CSIRO PUBLISHING

International Journal of Wildland Fire, 2007, **16**, 702–711 www.publish.csiro.au/journals/ijwf

A computational method for optimising fuel treatment locations

Mark A. Finney

USDA Forest Service, Missoula Fire Sciences Laboratory, PO Box 8089, Missoula, MT 59808, USA. Email: mfinney@fs.fed.us

Abstract. Modelling and experiments have suggested that spatial fuel treatment patterns can influence the movement of large fires. On simple theoretical landscapes consisting of two fuel types (treated and untreated), optimal patterns can be analytically derived that disrupt fire growth efficiently (i.e. with less area treated than random patterns). Although conceptually simple, the application of these theories to actual landscapes is made difficult by heterogeneity (fuels, weather, and topography). Here a computational method is described for heterogeneous landscapes that identifies efficient fuel treatment units and patterns for a selected fire weather scenario. The method requires input of two sets of spatial input data: (1) the current fuel conditions; and (2) the potential fuel conditions after a treatment is conducted (if treatment is permitted in a particular location). The contrast in fire spread rate between the two landscapes under the weather scenario conditions indicates where treatments are effective at delaying the growth of fires. Fire growth from the upwind edge of the landscape is then computed using a minimum travel time algorithm. This identifies major fire travel routes (areas needing treatment) and their intersections with the areas where treatments occurred and reduced the spread rate (opportunity for treatment). These zones of treatment 'need and opportunity' are iteratively delineated by contiguous patches of raster cells up to a user-supplied constraint on percentage of land area to be treated. This algorithm is demonstrated for simple and for complex landscapes.

Additional keywords: fire modelling, prescribed burning.

Introduction

Fuel treatment effects on wildland fire behaviour have long been documented at the stand level (Biswell *et al.* 1973; Helms 1979; Wagle and Eakle 1979; Pollet and Omi 2002; Fernandes and Botelho 2003; Graham 2003). Prescribed burns and thinning operations change fuel structure and have, when applied together, been successful in modifying fire behaviour and consequent effects in the areas treated (Weaver 1943; Kallander *et al.* 1955; Cooper 1961; Martin *et al.* 1989; Graham *et al.* 1999; Graham *et al.* 2004; Schoennagel *et al.* 2004; Agee and Skinner 2005; Cram *et al.* 2006). The landscape level, however, is composed of many stands and mixtures of fuel conditions through which large fires burn, and there has been little work on strategies for treatment at this broad scale. Evidence shows that even widespread treatments that change fire behaviour at the stand-level can be circumvented by larger fires (Salazar and Gonzalez-Caban 1987; Dunn 1989; Finney *et al.* 2005).

Precedence for landscape-level fuel modifications is found in the patchwork or mosaic formed by free-burning fires in large wilderness areas in the western United States. Here, patterns of old burns have been observed to delay and detour later fires (van Wagtendonk 1995; Parsons and van Wagtendonk 1996; Rollins *et al.* 2001). These interactive effects are possible when fire frequency is high enough to maintain some unknown fraction of the landscape in a modified condition. By comparison, intensive fuel treatment methods are expensive and wholesale treatment of large landscapes is impossible for practical reasons including land ownership, conflicting management objectives, and funding. With constraints on the total amount and location of possible treatments, the question of where to place limited treatment efforts becomes a problem suitable for optimisation.

Theoretical work for artificial landscapes has shown optimum efficiency from a pattern of rectangular treatment units that reduces fire growth rates with a minimum of area treated (Finney 2001*a*). Rectangular units that partially overlap in the predominant fire spread direction (determined from historic climatology) allow the fire to move through and around them at the same rate. Fire growth is slowed by the pattern because fire progress is dominated by lateral movement. When small fractions of land are treated, these patterns are efficient compared with random arrangements (Finney 2003; Loehle 2004). Random patterns may require several times as much treatment to reduce fire growth rates to comparable levels (Gill and Bradstock 1998; Bevers *et al.* 2004). Although conceptually simple, the application of these theories to actual landscapes is only just beginning (Hirsch *et al.* 2001) and is made difficult by the heterogeneity of real landscapes (fuels, weather, and topography) compared with the assumptions required for analytical solutions (Finney 2001*b*).

The present paper reports on an algorithm that optimises the placement of treatment units for the purpose of interrupting the movement of large fires. The computational method reported here uses spatial geographic information system (GIS) data to represent the heterogeneity of actual landscapes and produces a map of treatment units that collectively disrupt fire growth. The algorithm is applied to simple and complex landscapes and

