

Simulation of long-term landscape-level fuel treatment effects on large wildfires

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Abstract. A simulation system was developed to explore how fuel treatments placed in topologically random and optimal spatial patterns affect the growth and behaviour of large fires when implemented at different rates over the course of five decades. The system consisted of a forest and fuel dynamics simulation module (Forest Vegetation Simulator, FVS), logic for deriving fuel model dynamics from FVS output, a spatial fuel treatment optimisation program, and a spatial fire growth and behaviour model to evaluate the performance of the treatments in modifying large fire growth. Simulations were performed for three study areas: Sanders County in western Montana, the Stanislaus National Forest in California, and the Blue Mountains in south-eastern Washington. For different spatial treatment strategies, the results illustrated that the rate of fuel treatment (percentage of land area treated per decade) competes against the rates of fuel recovery to determine how fuel treatments contribute to multidecade cumulative impacts on the response variables. Using fuel treatment prescriptions that simulate thinning and prescribed burning, fuel treatment arrangements that are optimal in disrupting the growth of large fires require at least 1 to 2% of the landscape to be treated each year. Randomly arranged units with the same treatment prescriptions require about twice that rate to produce the same fire growth reduction. The results also show that the topological fuel treatment optimisation tends to balance maintenance of previous units with treatment of new units. For example, with 2% landscape treatment annually, fewer than 5% of the units received three or more treatments in five decades with most being treated only once or twice and ~35% remaining untreated after five decades.

Additional keyword: fire modelling.

Introduction

Benefits of fuel treatments for mitigating the severity of wildfires have been documented at the stand level for much of the 20th century (Weaver 1943; Cooper 1961; Biswell *et al.* 1973), particularly in ponderosa pine and dry mixed conifer forests in the western United States (ponderosa pine and Douglas-fir). Recent large wildfires have stimulated renewed interest in fuel treatments and prompted new studies that have confirmed these findings (Pollet and Omi 2002; Graham 2003; Graham *et al.* 2004; Agee and Skinner 2005; Raymond and Peterson 2005; Cram *et al.* 2006). Treatment effects beyond the immediate stand scale (i.e. fuel changes over time and large spatial scales) are poorly understood. Only a few studies of treatment longevity exist (Biswell *et al.* 1973; van Wagtenonk and Sydoriak 1987; Finney *et al.* 2005) and indicate diminishing benefits beyond about a decade. Landscape-level effects from various treatment patterns are still largely theoretical (Finney 2001a, 2003; Hirsch *et al.* 2001) with few observations of treatment performance in altering fire growth (Finney 2005). Given the difficulty with implementing large-scale and long-term experiments in fuel

treatment, the present study sought to use computer simulation to explore complex interactions of landscape treatment pattern and temporal vegetation and fuel changes in addressing the following questions:

1. What effect does spatial treatment pattern have on fire growth on complex landscapes that typify forest conditions found in the western US?
2. At what rate must fuel treatments be implemented across a landscape to produce aggregated or cumulative effects on large wildfire growth?
3. For purposes of disrupting fire growth, should existing fuel treatment units be maintained or should effort be made to implement new treatment units?
4. How do restrictions or constraints on fuel treatment location (because of conflicting land management objectives) affect treatment benefits?
5. How do landscape-level fuel treatment patterns perform under weather scenarios more moderate than the extreme conditions specified in their design?

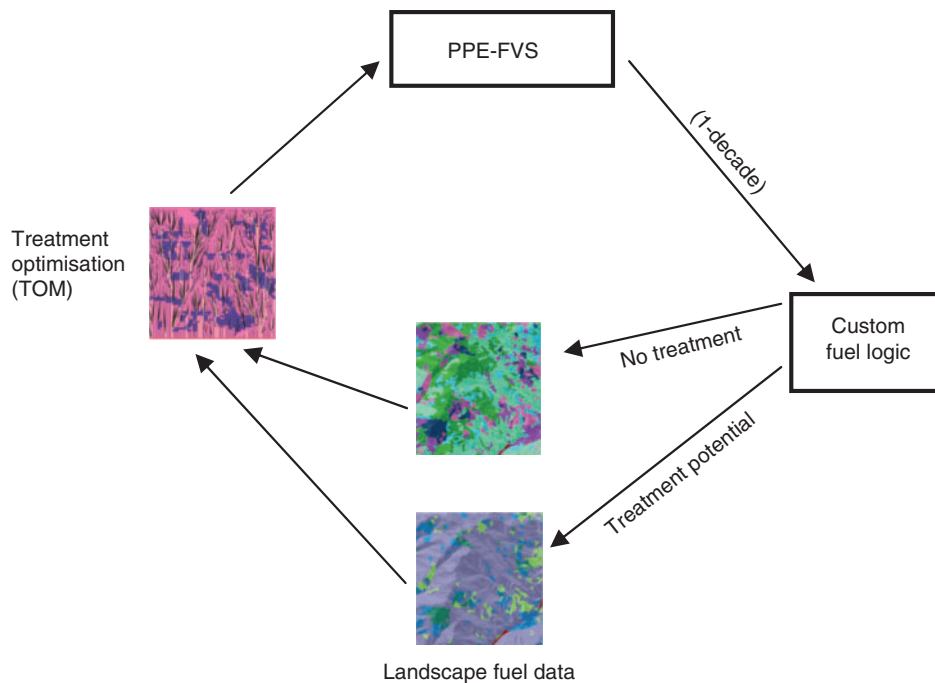


Fig. 1. Schematic diagram of the simulation system used in the study. This system consisted of the Parallel Processing version of the Forest Vegetation Simulator (PPE-FVS) that simulated forest development with and without treatment, derivation of surface fuel models from the biomass categories and production of spatial landscapes for each scenario, spatial optimisation of fuel treatment locations for disrupting fire growth, and implementation of treatments as feedback for the next simulation cycle in PPE-FVS.

Methods

Our objectives were to produce a simulation system that implemented fuel treatments over large landscapes in order to evaluate the impact on potential fire behaviour over multiple decades. To isolate the effects of fuel treatment on the responses of interest, the variables considered were restricted to only those of fuel treatment, fire behaviour, and vegetation modelling. The system (Fig. 1) consisted of:

1. The Forest Vegetation Simulator (FVS) for simulating the changes over time in forest vegetation (Crookston and Stage 1991) and fuels (Reinhardt and Crookston 2003). The FVS models were used for multiple stands comprising a landscape and for implementing the treatment prescriptions.
2. A spatial model for choosing the location of treatment units using topologically optimal or random selection logic (Finney 2002a, 2004, 2007).
3. A fire growth simulation model (Finney 2002b) used to evaluate the impact of treatments in terms of fire growth rate, fire sizes, and conditional burn probability.

The simulation system intentionally excluded random wild-fire events even though it would be expected that numerous wildfires would actually occur throughout the multiple decade timeframe of the study. Accounting for wildfire impacts on vegetation and fuels would require a large number of replications to represent the introduced variability and would have therefore exceeded the capability of the available computational resources and practical time-limits.

Simulating forest and fuel conditions and treatment prescriptions using FVS

The FVS is widely used in the USA for forest growth and yield modelling (Wykoff *et al.* 1982) and has recently been modified to record information on fuels and woody debris (Reinhardt and Crookston 2003) using the Fire and Fuels Extension (FFE). FVS has multiple variants that correspond to species, growth rates, and fuel types of forests in numerous regions throughout the US. The FVS program simulates forest dynamics on a multi-year cycle, typically 5 or 10 years in length. Our system relied on a custom version of the Parallel Processing Extension (PPE) of FVS (Crookston and Stage 1991) that includes FFE. PPE processes the stand list cycle-by-cycle (rather than one stand at a time for all cycles as in the normal version of FVS) and implements specific silvicultural and fuel treatment prescriptions (i.e. modifies forest and fuel structures). This custom version of PPE also controls the simulation loop that calls separate routines outside of PPE that identify specific stands to treat. The PPE module then implements the prescriptions and processes the growth and fuel deposition for the next simulation cycle.

