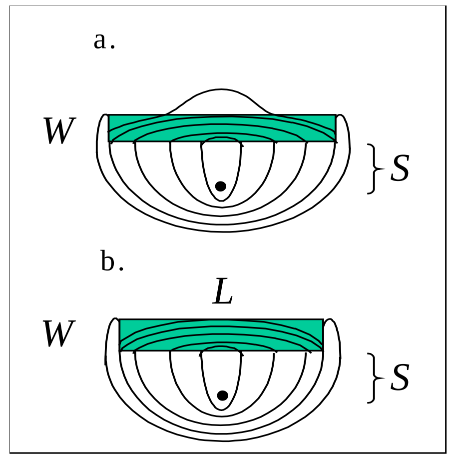


Figure 4. Fire spread rates through and around treatment units will be (a) different using equation [8] or (b) equal with equation [9].

This translates to an effectively greater spread rate through the units than around them. So, to equalize the heading spread rate through the unit with the combined flanking and heading spread around it, equation [8] is modified to reduce the influence of *W* on *L/2* in equation [4]:

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

This synchronizes the fire exiting the lee of the unit with the fire advancing to the same forward position around the ends (Figure 4b). Together equations [4-7 and 9] now 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 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 equation [9] can be extended to address fire spread through a repeating regular pattern of identical rectangular units across a landscape (*e.g.* the partial overlap pattern). Assuming that the fire burns steadily across the landscape 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). Equation [4] then relates only to the portion of the treatment unit causing the fire to flank (*e.g.* the overlap *O*) not *L/2*. Also, the ignition point, as it affects fire growth and shape between the units, is effectively located at the leeward corner of the previous unit (Figure 5). Lateral spread before this point, and in the direction of the overlap, is essentially excluded by the edge of the unit; fire flanks into the unit but its progress is overtaken by fire flanking through the matrix after reaching the "ignition point" and becomes irrelevant. Once embedded in a repeating pattern, the width of

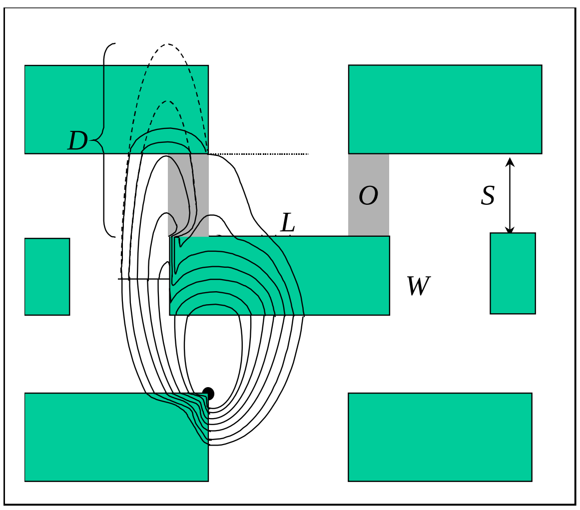


Figure 5. Embedding a single treatment unit in a pattern of identical units requires a reduction in *O* by ½ relative to *W* (equation [10]). *W* now delays fire growth during flanking around 2 sides of the unit. Dashed lines indicate the hypothetical forward spread distance *D* with no treatment.

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* only needs to be half that described by equation [9] to produce the maximum delay of the fire:

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

With this modification, equation [4] can be relabeled to more properly equate to overlap *O* instead of *L/2*:

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

Equations [5, 6, 7, 10, 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*:

$$W = 2(D - S)\Big/\left(\frac{r_m}{r_t} - 1\right) \qquad [12]$$

but requires iteration to estimate *D*. Because *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, *D* can be estimated as:

$$D = O\frac{r_m}{a\sin\theta} \qquad [13]$$

where

$$0 < \theta \le \pi \quad \Big| \quad \frac{O}{S} = \frac{a\sin\theta}{c + b\cos\theta} \qquad [14]$$

Together, equations [5, 6, 7, 10, 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 effective 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):

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

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

$$h_2 = \frac{S + W}{S/r_m + W/r_t} \qquad [16]$$

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

$$T = \frac{LW}{2(L-O)(S+W)} \qquad [17]$$

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. This reinforces the interpretation that the harmonic mean (Fujioka 1985, Martin 1987) assumes fire spreads only in a single direction. The proportions used in equation [1] are non-spatial, referring to both area and distance fractions of each fuel type.