10.1071/WF06063 1049-8001/07/060702

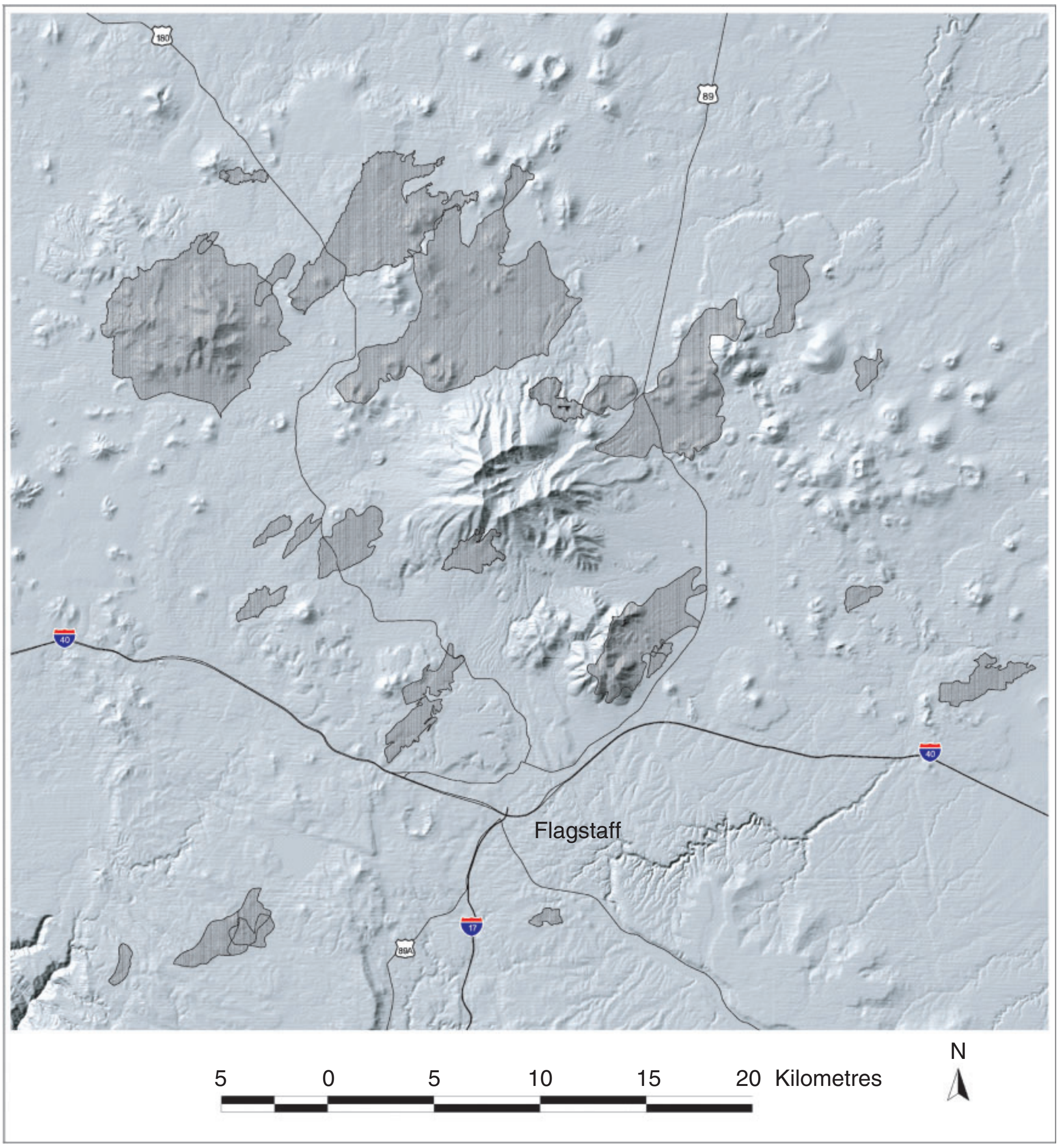

Fig. 1. Fire history atlas around Flagstaff, Arizona, shows large fires are mostly oriented along a south-west–north-east axis. Wind conditions associated with these fires are $\sim$35 mi h^{-1} (56 km h^{-1}) with fuel moistures from 3 to 5%.

shown to produce treatment patterns that reduce fire growth rates comparable to theoretical trends.

Methods

Fire sizes and behaviour

The objective explicitly assumed by the present analysis for landscape fuel management is to delay the growth of large or 'problem' fires. Information on such fires is readily obtained for most wildland areas from local or regional fire history or fire atlases (Fig. 1). The reasoning for this assumption follows from the conditions that foster the growth of such fires in areas dominated by suppression-oriented management in western North America. Here, fires become large by escaping initial attack and then spreading far from where they start. Large fires are resistant to suppression efforts because of the dry and windy weather that contributes to their rapid growth, the sheer size and length of perimeter they present to control, and the fire behaviours produced under the extreme weather conditions permitting their escape (crown fire, spotting). Suppression success typically occurs only when durable changes in the weather abate rapid fire growth. During periods of active spread, such fires are responsible for the greatest damages to watersheds and ecosystems, and present the greatest threats to human developments beyond the borders of the wildlands *per se*. Managing the condition of the landscape and the spatial fuel structure, therefore, offers the only possible means to resist the growth of fires under such conditions, reducing the spread rate and ultimate size of the fires (Brackebusch 1973; Gill and Bradstock 1998). This contrasts with the use of fuel breaks (Green 1977; Weatherspoon and Skinner 1995; Agee *et al*. 2000), which require active fire suppression for benefits to be realised. Fuel is the only element of fire behaviour that is manageable, as weather and topography are beyond human control.

Weather conditions

By targeting large fires for treatment efforts, the analysis of fire behaviour can be restricted to a small subset of weather conditions contributing to the growth of those kinds of fires. Large fires typically occur under the most extreme weather conditions that foster their escape from initial attack efforts. The weather during historic large fires is well known to local fire management officials and can be synthesised from climatological records (Mutch 1998; Rothermel 1998). These weather conditions provide critical data on general fire spread directions (Fig. 1) and spread rates for all fuel types on the landscape and narrow the focus of fuel management efforts to specific ranges of humidity, fuel moisture, and winds. By assuming a single set of specific weather conditions for large fires, fire behaviour can be calculated for all areas of each landscape. Weather factors may vary spatially (i.e. fuel moisture, wind direction, wind speed) but are assumed to represent a single scenario associated with large fires that does not vary in time.

Sizes of fires greater than fuel treatment units

The large size of these fires relative to the size of treatment units also suggests that the starting locations of fires can be ignored for purposes of the analysis. This assumption allows the analysis to focus on the directions of fire movement. Large fires moving across landscapes encounter smaller treatment units with relatively wide fronts that have become largely independent of the exact ignition location. The major direction of fire movement is, however, critical because the rapid spread rates of the heading fire (moving with wind and slope) burn the most acreage with the highest intensities (Catchpole *et al*. 1982). Heading fire is more important to modify than flanking and backing portions of the fire, which have lower intensities and cause less severe fire effects.

Fuel treatments

The fuel treatment optimisation procedure described below depends on fire behaviour contrasts between the two fuel profiles burning under the same target weather conditions: one represents the starting conditions or current state of fuels and forest structure, and the second represents the fuel conditions following treatment (Fig. 2). The assumption here is that desired fuel conditions can be identified on a stand-by-stand basis across the landscape for all stands where treatment is possible. These fuel conditions are represented across a large landscape as a rectangular grid at a fixed resolution. The cells of the grid are assumed uniform at scales finer than the resolution in terms of fuels, topography, and weather. The treated landscape describes the potential areas for treatment that must total more than the specified constraint on total area treatable within the planning horizon. Treatment prescriptions within each stand or cell on a landscape, such as prescribed burning or various stand-level thinning guidelines can be different and thereby reflect local objectives or restrictions on activities. Although any prescription can be applied, field evidence consistently suggests that fuel treatment prescriptions achieve reductions in wildfire spread rate and intensity by removing surface fuels through prescribed burning and decreasing the continuity between surface and canopy fuel strata through ‘low-thinning’ (van Wagtendonk 1996; Pollet and Omi 2002; Agee and Skinner 2005). Mechanical treatments that leave slash or don’t remove pre-existing surface fuels may not change fire behaviour sufficiently (Graham 2003; Raymond and Peterson 2005; Cram *et al*. 2006) or even exacerbate fuel hazards (Alexander and Yancik 1977). Lands that are not available for treatment retain the identical fuel descriptions in both landscapes or involve prescriptions that increase the fire spread rate. Thus, the optimisation will choose from the lands where treatments change fire behaviour to achieve the greatest collective reduction in landscape fire spread rate.

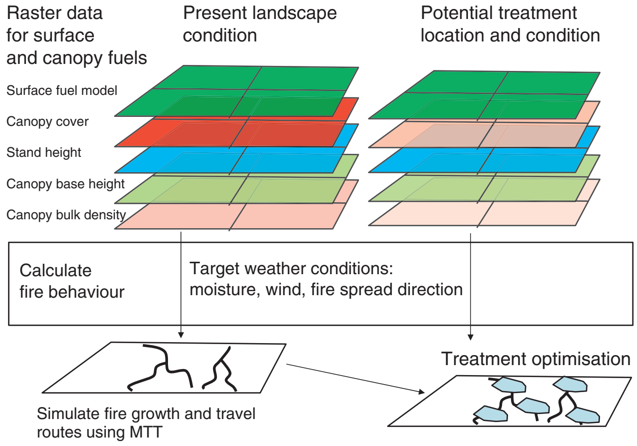

Fig. 2. Two landscape fuel conditions are required for the optimisation algorithm. The first landscape represents the pretreatment or current fuel conditions whereas the second landscape represents the potential treatment conditions (i.e. modifications of fuel strata) everywhere treatments can be potentially located (determined from external criteria, for example land management plans and ownership). Both landscapes are processed to calculate fire behaviour under the ‘target’ weather conditions (i.e. those weather conditions that the treatments are designed for).