FVS requires a 'tree list' to be supplied for each stand. A tree list contains the number of trees by species and stem-diameter class. As a landscape is composed of polygons that delineate individual stands, all stand polygons must be assigned a tree list. We used nearest-neighbour techniques that use a representative sample of tree lists from areas throughout the landscape to impute a tree list to polygons with no local measurements. One such technique is the Most Similar Neighbour method (Crookston *et al.*

Table 1. Forest Vegetation Simulator (FVS) treatment prescription parameters used to simulate fuel treatments in FVS for the Montana and California study sites

Prescriptions for the Washington site were varied according to stand density index as described in the text

Sanders County, MT	Stanislaus National Forest, CA
Seedling or sapling size class (<5-cm diameter at 1.4 m)	
Thin from below to 1580 trees ha ⁻¹ (640 trees acre ⁻¹) if 0 to 7.62-cm diameter fuel loading (0–3 inch) ≥5.6 Mg ha ⁻¹ (2.5 tons acre ⁻¹)	Thin from below to 45% canopy cover
Pile and burn fuel treatment	Pile and burn fuel treatment
Poletimber size class (5–20-cm diameter at 1.4 m)	
For fire tolerant forest types (ponderosa pine and Douglas-fir)	For fire tolerant forest types (ponderosa pine)
Thin from below to 30 m ² ha ⁻¹ (130 ft ² acre ⁻¹) of basal area	Thin from below to 45% canopy cover
Prescribe burn	Prescribe burn
For fire intolerant forest types (all others)	For fire intolerant forest types (all others)
Thin from below to 34 m ² ha ⁻¹ (150 ft ² acre ⁻¹) of basal area	Thin from below to 45% canopy cover
Pile and burn fuel treatment	Pile and burn fuel treatment
Sawtimber size class (>20-cm diameter at 1.4 m)	
For lodgepole pine forest type	
Clearcut with reserves	
Prescribe burn	
For fire tolerant forest types (PP, DF, WP, and WL)	For fire tolerant forest types (PP, DF, SP, and RF)
Thin from below to 32 m ² ha ⁻¹ (140 ft ² acre ⁻¹) of basal area	Thin from below to 45% canopy cover
Prescribe burn	Prescribe burn
For fire intolerant forest types (all others)	For fire intolerant forest types (all others)
Thin from below to 34 m ² ha ⁻¹ (150 ft ² acre ⁻¹) of basal area	Thin from below to 45% canopy cover
Pile and burn fuel treatment	Pile and burn fuel treatment

2002). Tree lists for measured stands were obtained from existing data collected by (a) local forest stand exams, and (b) Forest Inventory and Analysis plots (FIA) (Van Deusen *et al.* 1999; McRoberts *et al.* 2000; Reams *et al.* 2001). The size of stand polygons assigned to the most similar tree list was varied from 5 to 10 ha at all study sites. FVS requires initialisation of dead and downed loading by size class components, called fuel-pools, which represent the initial loading states of various fuel components and are critical to consequent fuel dynamics. The initial values for all surface fuel, canopy fuel, and stand characteristics for the landscapes at each study site are described below in the *Study area and simulation* section.

The stand-level prescriptions representing fuel treatments in FVS were specifically developed for treating fuels rather than to extract forest products (e.g. timber volume) or meet long-term ecological objectives (Table 1). Treatments that include removal of surface fuels by prescribed burning have shown the greatest effectiveness in reducing fire intensity and severity (Helms 1979; Martin *et al.* 1989; Fernandes and Botelho 2003; Agee and Skinner 2005; Raymond and Peterson 2005), either alone or in combination with silvicultural activities that reduce vertical and horizontal continuity of canopy fuels (van Wagtenonk 1996; Stephens 1998; Graham *et al.* 1999; Hirsch and Pengelly 1999; Agee *et al.* 2000; Cram *et al.* 2006). Canopy fuel parameters that influence crown fire include canopy base height and canopy bulk density (Agee 1996; Scott and Reinhardt 2001; Agee and Skinner 2005). Treatments that only involve cutting or canopy manipulation without surface fuel mitigation were not implemented here because these activities often increase fuel

availability (Alexander and Yancik 1977; van Wagtenonk 1996; Brown *et al.* 2004; Raymond and Peterson 2005; Stephens and Moghaddas 2005) (i.e. made fuel components more ignitable or combustible by changing their physical properties or position relative to the ground). Based on the requirement of modifying surface fuels whenever canopy fuels are manipulated, prescriptions were developed for each stand on the entire landscape based on the forest species composition, tree density, structural stage, and general understorey fuel type (e.g. shrubs, grass, litter).

- Prescribed burning only. This prescription was used for maintenance of the surface fuels when there was no need to mechanically reduce aerial fuels. This prescription reduces surface fuels only and may kill small understorey trees (through crown scorch) and regeneration using the mortality functions in FVS. This prescription also increases canopy base height by scorch-pruning of the lower limbs of the trees.
- Thinning, site removal of fuels, and prescribed burning. Harvest and non-harvest thinning were not differentiated but merchantable material was assumed to be removed and not added to the fuel pools. This treatment removes slash from the mechanical activities as well as the pre-existing surface fuels from the fuel pools.

Prescribed fire treatments were implemented using the FFE keywords SIMFIRE, PILEBURN, and FUELMOVE. Thinning was implemented with various FVS thinning keywords and fire intolerant species were given preference for removal. Specific prescription logic for each study site is described below in the *Study area and simulation* section.

The output from FVS-PPE was written to a table of stand conditions for each year in the FVS cycle (we simulated five cycles of 10 years each). This table contained surface and aerial fuel conditions that would have occurred with no treatment along with those that would result from application of the treatment prescription. Thus, the treatments simulated in FVS-PPE and the resultant fuel conditions were passed to the spatial location routine described below through this table. The contrast in fire behaviour between the treated and untreated conditions is critical for assessing the impact of the treatment on potential fire behaviour. Thinning treatments were implemented on the third year of the 10-year cycle, with prescribed burning of harvest residues and pre-existing surface fuels in the fourth year. Within a 10-year cycle, this convention explicitly assumes a single fuel condition for all areas treated, although FVS operates on an annual cycle and produces fuel changes annually that carry forward to subsequent cycles.

Fuel conditions from FVS were used to build raster-based Landscape files (.LCP) required by wildfire growth models (Finney 1998). The FVS polygon fuel data specifically included canopy cover, stand height, canopy base height, and canopy bulk density, as well as fuel-pools, treatment history, and stand species information for assigning a fuel model (Anderson 1982; Scott and Burgan 2005). Because FVS currently does not utilise the Scott and Burgan surface fuel models, the fuel model assignment for each stand was accomplished outside of FVS-PPE. We mapped the stand conditions simulated in FVS to the polygon locations to create a forest landscape and contrast the effects of treatment for all stands in terms of fire behaviour variables. FVS cannot simulate dynamics of non-forest vegetation, and fuel characteristics in shrub-dominated polygons were assumed to fully recover 20 years after burning treatment. Grass-dominated polygons were assumed to retain constant fuel characteristics throughout the simulation (no treatment effects). Unburnable polygon fuel conditions (e.g. water, rock) were held constant through the simulation.

Spatial locations of fuel treatments

Having two sets of landscape fuel conditions each decade (depicting conditions with and without treatment) made it possible to spatially delineate areas where fuel treatments are effective at changing stand-level fire behaviour. Treatments were only considered possible for areas where fire behaviour would be modified by implementing that prescription. For example, thinning and prescribed burning of a particular stand could not be conducted in sequential decades if the second treatment did not reduce fire spread rate. Thus, the landscape configuration of areas suitable or available for fuel treatment would vary from decade to decade.

To move from the stand level to the landscape level, the spatial treatment optimisation attempts to locate a specified percentage of these stands to treat that optimally disrupt the growth or movement of large fires across that landscape (Finney 2002a, 2004, 2007). This optimisation numerically implements the concepts described by Finney (2001a) for an optimal spatial arrangement of discrete units on a uniform landscape that can be solved analytically. For complex real landscapes (those with spatially varying fuels and topography), a numerical technique is required, and

makes use of a fire growth simulation technique (Finney 2002b) to identify fire travel paths produced by fires growing under specified weather conditions. These weather conditions (fuel moisture, wind speed, wind direction) are obtained from historic local climatology associated with large and extreme fires.

The algorithm finds intersections between the fire travel paths and stands where the treatments slow the fire under the specified 'target' weather conditions. Target weather conditions are synthesised for a particular study area from weather associated with historic large fires for which suppression is ineffective (Finney 2001a). Weather parameters include fuel moisture, wind speed and wind direction for the afternoon burning period (when the majority of fire area is burned). Typically, the areas that have been burned by large fire events in a particular region display a similar orientation produced by the wind direction associated with a synoptic weather system that repeatedly contributes to the escape and rapid growth of fires. Thus, selecting these conditions ensures that treatment prescriptions modify fuels to sufficiently change fire behaviour when fire suppression is impossible. Stands that slow the fire are identified by the contrast in fire spread rate between treated and untreated stands. Fire behaviour is calculated for each grid cell of each landscape using an implementation of fire behaviour models described by (Finney 1998). Thus, a comparison of spread rate between two locations indicates where treatments reduce spread and can thereby contribute to retarding fire movement.

The spatial optimisation technique begins by dividing the landscape into rectangular strips oriented normal to the predominant wind direction (Finney 2002a, 2004, 2007). Beginning with the strip farthest upwind, fire growth is simulated to identify major fire travel routes and their intersection with potential treatment areas (areas where the fire is slowed by the treatment). The process then iterates to delineate separate treatment units (one for each travel route) as constrained by unit size and total treatment area. The orientation of the treatment units will typically be perpendicular to the major fire spread direction because this intercepts the main direction of fire movement. This procedure is followed for each strip moving successively in the direction of the wind because treatments imposed on the landscape affect the downwind fire travel routes and subsequent treatment areas.