It is clear that the separation distance S is critical to 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 above, S affects
β the treatment fraction (of the total landscape) as well as the directions that gaps between the treatment units align to make the pattern porous. With a constant L, a larger S narrows the directional range that the pattern blocks heading fire spread. 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:

$$\alpha = \tan^{-1}\left(\frac{S}{n(L-O)}\right) \qquad [18]$$

where n is any odd integer. Heading spread is blocked by the pattern for fires moving at intervening angles (when n is even) and when

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

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 still maintaining the reduction in effective spread rate in a single heading direction according to equations [10]-[13]. The modification involves slanting the treatments by row, like louvered window blinds, in alternating directions by an angle β. If L is lengthened so that the corners of the rectangular treatment units remain perpendicular to the slant angle and the lateral dimension of the treatments stays equal to L (Figure 6):

$$L' = \frac{L}{\cos\beta} - W' \sin\beta \qquad [20]$$

the values of O and S remain effectively the same (Figure 6). W must be reduced to compensate for the in-

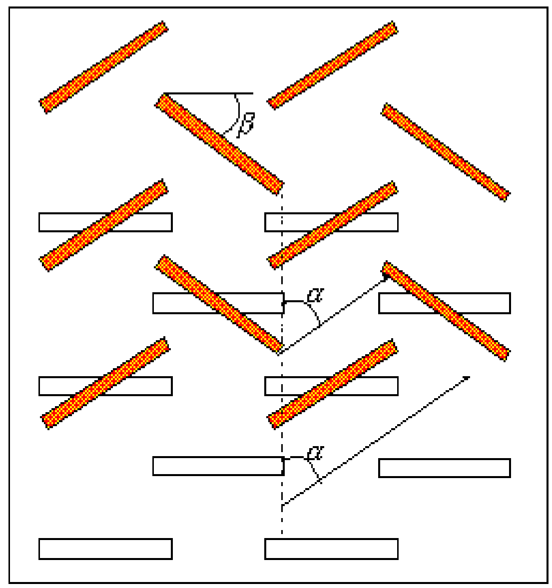


Figure 6. The parallel treatment pattern (open rectangles) can be louvered at an angle β to block porous angles α through the pattern (shaded rectangles). The same O and S can be maintained by increasing L and reducing W (equations [20] and [21]).

crease in thickness of the slanted unit in the forward direction and the slower spread rate of the fire edge that contacts the slanted treatment:

$$W' = W\left(1 - \frac{(r_m - r'_m)\sin\beta}{r_m}\right) \qquad [21]$$

where is the fire spread rate in the matrix at a point on an elliptical front facing angle away from the head of the fire (Catchpole et al. 1982):

$$r'_m = a\cos\beta + \sqrt{b^2\cos^2\beta + a^2\sin^2\beta} \qquad [22]$$

As long as $S<L$, it will be possible to block the porous angles by slanting the pattern alternately at some β The porosity of the pattern at:

$$\alpha = \pi/2$$

becomes completely blocked when:

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

The steeper slant angles requires a larger treatment fraction (T') of the pattern for a given ratio of untreated and treated spread rates because treatment units must be longer. However, as O increases, L' eventually decreases because of the contribution to L by W' in equation [20] (Figure 7).