Algorithm

The objective of the fuel treatment optimisation is to find the specific treatment areas that reduce fire growth for the target weather conditions by the greatest amount. In other words, the algorithm is designed to maximise the minimum travel time for fire moving across the landscape. With the emphasis on fire travel time, a critical component of this optimisation is a method for calculating fire growth under the target weather conditions. Fire growth simulation using a minimum-travel-time algorithm (Finney 2002*b*) is well suited to this task because it rapidly produces a fire arrival-time field for a given ignition (which can be contoured to visualise fire growth at constant time intervals) and records the travel routes of fire movement from one node to

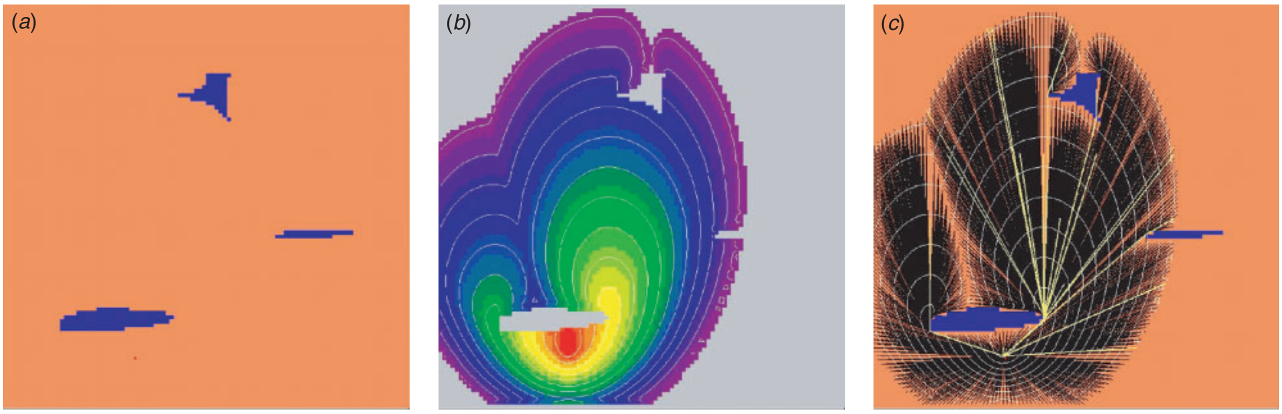

Fig. 3. The fire behaviour simulation uses a minimum travel-time (MTT) algorithm that (*a*) for a simple landscape with several slow-burning fuel patches; (*b*) produces an arrival time map that can be contoured to indicate fire progression; and (*c*) displayed along with fire travel routes that correspond to calculations of 'fire influence' (i.e. the area burned as a result of burning through that grid cell). All travel paths are shown in (*c*) as fine black lines with 'Major' travel paths chosen at specified distance intervals indicated by bold yellow lines.

the next (Fig. 3). Both fire growth contours and travel routes are used by the fuel treatment optimisation.

In optimal regular patterns (Finney 2001*a*), the most efficient treatment unit size depends on overlap and separation of neighbouring treatment units. These dimensions are constant among units because the landscape is assumed to be uniform, and as such, they are difficult to transfer directly to actual landscapes that contain complex variation in fuels, topography, and perhaps weather (wind direction, fuel moisture). The regular patterns don't apply under complex conditions because the size and orientation of a given treatment unit is only efficient in the context of other possible units encountered immediately before and after by fire moving across the landscape. Yet, each unit modifies the path of fire into succeeding units. The simplifying approach used in this algorithm assumes that the delay of fire spread through the unit must be twice the delay in circumventing it. Although this assumption facilitates computations, it will produce solutions that are less efficient than a theoretical optimum where fire spread rates downwind of the treatment unit are substantially different than the upwind conditions.

To accommodate the interaction of fire growth among multiple treatment units, the algorithm begins by dividing the landscape into a series of parallel strips oriented perpendicularly to the main fire spread direction (Fig. 4). The width of these strips regulates the maximum distance dimension of treatment units allowed. The method produces a deterministic solution but is similar to the procedure described by Finney (2002*b*):

1. For each strip, beginning with the upwind strip that received the ignition, fire growth and minimum travel routes are computed (Fig. 4*a*). Concave segments along the fire arrival time contour are identified. These segments are defined as starting and ending with local maximum arrival times and each contain a single local minimum fire arrival time (Fig. 4*b*).
2. Within a given strip, the travel path connected to the minimum arrival time in each segment is identified and followed backwards in time and space to record intersections with areas where fire spread rate is slower in the post-treatment landscape. These travel paths are 'major' paths because they produce shorter arrival times and give rise to many minor paths (Fig. 3). These areas of slower spread rate often represent a subset of the total strip and are shown as shaded regions in Fig. 4*c*.
3. A choice must be made for the best place to start the fuel treatments for each segment. Here, the start location for each segment is chosen to be the cell with the earliest time where fuel treatments are possible (i.e. fire spread rate was slower in the treated landscape (see circles in Fig. 4*c*)). Based on this earliest arrival time, all later arrival times are reset to infinity for all nodes (on the entire landscape).
4. The minimum travel-time algorithm is then rerun for the strip using the post-treatment landscape data (Fig. 4*d*). The calculations are done for the entire strip separately for each segment identified in Step 1 above because the arrival-time contour used as starting point for fuel treatments identified in Step 3 (above) is typically different for each segment. The new arrival time map is stored for each segment and represents the rate of fire growth assuming all fuel treatments have occurred.
5. An iterative procedure identifies and delineates treatment units within the strip that have sizes and shapes for efficiently retarding fire growth. The idea is to find the arrival-time contours that bound a total area (of discrete units) equalling the desired treatment fraction. This procedure identifies a treatment unit as a contiguous group of treatable cells (Fig. 4*e*) along each travel path. A simple contagion algorithm is used to mark an increasing number of treatable adjacent cells subject to the constraint that their arrival times are greater than the starting point but less than or equal to an upper arrival-time limit. By iteration, this upper time-limit is increased until the specified fraction of the landscape strip is treated (among all segments in the strip). At each iteration, the lateral extent of the marked block of treated cells is limited so that the arrival-time difference of fire spread around the left and right sides is ~1/2 the arrival-time difference in the forward direction.