To measure the relative effectiveness of the spatial treatment optimisation, we also simulated random treatment of forest stands within the fuel treatment module linked to FVS-PPE.

Modelling landscape-effectiveness of fuel treatments

The performance of the various fuel treatment patterns at each decade were evaluated in terms of the responses of fire growth (Finney 2002b) under the 99th percentile target conditions. Effects of treatment were measured entirely assuming an absence of fire suppression because the weather conditions targeted for fuel treatment performance have historically been associated with large fires for which suppression efforts were ineffective (i.e. 99th percentile). However, reductions in overall fire growth rates, fire intensity, and fire sizes that would be expected to facilitate suppression action in treated areas by linking or connecting treatment units by fire control lines (Bunnell 1998).

Table 2. Summary of study area attributes and fire weather conditions simulated for fuel treatment optimisation

Study area, location and size	Land ownership	Historical fire intervals and severity	Fire weather conditions used for fire modelling
Blue Mountains, WA 54 600 ha	Umatilla National Forest Private (non-industrial) Private (industrial)	Mean fire intervals 12–50 years Low-mixed severity	Wind (56 km h ⁻¹ , West) Fuel moisture content (1 h 3%; 10 h 4%; 100 h 6%; live herb 75–120%; live woody shrubs 100%)
Sanders County, MT 51 700 ha	Lolo National Forest Kootenai National Forest Private (non-industrial) Private (industrial) Salish and Kootenai tribes MT Department of Natural Resources and Conservation	Mean fire intervals 12–200 years Low, mixed, high severity	Wind (56 km h ⁻¹ , West) Fuel moisture content (1 h 3%; 10 h 4%; 100 h 65%; live herb 125%; live woody shrubs 125%)
Stanislaus National Forest, CA 40 500 ha	Stanislaus National Forest Private (non-industrial) Private (industrial)	Mean fire intervals 12–50 years Low severity	Wind (56 km h ⁻¹ , South) Fuel moisture content (1 h 3%; 10 h 4%; 100 h 6%; live herb 125%; live woody shrubs 125%)

Wildfire responses were measured with the following metrics:

1. Total fire travel time (and thus, aggregated spread rate across the landscape) under the target weather conditions;
2. The mean sizes of randomly ignited fires on the landscapes; and
3. The average conditional burn probability for all places on the landscape by randomly ignited fires.

The fire travel time was used to calculate the aggregated average fire spread rate of a fire from the upwind to the downwind edge of the landscape. This was performed by igniting the full length of the upwind edge of the landscape and running the wildfire simulation until it arrived at the downwind edge. The fire size distributions were obtained from simulations of 3000 randomly ignited fires across each landscape. These fires were simulated for the same weather condition (identified as the ‘target’ condition) used for the optimisation (Table 2) because the fires targeted for treatment performance are those that escape initial attack efforts. This assumes that fire management policies attempt to suppress all fires, leaving to spread only those that cannot be controlled under extreme weather conditions. The simulated fires were used to estimate the conditional burn probability for the landscape, which was derived by tallying the total number of fires that cross each grid cell of the landscape. These burn probabilities were considered conditional on having an escaped fire, and are not accurate estimates of the actual annual burn probability for the study areas.

Study areas and simulation scenarios

A large number of scenarios were developed and simulated to examine five decades of vegetation dynamics and treatment activity. The main variables evaluated were:

1. Treatment amount (e.g. proportion of the landscape, from 0 to 50% by 10% increments);
2. Maximum treatment unit dimension (400, 800, 1200, and 1600 m per unit);
3. Treatment unit pattern (optimal *v.* random);

4. Reserves of randomly selected areas in the proportion of 15 to 65% of the landscape;
5. Fire simulations under weather percentiles of 90th, 95th, to test performance of treatment patterns designed for weather of the 99th percentile.

The study areas were selected to represent some of the variability in forest conditions that exist in the western USA. The variety of conditions at these sites is intended for comparison of how fuel management objectives (specific in both space and time) can be accomplished in the context of realistic variability, constraints on management activities, and understanding of fire weather conditions. Table 2 contains the fire weather conditions used for each study area associated with 99th percentile Energy Release Component (ERC) from the USA National Fire Danger Rating System (Deeming *et al.* 1977).

Sanders County, Montana

Sanders County consists of 680 000 ha in western Montana along the Idaho border, from which a study site of 51 700 ha was selected (Fig. 2; Table 2). Land ownership is ~65% National Forest, 10% Plum Creek Timberlands, 5% owned by the Montana Department of Natural Resources and Conservation, and 20% small private landowners. A wide variety of fuel and forest types are present, with sagebrush and grasslands at the lower elevations in the eastern half of the county, ponderosa pine (*Pinus ponderosa*) stands dispersed at low elevations, western red cedar (*Thuja plicata*) stands at the west end of the county and lodgepole pine (*Pinus contorta*) and whitebark pine (*Pinus albicaulis*) stands perpetuated by stand replacement fires at higher elevations. Mean fire intervals historically vary from ~12–20 years at the lowest elevations and dry forest types to several centuries at the high elevations and wet sites to the west (Smith and Fischer 1997). Private lands with the associated towns and improvements are concentrated in the lower elevations along the rivers and consist of the flashier fuel types. Barriers to fuel treatment include habitat concerns for a variety of endangered species: grizzly bear, wolves, lynx, and bull trout. Other issues are water quality-limited streams and checkerboard ownership.

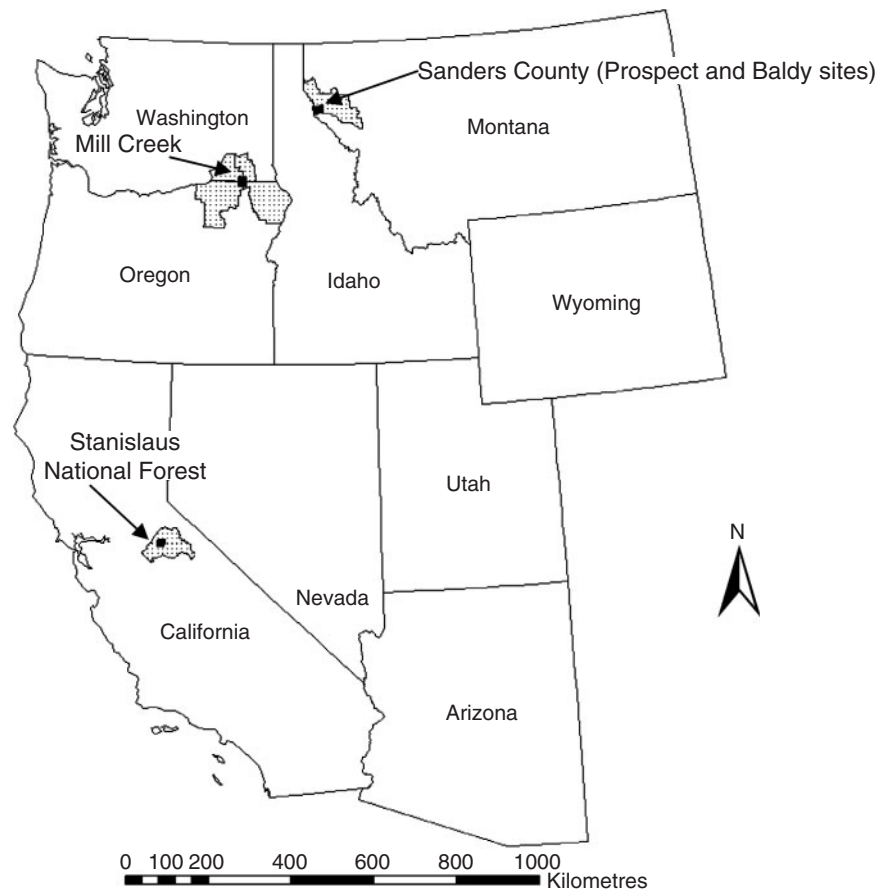


Fig. 2. Location of the study sites in western Montana (Prospect, Sanders County), the Sierra Nevada mountains of California (Stanislaus National Forest), and south-eastern Washington (Mill Creek).

Data for the study area of Sanders County, Montana, consisted of continuous polygon coverage across all land ownership categories attributed with tree list data for the forested polygons. The polygon coverage was derived from that used in the Northern Region Vegetation Mapping Project (Brewer *et al.* 2004). Data from USDA Forest Service FIA and Salish–Kootenai Tribe Continuous Stand Inventory (CSI) plots (commonly referred to as stand exam, forest inventory data, or observations) were used to create tree lists. Each tree list location or observation was attributed to the polygon it was located in and then imputed to other similar polygons, using nearest-neighbour analysis, resulting in all forested polygons having a tree list attributed. FFE fuel pools were initialised using the FFE defaults.