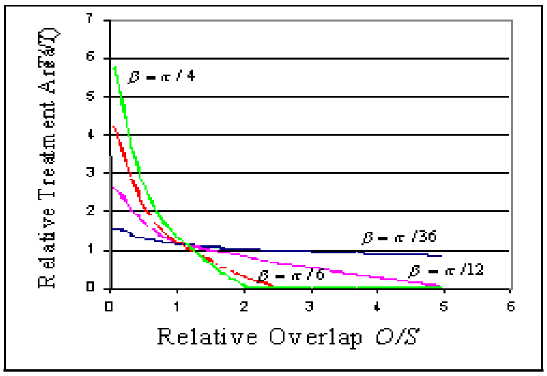


Figure 7. Treatment area of slanted units relative to parallel units depends on the amount of overlap. The slanted pattern requires less treatment area as overlap increases, and even less than the parallel arrangement where *T'*/*T* < 1.0.

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.

These relationships permit a depiction of tradeoffs between intensive and extensive treatment strategies (Figure 8). As the relative spread rate due to treatment decreases, the fraction of the landscape requiring treatment decreases (at a given spread rate through the pattern). For example, at a constant S for a fire with L/B=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.

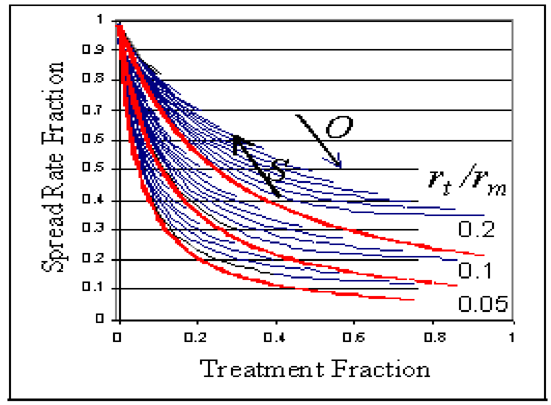


Figure 8. Relative fire spread rate in relation to the fraction of landscape treated for fires with a *LB* ratio of 2.0. Three levels of treatment are defined by the relative spread rate in the matrix (r_m) and treatment (r_t). Thick lines are the harmonic mean spread rate (*h*: equation [1]). Thin lines 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.

Another consequence of the fuel treatment pattern is that it changes the distribution of spread rates within the burned area. An elliptical fire burning under homogenous conditions produces a spread rate or fireline intensity distribution (kW m^{-1}) that varies by fire shape (Catchpole et al. 1993). Spread rate distributions were compared from *FARSITE* (Finney 1998) simulations of fire growth for the various fuel patterns. The *FARSITE* model (Finney 1998) simulates fire growth for complex conditions of terrain fuels and weather. These simulations were simplified to maintain constant weather, fuel moistures, and wind direction with the only variation coming from fuel patterns and structure. The simulation assumes a perfect elliptical fire under uniform conditions and was therefore suited to testing the relationships developed here. For each simulation, two simultaneous ignition points were located at the corners of the treatment units. The simulations produced different forward spread rates for the treatment patterns that were consistent with equations [1] and [15] with r_t/r_m=0.1 (Figure 9). Additionally the complete and partial overlap patterns shifted the modes of the spread rate distributions to the lower 1/3rd of the spread rate range. The smaller mode in the spread rate distribution was caused directly by the slower spread within the treated areas (Figure 10). However, peak concentration of spread rates was caused by the fire flanking within the overlapping region of the matrix. These regions occur outside the actual treatment unit as a lee-side effect of the overlap between treatments (Figure 9). This suggests that a pattern might exist that specifically improves these properties of the spread rate distribution.

DISCUSSION

This analysis showed that there is an ideal pattern of overlapping units that efficiently reduces fire spread rate per area treated. The assumptions 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 increase fire spread rates if burning and harvesting encourage the growth of understory vegetation.

However, much evidence suggests that spread rates after treatment are decreased until fuels accumulate and vegetation re-grows. The patchwork of free-burning fires at Yosemite and Sequoia National Parks shows fire slowing and stopping along boundaries of previously burned areas (Van Wagtendonk 1985, Parsons and Van Wagtendonk 1996). Frequent chaparral fires in Baja California are kept small by the fine-scale pattern of recent burns, but infrequent large fires burn across more homogeneous chaparral landscapes in the U. S. (Minnich and Chou 1997). Weight of fine dead fuels accumulated to preburn-levels within 7 years of prescribed burning (Van Wagtendonk 1985). Even with faster spread rates, the benefits of fuel management would be seen in reduced fire damage to the forest and improved controllability of fire (*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 cause 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 resulting in a reduced amount of spotting.