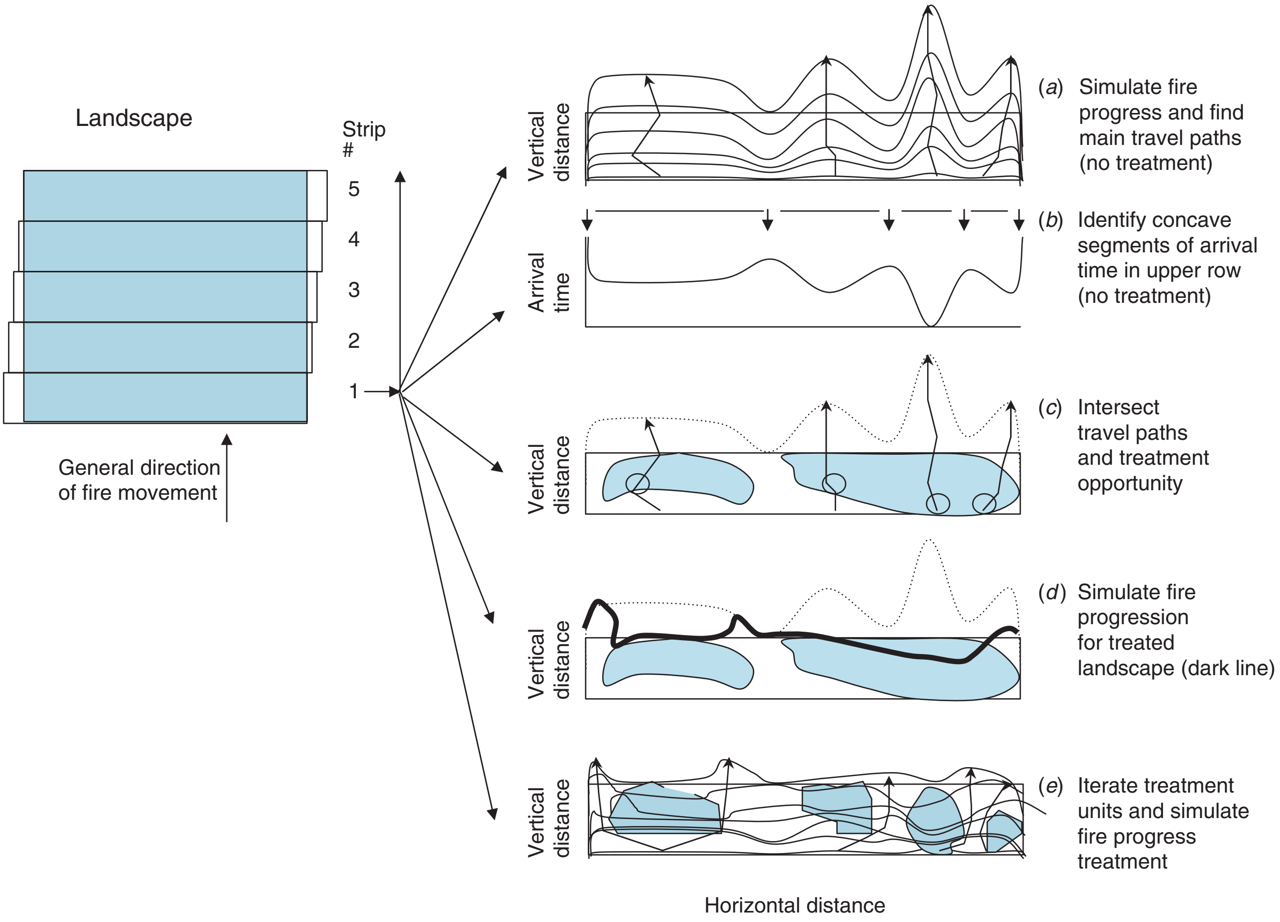

Fig. 4. Optimisation process begins by dividing the landscape into rows. For each row beginning with the row farthest upwind (*a*) fire growth for the pretreatment landscape is calculated using the minimum travel-time (MTT) calculation to identify travel routes and produce an arrival time map; (*b*) the concave segments of arrival time are identified at the ending row; (*c*) intersections of the major fire travel paths and the treatment opportunity are identified (areas where treatments reduce the fire spread rate) and the point with the earliest arrival time of this intersection is recorded; (*d*) fire growth for the potential landscape is calculated from the starting time identified in (*c*); and (*e*) iteration of treatment unit size and shape is performed.

The algorithm assumes that the fire front will have a rippled time contour or 'fingers' at the forward edge produced by varying spread rates that result from fuels, topography, or wind patterns. The algorithm targets fuel treatments to block these fingers as they are local zones of faster spread. For relatively uniform conditions, where little or no variation exists, the algorithm must be modified to place fuel treatments by some other rule. The rule used here within a given strip is a systematic and regular spacing, which produces the ripples at later time periods.

Evaluation of the algorithm

Two kinds of landscapes were used to evaluate the performance of the algorithm. First, an artificial simple landscape with several slow-burning fuel patches was used to test the ability of the algorithm to produce treatment patterns similar to the theoretical patterns described by Finney (2001*a*) and illustrate the sensitivity to localised non-uniformities in the landscape. In the current paper fuel treatments were implemented to reduce spread rate to 1/20th of the untreated rate. The second landscape was located near Flagstaff, Arizona, in the ponderosa pine forests. The fire regime in this area was historically characterised by short-interval surface fires (Allen *et al.* 2002) but, with continued fire exclusion, crown fires under extreme conditions now dominate. Such wildfires from the past 30 years suggest a predominant SW to NE orientation (Fig. 1) associated with extreme weather conditions. This direction angle was, therefore, used to orient the treatment units for optimisation as discussed above. Fuel moisture for the fire simulations was chosen at 99th percentile of the historic National Fire Danger Rating System (NFDRS) index Energy Release Component (ERC). In this case, fuel model 'G' was used for ranking daily ERC values because it has been found to be strongly related to large fire activity (Andrews *et al.* 2003) and reflects influence of live and dead fuel components. Wind speed and wind directions were chosen to reflect the period of major fire growth associated with the historic large fires (Fig. 1) that have burned in this area. Treatment prescriptions were only applied to ponderosa pine and mixed conifer forest areas in public ownership and consisted of changing surface fuels to fuel model 9 (long-needle conifer litter, Anderson 1982), increasing the crown base height, and decreasing crown bulk density (both

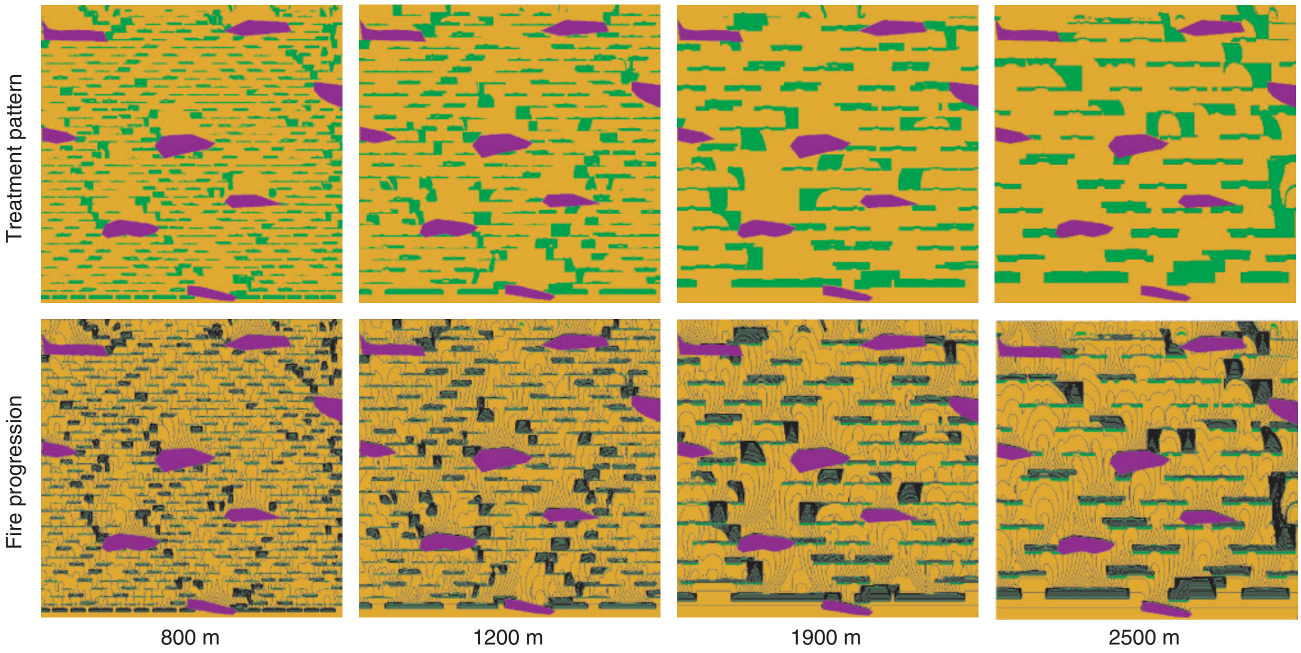

Fig. 5. Optimisation results for 20% treatment on a flat landscape that contains eight small patches of slow-burning fuel (purple) within the matrix of faster-burning fuels. From left to right, the maximum treatment dimension is increased from 800 to 2500 m. The location of treatment units (shown in green) relative to the fire progression contours reveal that treatment units cause repeated disruptions of head fire movement.

making crown fire more difficult). No treatment was permitted in meadows, on privately owned lands, or in a designated USDA Forest Service Wilderness area in the northern part of the area.