Two sub-areas were chosen from Sanders County (labelled Prospect and Baldy) because of the large size of the County and varying forest types and treatment options. The Prospect area represented the north Idaho forest types such as western hemlock (*Tsuga heterophylla*) and true firs (*Abies* spp.), limited past management activities, continuous dense forest cover, prevalent brush fuels beneath the forest canopy, and predominance of National Forest ownership. The Baldy landscape was smaller and more variable than Prospect. It contained a large rocky area at high elevation surrounded by drier forest types including ponderosa pine and Douglas-fir, and was composed

of lands administered by Indian tribal governments (Salish and Kootenai tribes) and US National forest. Significant past management activities have created a variety of age classes, forest structures, surface and aerial fuel conditions.

We simulated stand-level treatments that consisted of thinning from below, piling and burning fuels treatment, and underburning (Table 1). The thinning prescriptions targeted removal of the late-seral, fire intolerant species grand fir and favoured the early-seral species ponderosa pine, western larch, and Douglas-fir.

Stanislaus National Forest, California

The Stanislaus National Forest is 363 000 ha and lies in the heart of the central Sierra Nevada (Fig. 2). A 40 500-ha area was selected for simulation (Fig. 2, Table 2) containing 7754 tree-list polygons. The administrative boundary includes industrial private timberlands and small private parcels, many of which have been developed for housing. Vegetation varies from hard chaparral (*Manzanita* species), oak (*Quercus* species) woodlands and ponderosa pine (*Pinus ponderosa*) stands at the lower elevations to the west to mixed conifer and red fir (*Abies magnifica*) forest at middle and upper elevations to the east. The western edges of this area are representative of the wildland–urban intermix of the Sierra Nevada foothills. The fire regime has changed

from a predominantly surface fire regime among all forest types before settlement with mean fire intervals of 5 years at low elevation forest types to over 50 years in forests at high elevations (Skinner and Chang 1996). With fire exclusion for the past century, surface and crown fuels on all lands now contribute to a relatively continuous fuel complex with the potential for large and severe fires under extreme conditions. The foothills of the central and northern Sierra Nevada have recently been prone to these kinds of fires, which result in losses and costs in the hundreds of millions of dollars.

Data for the California study area consisted of continuous polygon coverage across all land ownership categories attributed with tree list data for the forested polygons. The Pacific Southwest Region Vegetation Inventory Strata map was used for the polygon coverage. USDA Forest Service FIA data, supplemented with additional plots in rare types and plantations, were used for the tree lists. Many of the tree lists were supplemented with fuel loadings from Blonski and Schramel (1981) to initialise the FFE fuel pools; otherwise, FFE fuel pools were initialised using the FFE defaults. Each tree list location or observation was attributed to the polygon it was located in and then imputed to other similar polygons, using most-similar-neighbour analysis, resulting in all forested polygons having a tree list and initial fuel pools attributed.

We simulated stand-level treatments that consisted of thinning from below, piling and burning fuels treatment, and underburning (Table 1). The thinning prescriptions targeted removal of the late-seral, fire intolerant species white fir and favoured early-seral species ponderosa pine, sugar pine, Jeffrey pine, and Douglas-fir.

Mill Creek, Washington

The Mill Creek study site consists of 54 600 ha of federal and privately owned lands situated south-east of Walla Walla, WA (Fig. 2, Table 2). The site contains 5732 stand polygons and is situated on the west slope of the Blue Mountains, bordered by agricultural lands on the west and the USDA Forest Service wilderness on the east. The private lands are located on the western edge. About half of the study area is forested, with the remaining area covered by a mixture of dry grasslands, wet meadows, and shrubs. Elevations range from 500 m along the lower western edge to over 1800 m in the east. The forest composition follows elevation, with dry forests of ponderosa pine (*Pinus ponderosa*) intermixed with grasslands in the west, cold forests dominated by subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) in the east, and a transition zone containing grand fir (*Abies grandis*), Douglas-fir (*Pseudotsuga menziesii*), and western larch (*Larix occidentalis*) in the mid-elevations. Prior to 1900, fire history evidence suggests that mean fire intervals of ~12–50 years were common in the low-elevation forest types (Heyerdahl *et al.* 2001).

Forest stand delineations on the Forest Service portion of the study area were obtained from existing vegetation geographic information system (GIS) layers on file at the Umatilla National Forest. Vegetation data and fuel loadings for these stands were obtained from the Umatilla National Forest vegetation database and fuels inventory information obtained from the Walla Walla ranger district. Tree lists were a mix of field exams and data obtained from nearest-neighbour analysis (Crookston

et al. 2002). Stands outside the Forest Service boundary were digitised on orthophotos taken in 2000, and vegetation and fuels data obtained by field surveys. Photo series including Fischer (1981) were used to estimate initial surface fuel loadings.

Prescriptions for the Mill Creek study area consisted of thinning from below, site removal of fuels, and underburning. The thinning prescription used the stand density index (SDI), and we triggered a thin in FVS when a stand's SDI exceeded 65% of the maximum SDI as specified in Cochran *et al.* (1994). The thinning prescriptions targeted removal of late-seral, fire intolerant species like grand fir in mixed-species stands, favouring early-seral species such as ponderosa pine, western larch and Douglas-fir. Underburning was simulated using typical fall burning conditions in the Umatilla National forest.

Results

The simulation system was designed for multiprocessor computers because of the intensive nature of the treatment optimisation program and fire growth model. The fire growth algorithms (Finney 2002a) and the treatment optimisation module were the most intensive and were run on 16-processor systems. Run times for five decades of simulation ranged from 6 h to several days depending on the size of the landscape (total area and number of grid cells) and the maximum dimension of the treatments (smaller treatments required smaller divisions of the landscape for the treatment optimisation module and thus longer run times). Treatment units were identified by the treatment optimisation model (Fig. 3) for each landscape for the target weather condition.

The performance of the treatments was measured in terms of the change in landscape-level fire behaviour, including changes in average spread rate, conditional burn probability, and average fire size. All three measures showed similar responses to the treatments (Fig. 4) because slower-moving fires, burning for a specified period of time, will be smaller and thus contribute to a lower overall probability of burning any portion of the landscape. Thus, only the relative spread rate is reported for the remaining simulation results. All measures revealed that the landscape fuel conditions, and thus fire behaviour, changed over time even in the absence of treatment (top line in all graphs on Fig. 4). Thus, the treatment effects were evaluated with respect to the untreated condition at each decade.

Optimal patterns of treatment units were found to reduce the average fire spread rate for all study areas in comparison with random patterns (Fig. 5). Treatment unit size, which was varied from 200 to 1600 m, had little influence on the effect of optimal treatment patterns on fire spread rate regardless of the rate of treatment, simulation time, or study area (Fig. 5). The Baldy study size (Sanders County, Montana) showed the greatest variation of relative spread rate (Fig. 5f) in relation to treatment sizes from 200 to 1600 m, especially as the percentage of area treated increased.

The average fire spread rate decreased with increasing treatment rate, but the amount of decrease varied by study area (Fig. 5). Treatments caused greater spread rate reduction at the Prospect study site in Montana than at either area in California or Washington (Fig. 5). After 20 years of treatment at a rate of 1% per year (10% per decade), the relative average fire spread rate