Fire suppression was assumed absent 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.

The idealized and artificial pattern used in this analysis would almost 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, wildlife issues etc. 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 wildfire growth and behavior for little extra effort. The primary considerations are:

- Treatment units need some overlap in an anticipated heading spread direction,
- The pattern should target fires burning under specific conditions (*i.e.* 90th percentile) because of their characteristic sizes and spread rates,
- 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 size of the treatment units (and dimensions *O*, *S*) are only relative to each other. The pattern is thus widely adaptable 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 size of *S* would need to be considerably shorter than the forward dimension of the fire. Coarse patterns with long *S* would allow most of the fire to burn without influence of the treatments (i.e. within the spaces of untreated fuels). Pattern dimensions would probably need to be between 10^1 and 10^3 meters to be involved in most fires.

Figure 9.

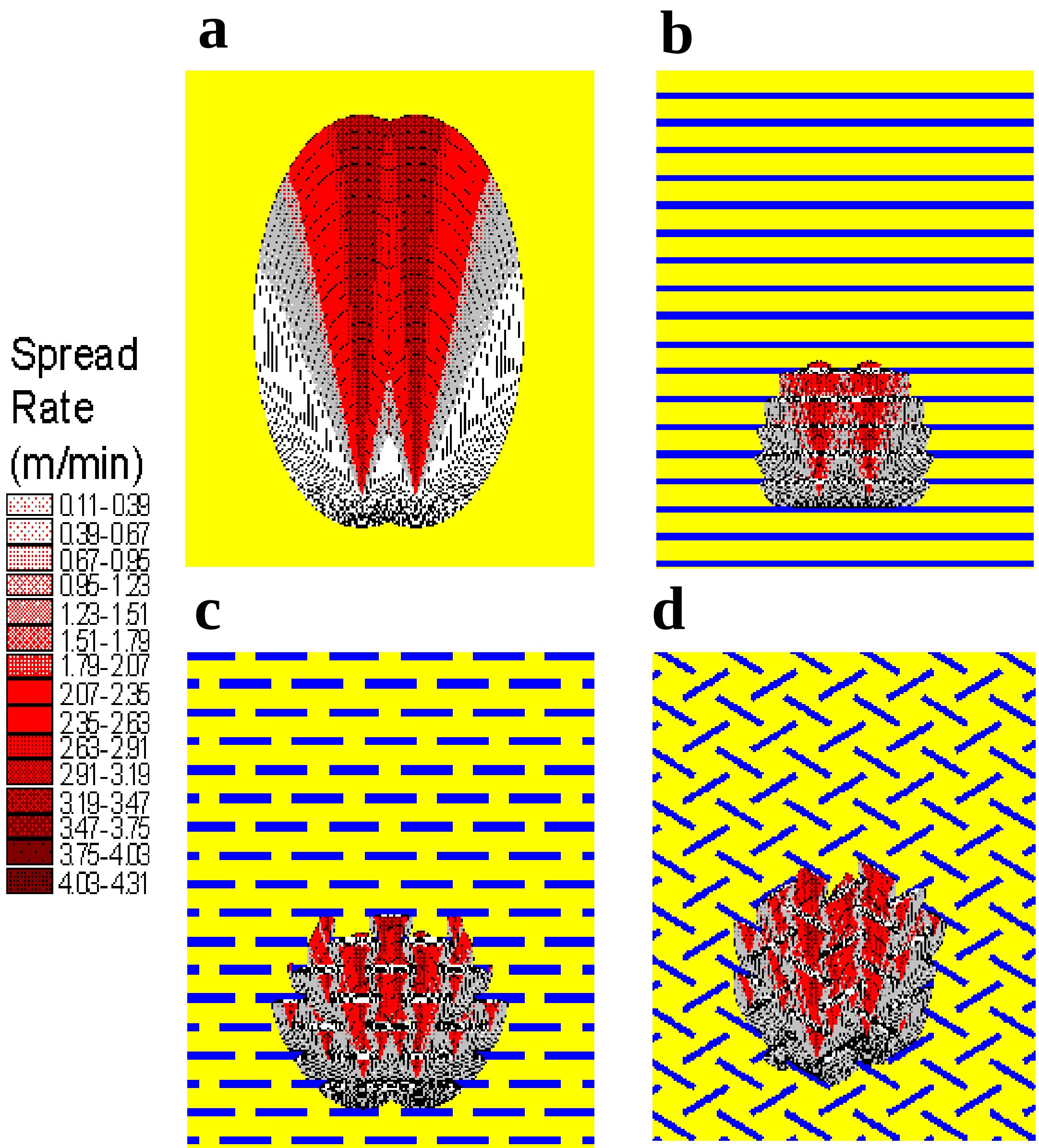
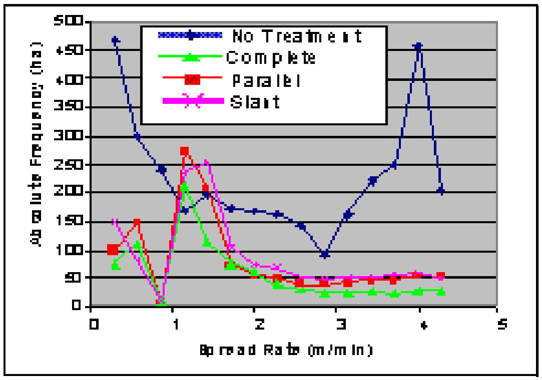