The response of the fire behaviour to the various treatment options was measured in terms of average spread rate, relative change in wildfire size, and conditional burn probability. The average conditional burn probability was determined by random fires simulated under the target weather conditions (Finney 2002*a*) for varying amounts of time (resulting in various fire sizes after 360, 720, and 1080 min of spread). This probability is 'conditional' because it represents the probability of burning once a fire becomes large or escapes initial attack, which typically occurs at a rate of less than 2% per year in the USA (Neuenschwander *et al.* 2000; NIFC 2002). Mean fire spread rate was obtained by dividing the linear horizontal distance across the landscape by the average fire travel time to the last row in the landscape.

Results

Treatment optimisation for the simple landscape (Fig. 5) produced partially overlapping patterns similar to those of the analytical model (Finney 2001*a*). Exceptions within this pattern occurred downwind of the slow-burning patches (Fig. 5) because these areas were burned only by flanking and backing spread; the algorithm will place treatments only to block major travel paths associated with heading spread. Varying the sizes of treatment units had little effect on the patterns for the simple landscape (Fig. 5) or the effects of treatment on average spread rate, conditional burn probability, and relative fire size (Fig. 6). In fact, all fire response variables (average fire spread rate, fire sizes and conditional burn probability) produced nearly identical trends (Fig. 6) and were more efficient than random fuel arrangements (Fig. 6*a*). Conditional burn probabilities were higher when larger fire sizes were simulated but responded the same across the range of treatment percentages (Fig. 6*b*, *c*).

The optimal patterns for the Flagstaff landscape were less systematic than the patterns on the real landscape (Fig. 7) and were strongly influenced by areas where treatment was precluded by ownership (private property and designated wilderness) or vegetation type (i.e. meadows represented by grass fuel model 1, Anderson 1982). The optimal pattern was more efficient at all levels of treatment than the random pattern (Fig. 8*a*). However, the presence of untreatable area interspersed among the forests provided conduits for rapid fire spread and decreased the efficiency of the optimal pattern in retarding overall fire growth compared with random patterns as seen in the simple landscape and theoretical comparisons (Fig. 8*a*). As with the simple landscapes, the relative fire sizes and conditional burn probability decreased with amount of treatment (Fig. 8*b*, *c*).

Discussion

The present study showed that an optimisation algorithm produced treatment patterns on simple landscapes with impacts on spread rate similar to the analytical solutions for similar landscapes (Finney 2001*a*). This is encouraging for interpretations of algorithm performance on complex landscapes that cannot be directly assessed relative to theoretical results. But relative performance of optimal patterns on both simple and complex landscapes could be assessed in relation to random patterns. This comparison suggested that optimisation efficiently reduced spread in both landscapes but that the presence of untreatable areas within the landscape compromises the efficiency of the

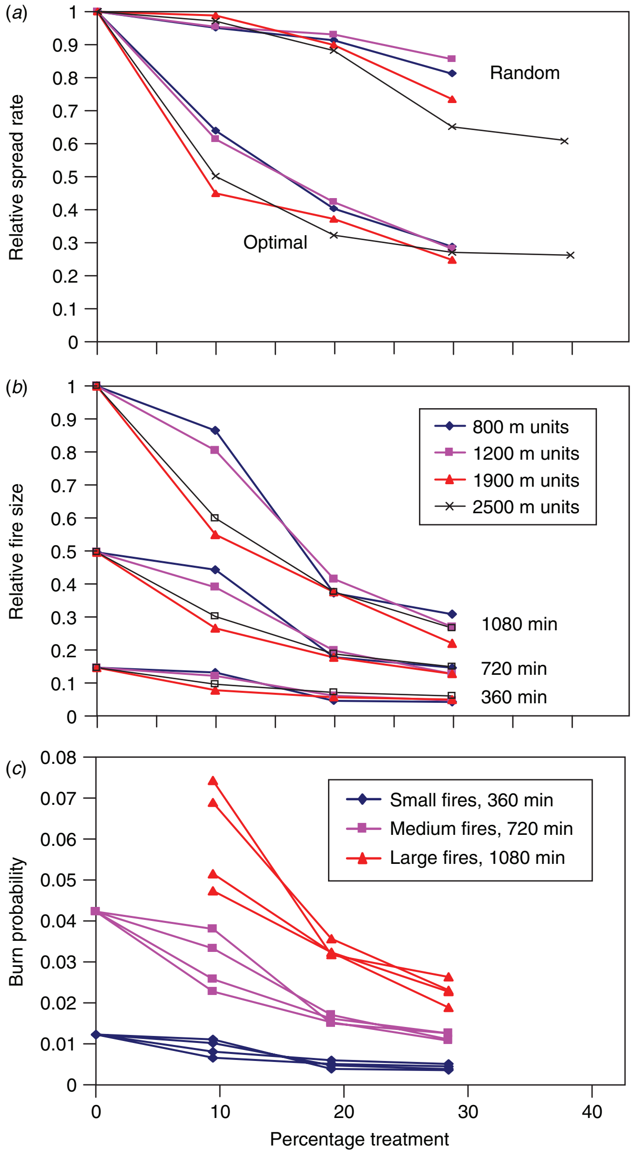

Fig. 6. Summary of optimisation results for simple landscapes over ranges of treatment amount were measured in terms of (*a*) average spread rate across the landscape; (*b*) average fire sizes for 1000 simulated randomly ignited fires of different durations; and (*c*) average burn probability for the landscape determined from 1000 random ignitions.

overall pattern. The relatively poor efficiency of the random patterns in reducing average fire spread rate is also similar to theoretical results (Finney 2003).

The intent of the optimisation was to target treatment locations in areas where fire impact is potentially the greatest, meaning that these areas have greater influence on the area burned downwind. The position of the treatment units relative to the slow-burning patches that existed before treatment (Fig. 5) illustrated how treatment units were positioned to avoid the lee-side wake on the back-side of each of these patches. The major flow paths were located laterally around the left and right flanks of the slow patches and directed the location of the treatment units.

Maximum treatment unit dimension was varied from 800 to 2500 m (∼0.5 to 1.5-mile diameter, or up to 160 to 960 acres (65 ha to 389 ha) if the units were square) in the optimisation but made little difference to the aggregated spread rate, burn probabilities, or the average fire sizes. The flexibility of treatment size would be important to application of treatment units to different landscapes, ecology, topography, and constraints on treatment as illustrated by the Flagstaff example where meadows could not be treated (Fig. 7). Treatment unit sizes also affect the optimal spacing between units and appropriateness for wildfires in different fire regimes. Large fire patterns may permit large treatment units and wide spacing, but smaller fires are theoretically little affected by widely spaced treatment units. The possible enhancement of treatment longevity associated with larger units (Finney *et al.* 2005) may be an additional consideration in selecting treatment sizes for the optimisation.