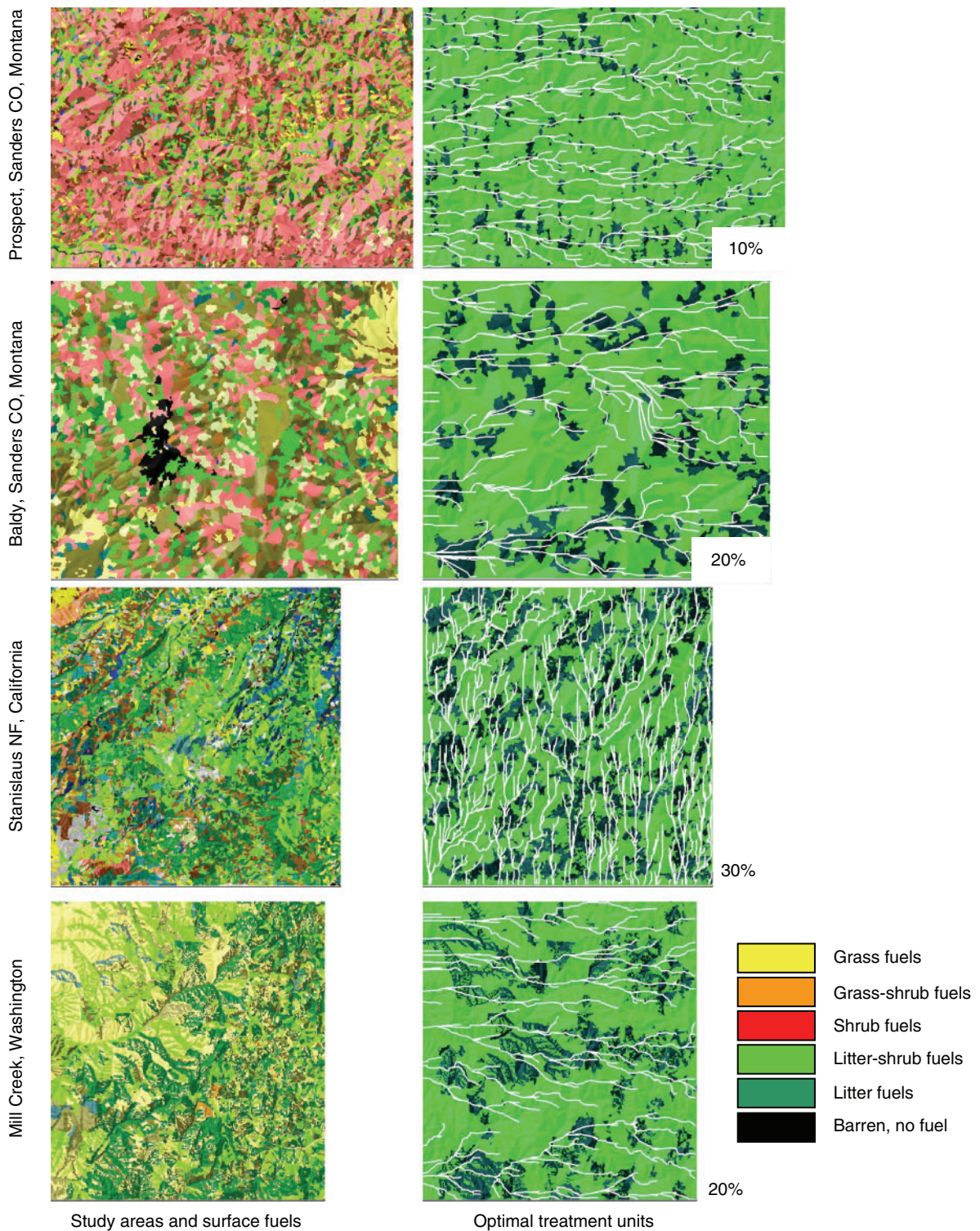


Fig. 3. Example data and outputs from the Montana, California, and Washington study areas showing surface fuel types and examples of optimised treatment locations along with major fire travel routes before placement of treatment locations (treatment locations are intersected by travel routes).

compared with the untreated condition was reduced to ~ 0.4 at Prospect, Montana (Fig. 5a), 0.6 at Baldy, Montana (Fig. 5b), 0.8 in California (Fig. 5c), and 0.6 in Washington (Fig. 5d). Increasing the rate of treatment to 3% per year improved the overall

reduction in relative average spread rate to 0.2 for Prospect, Montana (Fig. 5e), 0.4 for Baldy, Montana (Fig. 5f), 0.6 for California (Fig. 5g), and 0.4 for Washington (Fig. 5h). For all study areas and treatment rates, the effects of treatment were greatest the

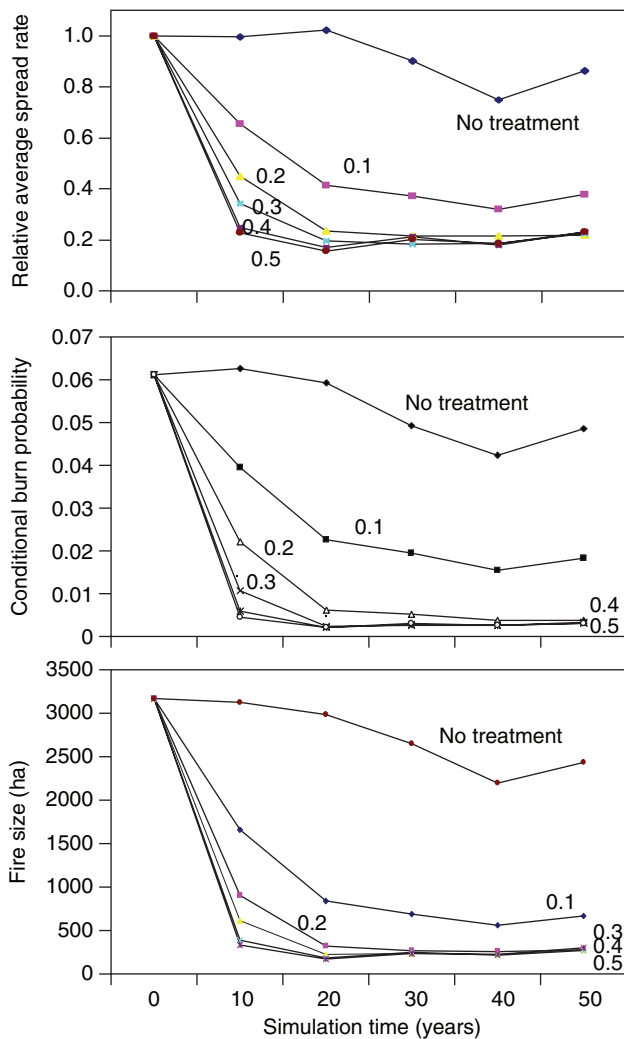


Fig. 4. Response measures for large fire growth include the average fire spread rate across the landscape, conditional probability of burning produced by simulating 3000 fires (conditional on having a large wildfire), and the mean fire sizes for the Prospect, Montana, study area. The three response variables had nearly identical trends for the other two study areas.

first decade and the marginal effect of additional treatment was negligible after the second decade of simulation. These trends were observed irrespective of the amount of treatment but were more noticeable with high treatment rates.

The rate of treatment in optimal patterns had a large effect on the cumulative treatment effectiveness up to $\sim 2\%$ per year for all study areas (Fig. 6). Increasing treatment rate beyond this point had little effect on the ultimate fire spread rates. For each rate of treatment (1 to 3% per year), the results suggested that cumulative effects of the optimal patterns reached a steady-state after the second decade (Fig. 6) as well as for random treatment patterns (Fig. 5). Higher rates of treatment (4–5% per year) produced little cumulative benefit to landscape fire spread metrics beyond the first decade.

Effectiveness of optimal treatment patterns in reducing fire spread rate was little affected by randomly reserving less than

$\sim 20\%$ of the study sites from consideration for treatment (Fig. 7). However, reserving 45 to 65% of the area from treatment diminished the effectiveness of optimal patterns to about the level of random patterns (Fig. 7).

As the rate of treatment increased, the amount of retreatment (maintenance) conducted over five decades in the optimal patterns was increasingly different from the amount re-treated in the random pattern (Fig. 8). The trends were so similar for study areas that only the Prospect, Montana, results are shown in Fig. 8. The random treatments produced the expected Poisson distributions of treatment frequency (Fig. 8a), which were similar to the treatment frequency produced for optimal patterns at a rate of 1% per year (Fig. 8b). However, treatment frequency was not random at higher rates of treatment in optimal patterns (Fig. 8c–f). Specifically, $\sim 35\%$ of the landscape would never be treated in an optimal pattern even with the highest rate of treatment (5% per year), most fuel treatments were not maintained every decade (Figs 6f, 8e).

Optimal treatments in all study areas remained more effective than random treatments (Fig. 9) in reducing fire growth rate under weather conditions more moderate (90th and 95th percentile) than specified in the design (99th percentile). The relative benefit of treatment, however, decreased as conditions became more moderate because fire behaviour contrasts decrease between treated and untreated areas.

Discussion

The present study of long-term landscape-level effects of fuel treatments required the development of a complex simulation system that linked several different models. Each system component had its own assumptions and contributed potential sources of variability to the behaviour of the whole system. Also, by comparison with reality, uncertainty and error in fire, fuel, and forest modelling can overwhelm many detailed settings of the models (i.e. differences between modelled and realised treatment prescriptions, the timing of thinning and burning, the occurrence and behaviour of wildfires, and the characterisation of fuel conditions). Within this context of uncertainty, we chose to limit the contribution of variability from the simulation system so that trends might be more easily interpreted. Among those detailed as our methods, we established the timing of all treatments occurring within the decadal cycle, identified a single wildfire weather scenario as the target condition, and selected the treatment location by optimisation and randomisation. The outputs from the simulation, therefore, reflect the various settings and assumptions as well as the intended interactions of the core models. The results hopefully elucidate trends to be expected at scales of time and space broader than can be readily observed.