Figure 9. Fire growth and spread rate patterns simulated using *FARSITE* with various fuel treatment patterns. The relative spread rate in the treated areas (blue) is 1/5 of that in the matrix (yellow). Two ignition points were needed to meet the assumptions of fire growing steadily among the overlapping treatment units. Homogeneous conditions (a) produce a relative forward spread rate of 1.0 for comparison with (b) complete overlap of treatment strips that produce the harmonic mean of 0.36 (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 0.46. Theoretically, there should be no difference in forward spread rate between (c) and (d). The difference is probably produced by imprecision of empirical measurements compared to the analytical solution (equation [15]); the forward progress of the fire at any particular time is dependent on where the fire is relative to the treatment units. See Figure 10 for distributions of spread rate within the burned area.

The dependency on fire sizes and shapes indicates that the patterns would need to target fires that burn under a specific range of weather conditions (*i.e.* historical 90th percentile). These conditions provide information on the primary spread direction, fire shapes, and



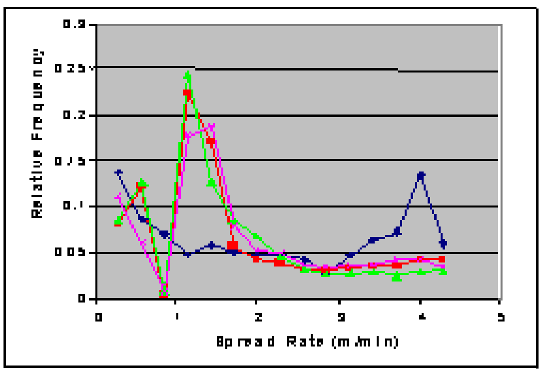


Figure 10. Spread rate distributions for the different treatment patterns show that the complete, partial, and slant overlap patterns all shift the mode of the spread rate distributions to the lower 1/3 of the range. This is caused by the increased flanking spread within the fire area. The smaller peak (~0.5 m/min) is produced the fire within the treated units. (r_t/r_m=0.1, LB=2.0).

estimates of relative spread rates. Very often, large fires in a given area are oriented along a particular axis 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 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 which 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.

Application to Heterogeneous Landscapes

It is obvious that this analysis was developed for the simplest of conditions, namely having only two fuel types and a single wind direction. 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 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.