The algorithm developed here was intentionally designed to produce 'greedy' solutions for individual treatment units by blocking flow-paths that are identified as 'major' only within the current strip. Greedy solutions are chosen from only the locally available information, in this case from the information supplied by the fuel treatment opportunity intersected by a major flow path. An alternative would be to identify and block fire flow-paths that become important farther downwind than the immediate strip. The two approaches will probably diverge for more complex landscapes because remote downwind landscape conditions (e.g. fuels and topography) may obviate a local pathway. The emphasis on a greedy solution has two advantages. First, it is faster computationally because fire growth does not have to be simulated far downwind from the current strip. Second, and perhaps more importantly for fire management applications, the greedy solution situates a treatment unit on a locally major pathway, which increases the proximity of a well-placed treatment unit to a randomly located ignition source.

Amount of treatment tested was limited to 30–40% because theoretical differences between the optimal and random treatment patterns diminish with treatment cover above some level around this point (van Wagtendonk and Sydoriak 1987; Finney 2003, 2004). This means that if financial or operational resources permit treatment at a rate sufficient to maintain ∼30 or 40% of a landscape in a treated condition annually, then the spatial pattern becomes less important and optimisation offers less possible improvement over random patterns. In natural fire regimes in the Sierra Nevada of California, observed interference by fire history patterns on subsequent wildfire growth (van Wagtendonk 1995; Parsons and van Wagtendonk 1996) is derived from largely random ignition patterns only because the frequency of fire is sufficient to maintain a large fraction of the landscape in a fuel-modified condition.

The spatial optimisation assumes that the spatial pattern is extant at a given instant in time. In reality, however, treatments are accomplished on an annual basis and treatment effects to reduce fire behaviour diminish with time. To achieve an effective spatial pattern means that the annual rate of treatment or maintenance must be high enough to achieve the cumulative spatial pattern while treatment effectiveness decreases. Little is known about treatment longevity but a few studies suggest that benefits to fire effects are limited to ∼10 to 15 years (Biswell *et al.*

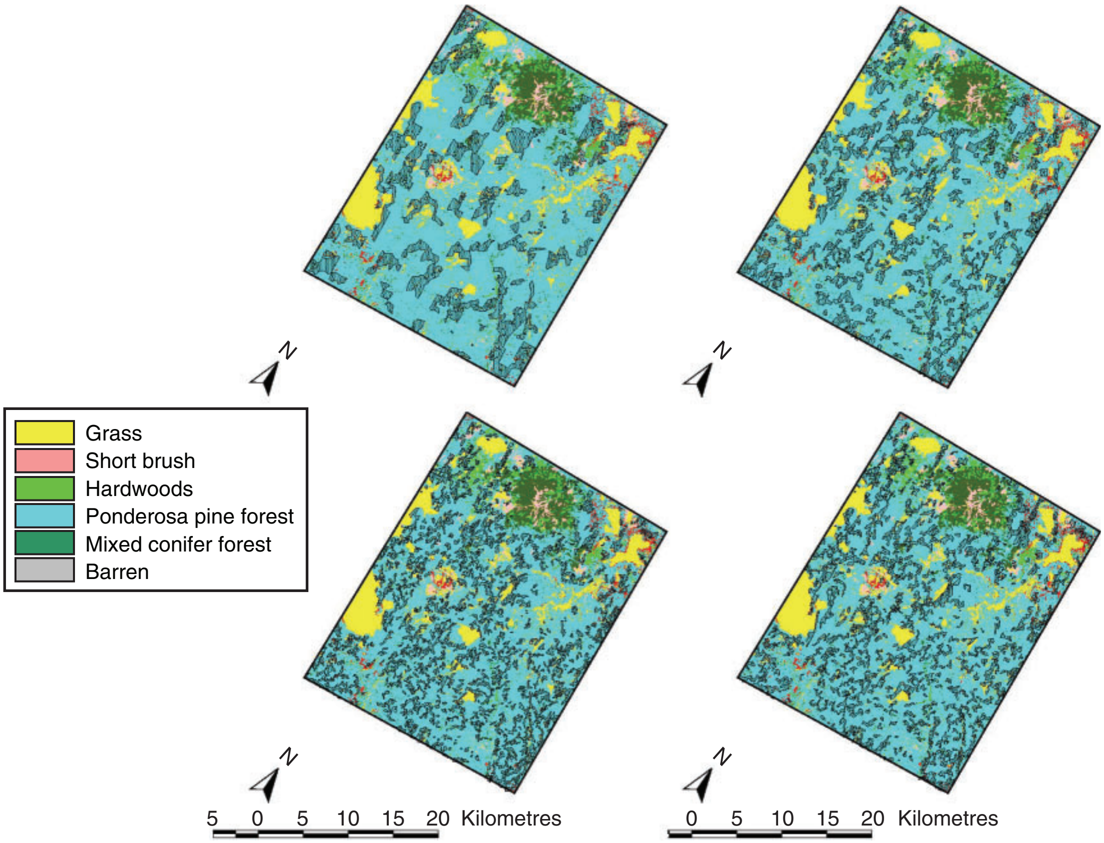

Fig. 7. Optimal treatment patterns for the Forest Ecosystem Restoration Analysis project (FERA) for an area surrounding Flagstaff, Arizona. Each pattern represents 20% of the analysis area in treatments with only the treatment size varying by alternative; 2500 m (*a*); 1200 m (*b*); 800 m (*c*); and 600 m (*d*). The analysis area is 2906 km^2 and 168 853 ha within the Kaibab and Coconino National Forests and is a portion of a larger landscapes (809 375 ha).

1973; Fernandes *et al*. 2004; Finney *et al*. 2005). If treatments are effective for one decade, this conservatively suggests that the minimum annual treatment rate can be estimated to be around one tenth of the total treatment cover desired. For example, if treatment of 20% of the landscape is the desired proportion, then the annual rate of treatment must be no lower than ~2%. This simple approximation provides insight as to the required treatment rate even though treatment effectiveness does change through time.

Spatial constraints are accommodated in the treatment optimisation automatically in locations where fire behaviour is identical between pretreatment and potential treatment landscapes. Areas where fuel treatments change the fire spread rate are considered by the algorithm as available for treatment and perhaps selected if intersected by major fire travel paths. Those areas where treatments are not possible contain the same fuel conditions in both landscapes, thereby offering no contrast in fire behaviour and no reason for selecting them for treatment even if major flow paths intersect these areas. Such effects can be seen in the large areas with no treatment in the Flagstaff example because of the location of grass meadows (Fig. 7) that were not treated even though the fire spread very rapidly under the target weather conditions.

The current algorithms neglect effects of spotting on fire progression and fuel treatment locations. Spotting is a fire behaviour that includes the lofting and transport of burning embers downwind, which start new fires and permit fire to breach barriers and discontinuities of fuels. Models for ember production and transport (Albini 1979) are included in other fire behaviour systems (Finney 1998) and can be included here in future. The exact effect of spotting on treatment performance is not clear because fuel treatments often limit the source of new embers as well as retard the growth of eventual spot fires. Spotting effects may be minimised by manually increasing the size of treatment units to mitigate overflight possibilities. But longer separation distances between larger treatments permit wider headfires to develop in between treatment units, which may increase spot fire generation. Even if spot fires breach the treatment units, an extensive landscape pattern of treatments would impose repeated interruption of any new fires.