The simulations for the four study sites consistently suggested that all treatment rates (1 to 5% per year) accumulated benefits to reduced fire spread rate, wildfire sizes, and burn probability out to about two decades. Beyond that point in time, additional treatment produced little marginal reduction in the landscape fire metrics but continued treatment would be required to maintain these benefits. Additionally, treatment rates beyond $\sim 2\%$ per year in optimal patterns produced little added benefit for the study areas. This is probably a result of the inherent

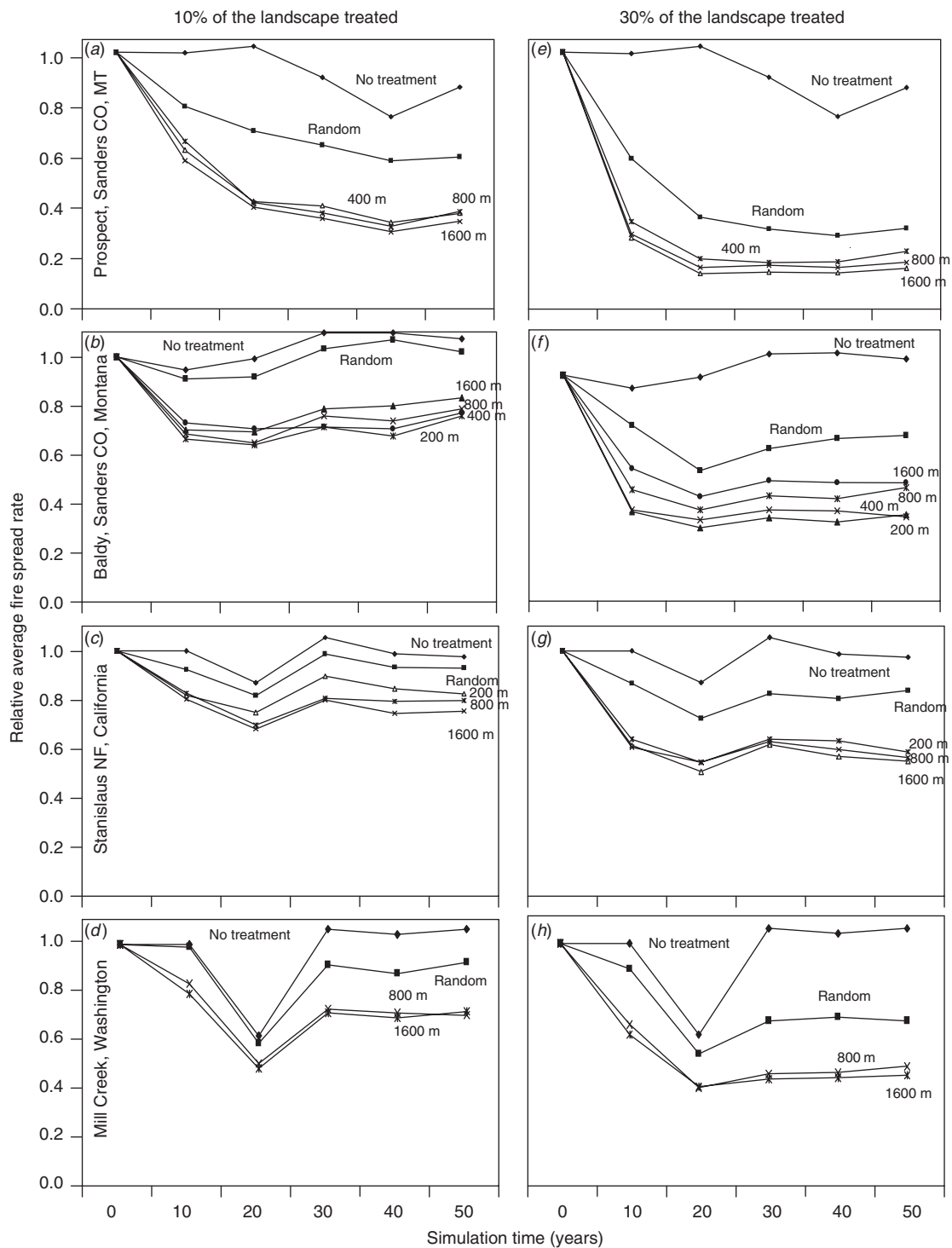


Fig. 5. The effect of treatment magnitude on average fire spread rate for the three study areas. The cumulative effects over time of random and optimally placed treatments were similar for all sites. There was little effect of maximum treatment unit dimension on the average fire spread rate.

fuel accumulation and decomposition rates, which determine longevity of individual treatments. Few studies have directly measured fuel accumulation, but van Wagtenonk and Sydoriak (1987) found that litter and fine twigs returned to preburn

levels in 5–7 years in the Sierra Nevada mountains of California. The results of the present study are generally similar to the findings of Biswell *et al.* (1973), Fernandes *et al.* (2004), and Finney *et al.* (2005), who reported fuel treatment mitigation of wildfire

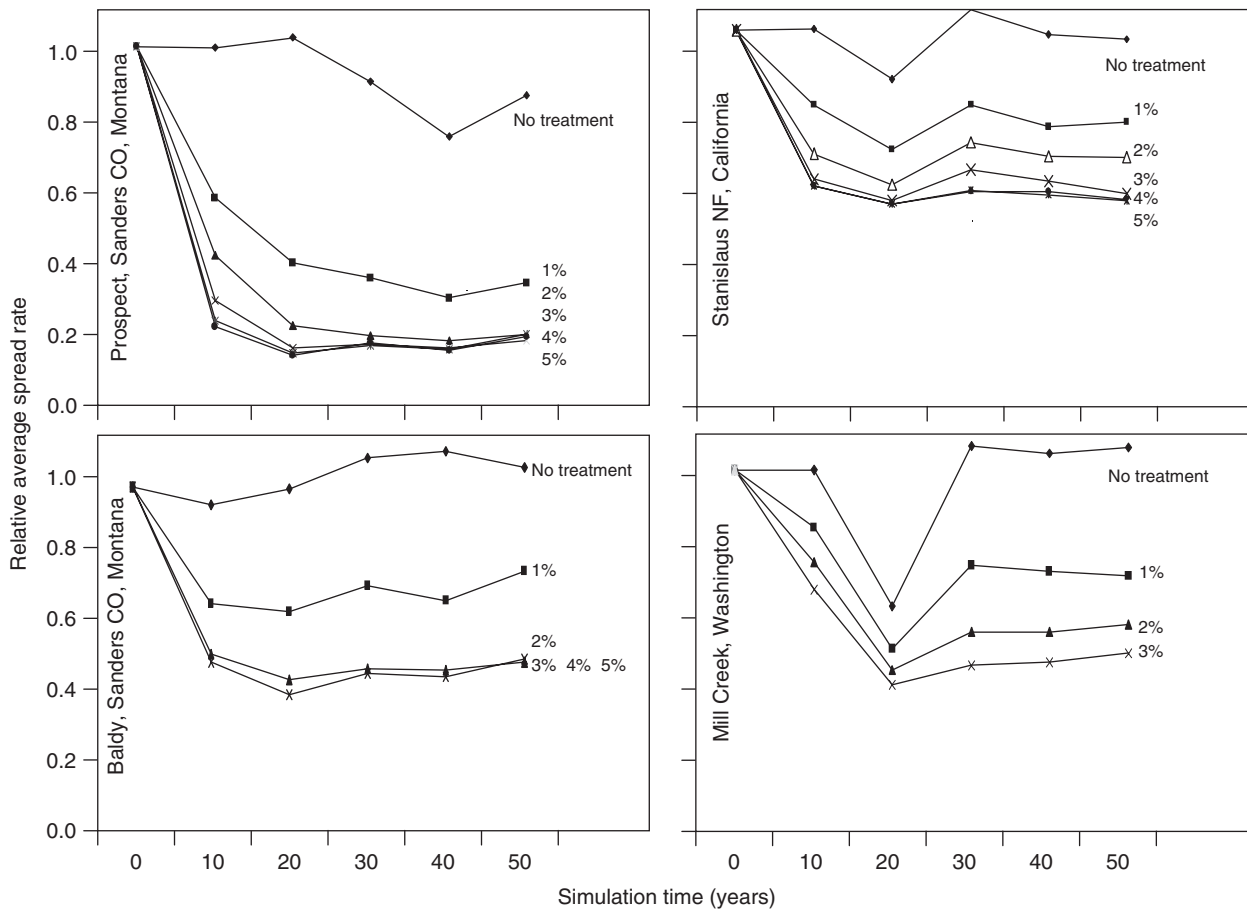


Fig. 6. Treatments implemented at a rate of $\sim 2\%$ per year produced overall reductions in average fire spread rate similar to higher treatment rates for all study areas. Treatment rates of up to 2% per year required about two decades to reach the cumulative benefit reached in the first decade for higher rates of treatment. All results are displayed for 800-m treatment units, but trends are nearly identical for unit sizes of 200, 400 and 1600 m.

severity out to 15, 13, and 9 years, respectively. These timeframes for treatment longevity imply certain rates of treatment by land management planners, namely that a substantial level of effort is required over the course of about two decades to realise fuel treatment benefits to mitigating large fire behaviours. Such effort has long been advocated as a critical part of overall fire management (Brackebusch 1973; Arno and Brown 1991). Evidence for effectiveness of such large-scale efforts was documented by Weaver (1957) and suggested that prescribed burning in eastern Washington State over 11 years, which covered $\sim 6\%$ of the landscape, reduced fire occurrence on the treated lands by 97% and area burned by 90% compared with the untreated areas. We did not study the trajectories of treatment benefit related to changing the treatment rate through time, but, because higher treatment rates seemed to accelerate the production of benefits, higher rates might be desirable in the first decade followed by later decreases.