ACKNOWLEDGMENTS

This research was supported by the USDA For. Serv. Rocky Mountain Research Station, Fire Sciences Laboratory, Fire Effects Research Work Unit, under Research Joint Venture Agreement INT-96095-RJVA. The author thanks Kevin Ryan for his support of this work.

REFERENCES

Agee, J. K, B. Bahro, M. A. Finney, P. N. Omi, D. B. Sapis, C. N. Skinner, J. W. van Wagtendonk, C. P. Weatherspoon. 1999. The use of fuelbreaks in landscape fire management. For. Ecol. Mgt. *In press.*

Alexander, M. E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Pp. 287-304. In: Proc. 8th conf. Fire and forest meteorology.

Anderson, H. E. Predicting wind-driven wildland fire size and shape. USDA For. Serv. Res. Pap. INT-305.

Catchpole, E. A, N. J. DeMestre, and A. M. Gill. 1982. Intensity of fire at its perimeter. Aust. For. Res. 12:47-54.

Catchpole, E. A., M. E. Alexander, and A. M. Gill. 1992. Elliptical-fire perimeter- and area-intensity distributions. Can. J. For. Res. 22:968-972.

Finney, M. A. 1998. *FARSITE*: Fire Area Simulator - Model development and evaluation. USDA For. Serv. Research Paper RMRS-RP-4. 47 p.

Fujioka, F. M. 1985. Estimating wildland fire rate of spread in a spatially non-uniform environment. For. Sci. 31(3):21-29.

Green, L. R. 1977. Fuelbreaks and other fuel modification for wildland fire control. USDA Agr. Hdbk. 499.

Martin, R. E. 1988. Rate of spread calculation for two fuels. West. J. Appl. For. 3(2):54-55.

Minnich, R. A. and Y. H. Chou. 1997. Wildland fire patch dynamics in the chaparral of southern California and northern Baja California. Intl. J. Wildl. Fire. 7:221-248.

Omi, P. N. 1996. The role of fuelbreaks. Proc. 17th Forest vegetation management conference, Redding. CA. Pp 89-96.

Parsons, D. J. and J. W. van Wagtendonk. 1996. Fire research and management in the Sierra Nevada. Chap. 3. In Halvorson, W. L. and G. E. Davis (eds) Science and ecosystem management in the National Parks. Univ. Ariz. Press., Tucson.

Van Wagner, C. E. 1969. A simple fire growth model. For. Chron. 45:103-104.

Van Wagtendonk, J. W. 1985. Fire suppression effects on fuels and succession in short fire interval wilderness ecosystems. In: Lotan, J. E. et al. (eds). Proc. – symp. and workshop on wilderness fire. USDA For.Serv. Gen. Tech. Rep. INT-182. pp 119-126.

Van Wagtendonk, J. W. 1995. Large fires in wilderness areas. In: Brown, J. K., R. W. Mutch, C. W. Spoon, and R. H. Wakimoto. Tech. Coords. 1995. Proc: symp. on fire in wilderness and park management. USDA For. Serv. Gen. Tech. Rep. INT-GTR-320. pp 113-116.

Van Wagtendonk, J. W. and C. A. Sydoriak. 1987. Fuel accumulation rates after prescribed fires in Yosemite National Park. Ninth Conf on fire and forest meteorology, San Diego CA. Am. Met. Soc. Pp 101-105.

Van Wagtendonk, J. W. 1996. Use of a deterministic fire growth model to test fuel treatments. Chap. 43 in Sierra Nevada Ecosystem Project: Final report to Congress, vol. II. Assessments and scientific basis for management options. Davis: Univ. Cal. Center for Water and Wildland Resources. Pp 1155-1165.

Weatherspoon, C. P. and C. N. Skinner. 1996. Landscape-level strategies for forest fuel management. In: Sierra Nevada Ecosystem Project: Final report to Congres, Vol II. Assessments and scientific basis for management options. Univ. Cal. Davis, Centers for Water and Wildland Resources. p1471-1492.