Conclusions

An optimisation procedure was developed with the intent of obstructing the movement of large wildfires rather than

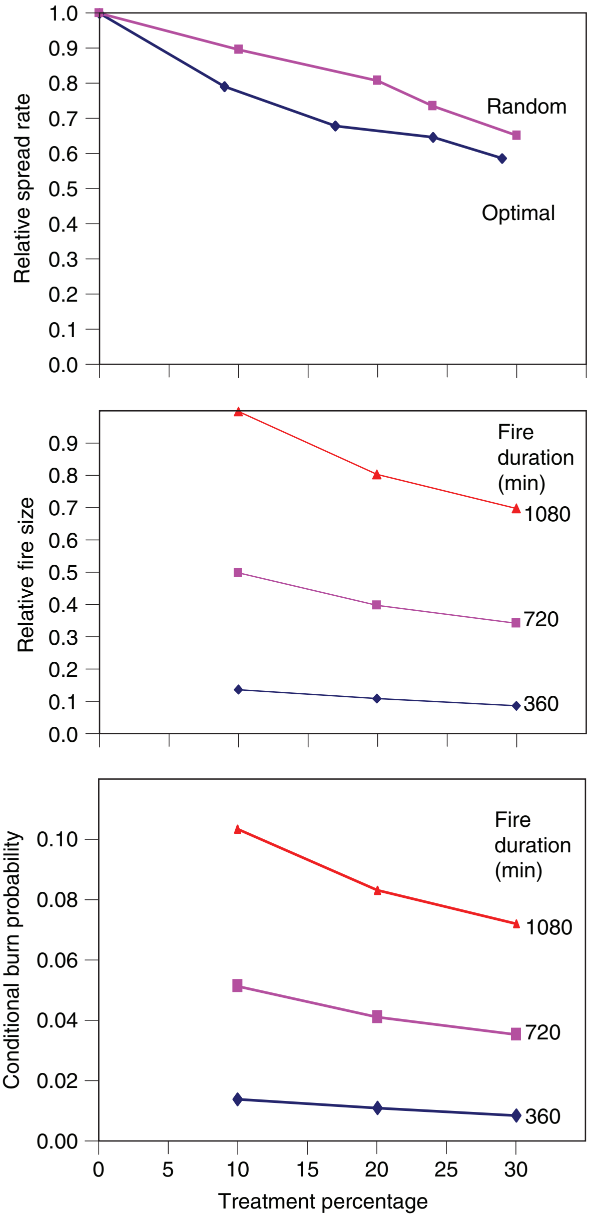

Fig. 8. Optimal and random treatment patterns for 1500-m units on the Flagstaff landscape reduced fire spread rate (*a*); mean fire sizes (*b*); and conditional burn probability (*c*) efficiently compared with random treatments. Although fuel treatments individually reduced fire spread rate by ~90%, the collective benefit of even the optimal pattern was compromised by the presence of large grass meadows that could not be treated. Grass fuels with full wind exposure had spread rates more than four times faster than the forest fuel types and served as conduits for fire growth, which reduced effectiveness of treatment pattern in minimising overall fire growth.

containing them. The algorithm was found to reduce the average fire growth rate efficiently for complex and simple landscapes compared with random treatment locations. This procedure can be useful for inclusion in fire management planning activities because it offers a means of measuring the performance of fuel treatments at both a stand- and landscape-level.

Acknowledgements

The present study was funded by the USA Joint Fire Sciences Program, the Bureau of Land Management (BLM), and the US Forest Service, Missoula Fire Sciences Laboratory. The author is grateful to Charles McHugh, Rob Seli, and Rick Stratton for their efforts in testing the optimisation model and helping prepare data and graphics for this paper. Howard Roose provided critical funding from the BLM for software development.

References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96. doi:10.1016/J.FORECO.2005.01.034

Agee JK, Bahro B, Finney MA, Omi PN, Sapsis DB, Weatherspoon CP (2000) The use of fuelbreaks in landscape fire management. *Forest Ecology and Management* **127**, 55–66. doi:10.1016/S0378-1127(99)00116-4

Albini FA (1979) Spot fire distance from burning trees – a predictive model. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-56. (Ogden, UT)

Alexander ME, Yancik RF (1977) The effect of precommercial thinning on fire potential in a lodgepole pine stand. *Fire Management Notes* **38**(3), 7–9.

Allen CG, Savage M, Falk DA, Suckling KF, Swetnam TW, Schulke T, Stacey PB, Morgan P, *et al.* (2002) Ecological restoration of south-western ponderosa pine ecosystems: a broad perspective. *Ecological Applications* **12**, 1418–1433. doi:10.1890/1051-0761(2002)012[1418:EROSPP]2.0.CO;2

Anderson HE (1982) Aids to determining fuel models for estimating fire behaviour. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-GTR-122. (Ogden, UT)

Andrews PL, Loftsgaarden DO, Bradshaw LS (2003) Evaluation of fire danger rating indexes using logistic regression and percentile analysis. *International Journal of Wildland Fire* **12**, 213–226. doi:10.1071/WF02059

Bevers M, Omi PN, Hoff J (2004) Random location of fuel treatments in wildland community interfaces: a percolation approach. *Canadian Journal of Forest Research* **34**, 164–173. doi:10.1139/X03-204

Biswell HH, Kallander HR, Komarek R, Vogl RJ, Weaver H (1973) Ponderosa fire management: a task force evaluation of controlled burning in ponderosa pine forest of central Arizona. Tall Timbers Research Station Miscellaneous Publication No. 2. (Tallahassee, FL)

Brackebusch AP (1973) Fuel management: a prerequisite not an alternative to fire control. *Journal of Forestry* **71**(10), 637–639.

Catchpole EA, de Mestre NJ, Gill AM (1982) Intensity of fire at its perimeter. *Australian Forest Research* **12**, 47–54.

Cooper CF (1961) Controlled burning and watershed condition in the White Mountains of Arizona. *Journal of Forestry* **59**, 438–442.

Cram D, Baker T, Boren J (2006) Wildland fire effects in silviculturally treated vs. untreated stands of New Mexico and Arizona. USDA Forest Service, Rocky Mountain Research Station, Research Paper RMRS-RP-55. (Fort Collins, CO)

Dunn AT (1989) The effects of prescribed burning on fire hazard in the chaparral: toward a new conceptual synthesis. In 'Proceedings of the Symposium on Fire and Watershed Management'. 26–28 October 1988, Sacramento, CA. General Technical Report PSW-109. (Tech. Coord. NH Berg) pp. 23–29. (USDA Forest Service, Pacific Southwest Forest and Range Experiment Station: Berkeley, CA)

Fernandes P, Botelho H (2003) A review of prescribed burning effectiveness in fire hazard reduction. *International Journal of Wildland Fire* **12**, 117–128. doi:10.1071/WF02042

Fernandes PAM, Loureiro CA, Botelho HS (2004) Fire behaviour and severity in a maritime pine stand under differing fuel conditions. *Annals of Forest Science* **61**, 537–544. doi:10.1051/FOREST:2004048

Finney MA (1998) FARSITE: Fire Area Simulator – model development and evaluation. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Paper RMRS-RP-4. (Ogden, UT)

Finney MA (2001*a*) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. *Forest Science* **47**, 219–228.