The three response variables of large fires (average fire spread rate, average fire size, and average burn probabilities) all showed similar decreases as fuel treatment amounts increased, both for optimal and for random patterns. Explanation for the similarity in these measures is straightforward, given that faster fires will produce larger fires in an equal amount of time; larger fires burn

a larger fraction of the landscape each time and thereby increase the burn probability. This is useful information for landscape fuel treatment planning in the context of risk assessment (Miller *et al.* 2000; Preisler *et al.* 2004; Finney 2005) because burn probability is a main component of risk analysis and calculation of expected loss. Fuel treatments can be designed to decrease burn probability by considering both the treatment prescription at the stand level and the spatial arrangement of the stands at the landscape level.

The reduction in spread rate from optimised treatments (compared with random) suggested differences among study sites possibly related to FVS simulation of temporal changes in forest structure and fuel dynamics following treatment. For example, biomass productivity was greatest and lowest in Montana and probably reduced the longevity of treatment effects on canopy structure and surface fuel accumulation. Differences could also be a function of the particular spatial configurations of fuel types for each landscape because the initial patterns dictated the areas suitable for treatment. Both of these factors likely affected the outcome of the simulations because the differences among study areas were consistent regardless of the use of optimal or random spatial fuel treatment patterns. Thus, either rapid recovery of

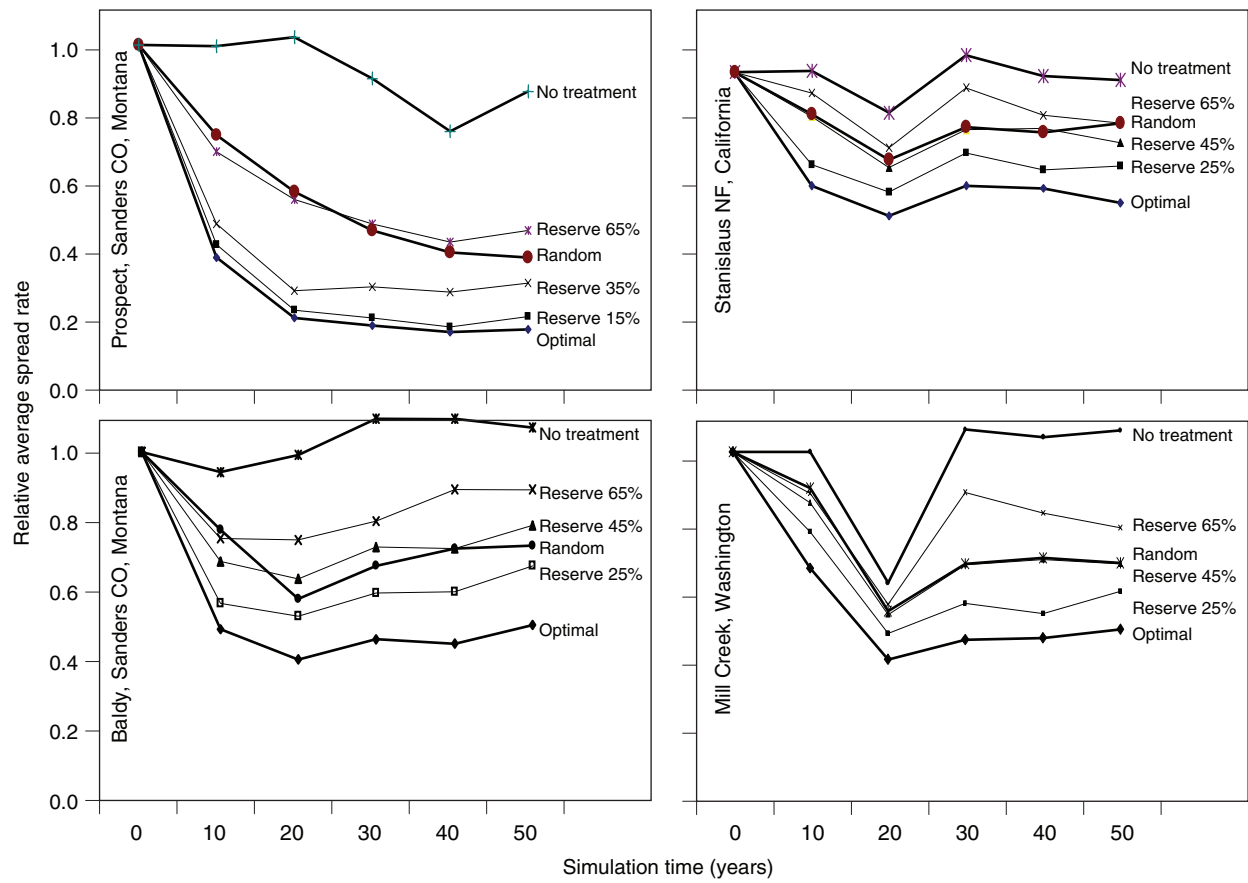


Fig. 7. Simulated reserves of land area from fuel treatment reduced the effectiveness of optimal treatment patterns to the point that reserving 45 to 65% produced results similar to or even less effective than random patterns.

fuels after treatment or limited positions of candidate treatment areas would have similar effects on reducing overall effectiveness on the landscape-level fire metrics. Variability in the fire spread rate also occurred even without treatment, for example the large decrease in spread rate during the second decade at the California and Washington study sites (Figs 5–7). The source of such variability is unknown, but is possibly an artefact of initial conditions used for FVS-PPE.

Despite the complexity of the landscapes studied here and the complexity of modelling required to characterise fuels, fires, and treatments units, these results of the optimal and random landscapes correspond well with those based on the theoretical analysis of simple landscapes (Finney 2001a, 2001b, 2003). For spatially optimal patterns, increasing the treatment rate reduces fire spread rate in a negative exponential-type fashion. This result was found for all study sites and treatment unit sizes, although the magnitude of the decrease depended on the particular landscape. Differences found here are interpreted to be the consequence of different spatial patterns of fast- and slow-burning fuel types on the real landscapes that dictate the opportunities and impacts of the particular treatment units. The decrease in spread rate with increasing treatment arranged in random patterns did not exhibit the sigmoidal trend found from analysis of simple spatial landscapes (Finney 2003), however, but the random pattern was

much less efficient in reducing large fire spread than the optimal patterns. The topological inefficiency of random patterns was also verified by other theoretical studies (Bevers *et al.* 2004; Loehle 2004). Together, these results are useful for drawing general conclusions about the role of spatial treatment patterns on fire growth. The theoretical and spatially simple results apply quite well to the expected trends for treatments on actual landscapes.

The benefits of optimal treatment patterns appear to be robust to uncertainties in weather (wind speed and fuel moisture) as revealed for weather conditions more moderate than those for which the patterns were designed (Fig. 9). Under moderate weather conditions, the contrast in fire behaviour between treated and untreated areas is diminished (fire spread rate and intensity tend towards similar values). This means that the treatments will result in a smaller proportional reduction in fire area than under extreme conditions. However, the primary reason that treatments were not designed for moderate fire weather is that modern suppression policies do not permit large wildland fires to spread when suppression organisations are generally successful in limiting fire spread. Thus, fire behaviour is generally more benign, fire suppression more effective, and treatments less necessary for changing fire behaviour when weather conditions are moderate.

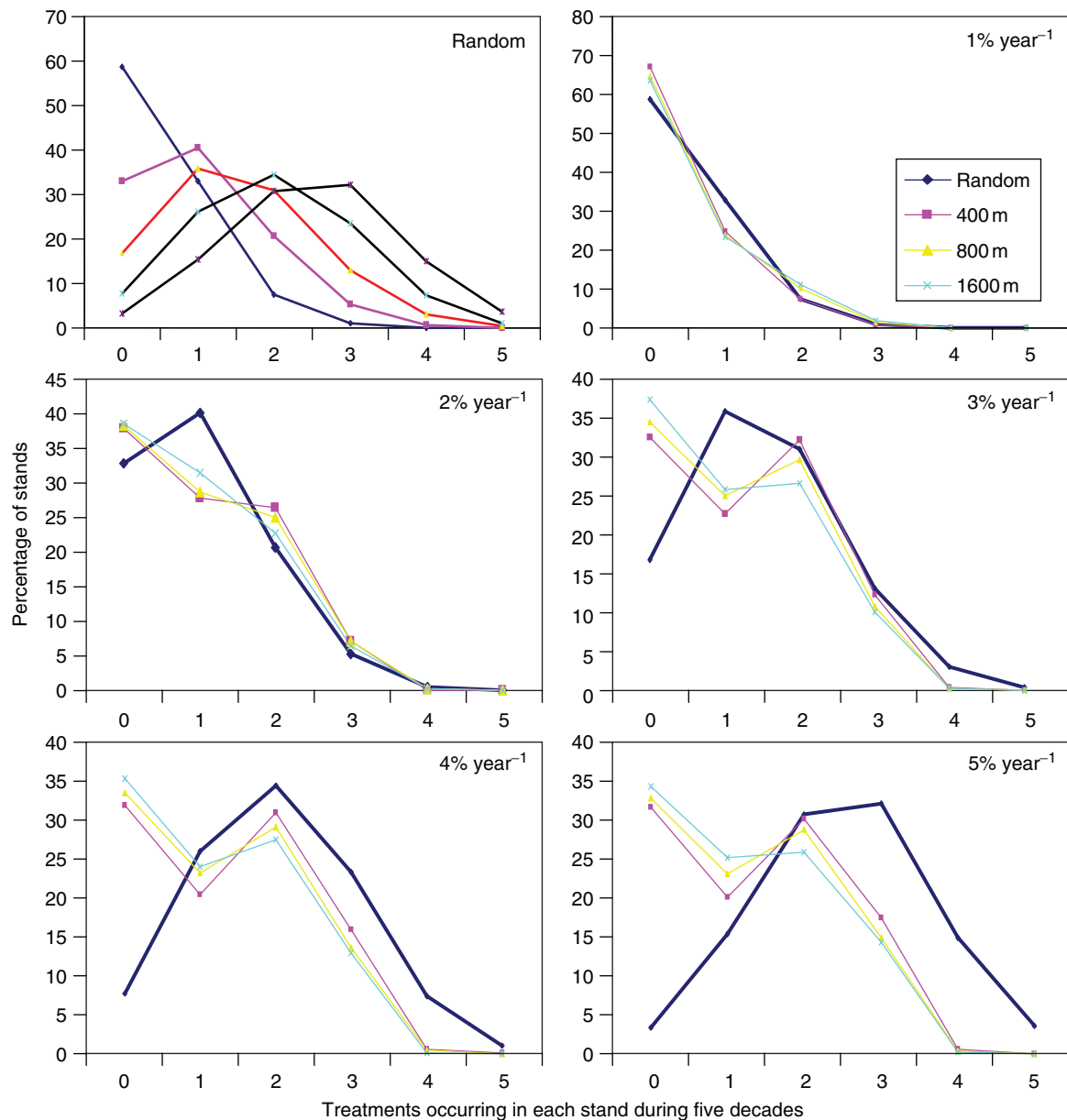


Fig. 8. The question of maintaining treatment areas or implementing new treatments was summarised by the frequency of treatment over five decades. Random treatment resulted in Poisson frequency distributions. At treatment rates of 2% and greater per year, the optimal treatment strategy consistently excluded some areas from treatment more frequently than random selection and refused frequent treatment for other areas.

The effects of reserving areas from treatment, irrespective of the location or need for treatment, decreased the effectiveness of an optimal treatment pattern and compromised the optimal solutions entirely at $\sim 50\%$ reserved. This has bearing on the treatment planning process in land management operations where restrictions are imposed for a variety of reasons, including concern for treatment impacts on wildlife habitat, restrictions on proximity to streams or rivers, road access, budget limitations, or ownership. These simulations generally suggest that treatment restrictions amounting to more than $\sim 40\%$ of a landscape would diminish any advantage an optimal solution would achieve over

purely random treatment placement. The specific topology of the various fuels and restrictions for a particular landscape, however, would likely be different than this generalisation. For instance, riparian reserves and habitat networks have spatial patterns that are substantially different than random patterns assumed in the present study. Nevertheless, if land managers intend to achieve reductions in large fires, collaboration with all concerned parties would likely be necessary to accommodate treatment locations to achieve landscape-level effects.

The five-decade simulations suggest that both maintenance of existing units and implementation of new units are important to

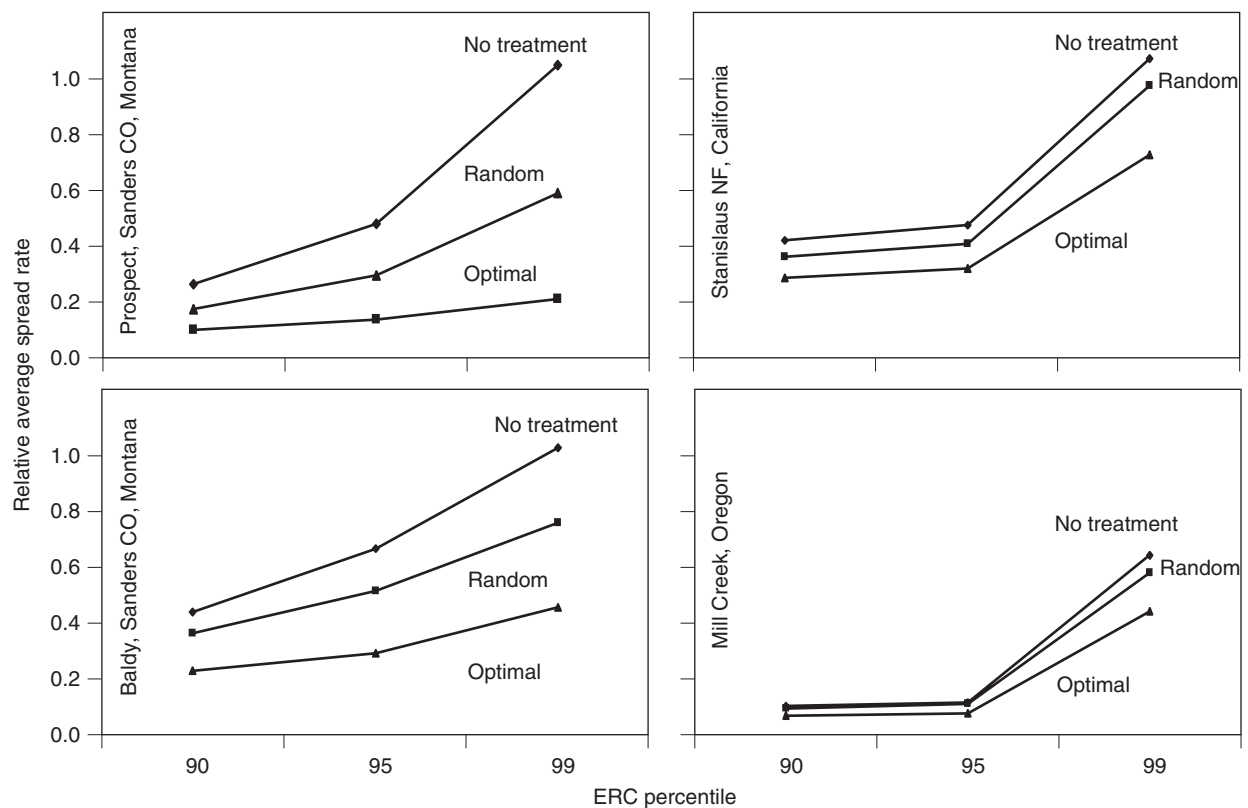


Fig. 9. Comparison of fuel treatment effects (at a rate of 2% per year) on relative fire spread rate across a range of fire weather percentiles suggests that optimal treatment effects are robust under weather more moderate than the conditions specified for optimisation (99th percentile). Spread rates are shown for the second decade of simulation (when collective treatment effects are near maximum) and normalised for each study area relative to the spread rate at the beginning of the simulation (i.e. 0 years). Weather percentiles are expressed in terms of Energy Release Component (ERC) from the National Fire Danger Rating System and primarily reflect changes in moisture content.

the optimisation of spatial treatment patterns. The frequency of retreatment in the optimal landscape was different than produced by chance with the random treatments (Poisson distributed), which indicates that the choice of fuel treatment activity was driven by functional concerns. Compared with the random patterns, the optimisation attempted more treatments on new stands than on re-treating old stands, probably because the treatment benefits endured for more than one decade. It is unknown how the pattern would change if the simulation were to have continued for 100 years, for example, which would have greatly exceeded the timeframe of treatment performance.

Variation in treatment unit sizes had the least impact on modifying large fires compared with treatment pattern and rate of treatment. This may have resulted because the fire modelling used here did not account for spotting and consequent breaching of treatment units by flying embers. In the absence of spotting, however, large and small units were found to produce similar reductions in fire sizes, spread rates, and burn probabilities at all levels of treatment. Slightly lower efficiency (e.g. amount of reduced spread rate per unit area treated) of the smallest treatment unit sizes for all study sites, however, suggests that emphasising small units may restrict opportunities to block fire movement in some critical locations that require large units. That is, small units cannot effectively block the movement through

large corridors where fire easily moves. The optimisation algorithm used here was not flexible enough to effectively mix both small and large units.

Conclusions

The simulations suggested that long-term treatment effects are primarily dependent on the rate of application of treatments and the spatial patterns of treatment units. Treatment rates of 1 to 30% per year reached a cumulative maximum effectiveness in about two decades in all study areas. Higher rates of treatment did not improve the cumulative effects beyond the first decade. Random treatment patterns also produced cumulative effects on fire behaviour but were less efficient than the optimised patterns, requiring about twice the area to be treated compared with optimal patterns. As this work focussed only on the consequences of fuel treatments optimised for changing large fire growth, any application of these results to land management would necessarily consider many other factors in treatment design that were not addressable by this research.

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