Finney MA (2001*b*) Spatial strategies for landscape fuel treatment. In 'Proceedings Workshop on Tools and Methodologies for Fire Danger Mapping'. 9–14 March 2001, Vila Real, Portugal. (Eds J Bento, H Botelho) pp. 157–163. (Universidade de Traz-os-Montes e Alto Douro, Departamento Florestal, Qunta de Prados: Vila Real, Portugal)

Finney MA (2002*a*) Fire growth using minimum travel time methods. *Canadian Journal of Forest Research* **32**, 1420–1424. doi:10.1139/X02-068

Finney MA (2002*b*) Use of graph theory and a genetic algorithm for finding optimal fuel treatment locations. In 'Proceedings of the 4th International Conference on Forest Fire Research'. 18–23 November 2002, Luso-Coimbra, Portugal. (Ed. DX Viegas) (Millpress: Rotterdam, Netherlands)

Finney MA (2003) Calculating fire spread rates across random landscapes. *International Journal of Wildland Fire* **12**, 167–174. doi:10.1071/WF03010

Finney MA (2004) Landscape fire simulation and fuel treatment optimization. In 'Methods for Integrated Modeling of Landscape Change. Ch. 9'. Interior Northwest Landscape Analysis System, General Technical Report PNW-GTR-610. (Eds JL Hayes, AA Ager, JR Barbour) pp. 117–131. (USDA Forest Service, Pacific Northwest Research Station: Portland, OR)

Finney MA, McHugh CW, Grenfell IC (2005) Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. *Canadian Journal of Forest Research* **35**, 1714–1722. doi:10.1139/X05-090

Gill AM, Bradstock RA (1998) Prescribed burning: patterns and strategies. In 'Proceedings of the 13th Conference on Fire and Forest Meteorology'. 27–31 October 1996, Lorne, VIC, Australia. pp. 3–6. (International Association of Wildland Fire: Moran, WY)

Graham RT (2003) Hayman fire case study. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, General Technical Report RMRS-GTR-114. (Ogden, UT)

Graham RT, Harvey AE, Jain TB, Tonn JR (1999) The effects of thinning and similar stand treatments on fire behaviour in western forests. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-GTR-463. (Portland, OR)

Graham RT, McCaffrey S, Jain TB (2004) Science basis for changing forest structure to modify wildfire behavior and severity. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-120. (Fort Collins, CO)

Green LR (1977) Fuelbreaks and other fuel modification for wildland fire control. USDA Forest Service, Agricultural Handbook Number 499. (Washington, DC)

Helms JA (1979) Positive effects of prescribed burning on wildfire intensities. *Fire Management Notes* **403**, 10–13.

Hirsch K, Kafka V, Tymstra C, McAlpine R, Hawkes B, Stegehuis H, Quintilio S, Gauthier S, Peck K (2001) Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. *Forestry Chronicle* **77**, 357–363.

Kallander H, Weaver H, Gains EM (1955) Additional information on prescribed burning in virgin ponderosa pine in Arizona. *Journal of Forestry* **53**, 730–731.

Loehle C (2004) Applying landscape principles to fire hazard reduction. *Forest Ecology and Management* **198**, 261–267. doi:10.1016/J.FORECO.2004.04.010

Martin RE, Kauffman JB, Landsberg JD (1989) Use of prescribed fire to reduce wildfire potential. In 'Proceedings of the Symposium on Fire and Watershed Management'. 26–28 October 1988, Sacramento, CA. General Technical Report PSW-109. (Tech. Coord. NH Berg) pp. 17–22. (USDA Forest Service, Pacific Southwest Forest and Range Experiment Station: Berkeley)

Mutch RW (1998) Long-range fire behavior assessments: your fire behavior future. In 'Proceedings of the 1994 Interior West Fire Council Meeting and Program'. 1–4 November 1994, Coeur d'Alene, ID. (Eds K Close, R Bartlette) pp. 69–74. (International Association of Wildland Fire: Fairfield, WA)

National Interagency Fire Center (NIFC) (2002) Wildland fire season summaries. Available at http://www.nifc.gov/fire_info/fire_summaries/summary_2002.htm [Verified 30 November 2007]

Neuenschwander LF, Menakis JP, Miller KM, Sampson RN, Hardy C, Averaill B, Mask R (2000) Indexing Colorado watersheds to risk of wildfire. *Journal of Sustainable Forestry* **11**, 35–55. doi:10.1300/J091V11N01_03

Parsons DJ, van Wagtendonk JW (1996) Fire research and management in the Sierra Nevada. In 'Science and Ecosystem Management in the National Parks. Ch. 3'. (Eds WL Halvorson, GE Davis) (University of Arizona Press: Tucson, AZ)

Pollet J, Omi PN (2002) Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. *International Journal of Wildland Fire* **11**, 1–10. doi:10.1071/WF01045

Raymond CL, Peterson DL (2005) Fuel treatments alter the effects of wildfire in a mixed evergreen forest, Oregon, USA. *Canadian Journal of Forest Research* **35**, 2981–2995. doi:10.1139/X05-206

Rollins MG, Swetnam TW, Morgan P (2001) Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. *Canadian Journal of Forest Research* **31**, 2107–2123. doi:10.1139/CJFR-31-12-2107

Rothermel RC (1998) Long range assessments. In 'Proceedings of the 1994 Interior West Fire Council Meeting and Program'. 1–4 November 1994, Coeur d'Alene, ID. (Eds K Close, R Bartlette) pp. 169–180. (International Association of Wildland Fire: Fairfield, WA)

Salazar LA, Gonzalez-Caban A (1987) Spatial relationship of a wildfire, fuelbreaks, and recently burned areas. *Western Journal of Applied Forestry* **2**(2), 55–58.

Schoennagel T, Veblen TT, Romme WH (2004) The interaction of fire, fuels, and climate across Rocky Mountain forests. *Bioscience* **54**, 661–676. doi:10.1641/0006-3568(2004)054[0661:TIOFFA]2.0.CO;2

van Wagtendonk JW (1995) Large fires in wilderness areas. In 'Proceedings: Symposium on Fire in Wilderness and Park Management'. 30 March–1 April 1993, Missoula, MT, USA. General Technical Report INT-GTR-320. (Tech. Coords JK Brown, RW Mutch, CW Spoon, RH Wakimoto) pp. 113–116. (USDA Forest Service, Intermountain Research Station: Ogden, UT)

van Wagtendonk JW (1996) Use of a deterministic fire model to test fuel treatments. In 'Sierra Nevada Ecosystem Project: Final report to Congress. Vol. II'. pp. 1155–1167. (Centers for Water and Wildland Resources, University of California: Davis, CA)

van Wagtendonk JW, Sydoriak CA (1987) Fuel accumulation rates after prescribed fires in Yosemite National Park. In 'Proceedings of the 9th Conference on Fire and Forest Meteorology. Vol. 9'. 21–24 April 1987, San Diego, CA. pp. 101–105. (American Meteorology Society: Boston, MA)

Wagle RF, Eakle TW (1979) A controlled burn reduces the impact of a subsequent wildfire in a ponderosa pine vegetation type. *Forest Science* **25**, 123–129.

Weatherspoon CP, Skinner CN (1995) An assessment of factors associated with damage to tree crowns from 1987 wildfires in northern California. *Forest Science* **41**, 430–451.

Weaver H (1943) Fire as an ecological and silvicultural factor in the ponderosa pine region of the Pacific slope. *Journal of Forestry* **41**, 7–15.

Manuscript received 18 May 2006, accepted 6 September 2007