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Evaluation of the effects of silvicultural and fuels treatments on potential fire behaviour in Sierra Nevada mixed-conifer forests

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Abstract

Fire suppression has increased fuel loads and fuel continuity in mixed-conifer ecosystems, resulting in forest structures that are vulnerable to catastrophic fire. This paper models fire behaviour in a mixed-conifer forest and investigates how silvicultural and fuels treatments affect potential fire behaviour. The computer program FARSITE was used to spatially and temporally model fire growth and behaviour. Fire modelling was performed in the North Crane Creek watershed of Yosemite National Park. Treatments were simulated by adjusting fuel (total load, load-by-size class, depth), height-to-live crown base, tree height, and crown density parameters. Treatments modeled included prescribed burn, pile and burn, cut and scatter, thinning and biomass, thinning and biomass followed by prescribed burn, and salvage or group selection harvest with and without slash and landscape-level fuel treatment. The prescribed burn, thinning and biomassing followed by prescribed burn, and salvage or group selection with slash and landscape fuel treatments resulted in the lowest average fireline intensities, heat per unit area, rate of spread, area burned, and scorch heights. Cut and scatter, salvage or group selection treatments that do not treat slash fuels resulted in fire behaviour that is more extreme than the untreated forest. Restoration of mixed-conifer ecosystems must include an examination of how proposed treatments affect fuel structures. Combinations of prescribed fire and/or mechanical treatments can be used to reduce wildfire hazard. © 1998 Elsevier Science B.V.

Keywords: Landscape fire modelling; Fire hazard; Silvicultural treatments; FARSITE

1. Introduction

Fire was once common in mixed-conifer forests of the Sierra Nevada. Fire-scar studies at Sequoia National Park, CA, demonstrated that presettlement (pre-1875) surface fires were frequent with 2 to 3-yr mean fire return intervals within watersheds of approximately 80–100 ha, and 5 to 9-yr mean fire return intervals in sites of 3–16 ha (Kilgore and Taylor, 1979).

Fire-scar studies in giant sequoia (*Sequoiadendron giganteum* [Lindley] Buchholz.) groves in Yosemite National Park, Sequoia and Kings Canyon National Parks, and Mountain Home Demonstration State Forest, CA, suggest mean fire return intervals were as low as 2.5–3 yrs for more than 1300 yrs

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(AD 500–AD 1875) (Swetnam et al., 1992; Swetnam, 1993). Occasionally, fire-free intervals of 20–30 yrs occurred in the record.

Fire frequency was reduced in the late 19th century because of the elimination of ignitions by Native Americans, introduction of livestock grazing, and fire suppression policies (Vankat, 1977; Kilgore and Taylor, 1979; Swetnam et al., 1992).

The absence of fire in the past century has modified the structure of mixed-conifer forests of the southern Sierra Nevada (Parsons and DeBendeetti, 1979; Bonnicksen and Stone, 1982). Increased density of small shade-tolerant trees and higher surface fuel loads have also increased the hazard of extreme fire behaviour (Kilgore, 1973; van Wagtendonk, 1985). Horizontal and vertical fuel continuity have increased, resulting in forests that are vulnerable to catastrophic fire.

Restoration of mixed-conifer ecosystems must include an examination of how proposed treatments affect fuel structure. A recent comprehensive strategy intended to improve firefighter safety and increase fire cost efficiencies was released by the USDA Forest Service Department of Fire and Aviation Management (United States Department of Agriculture Forest Service, 1995). This new strategy increases the area treated by mechanical and prescribed fire treatments to 1,200,000 ha per year in fire-dependent ecosystems by the year 2005. Fuel treatments have been suggested as a means to limit the size and intensity of wildfires, but few experiments are available to analyze the effectiveness of different treatments on potential fire behaviour (van Wagtendonk, 1996).

One study has investigated crown-fire potential in a giant sequoia mixed-conifer forest before and after the use of prescribed fire (Kilgore and Sando, 1975). Before burning, this southern Sierra Nevada forest had an almost continuous vertical fuel layer from ground level to 3–15.3 m. Frequently, vertical fuel continuity was increased to 30.5 m by intermediate sized trees that commonly reached the lower crowns of dominant trees. This ladder-like arrangement of fuels creates a high potential for a fire to pass from surface fuels into the crowns of giant sequoia (Kilgore and Sando, 1975).

Prescribed fire proved to be an effective tool in reducing the potential of passive crown fires. A moderate intensity prescribed fire reduced surface fuel load by 85% and increased mean live crown base height from 0.9 to 4.9 m (Kilgore and Sando, 1975). Combustion of ladder fuels reduced oven-dry crown weight at 2 m above the soil surface from approximately 300 kg/ha to 50 kg/ha.

Individual wildfires have been observed to change their behaviour when entering areas previously treated by prescribed fire. The 1988 Buckeye wildfire in Sequoia National Park began in a chaparral below ‘Giant Forest’ and quickly moved uphill. The perimeter of the ‘Giant Forest’ had previously been treated with prescribed five years earlier, and when the wildfire reached the treated areas, it dropped to the ground and was suppressed.

The 1987 Pierce wildfire burned with mixed to predominantly high intensity through a 20 ha section of Redwood Mountain Grove in Kings Canyon National Park (Stephenson et al., 1991). The majority of this area had not burned for over a century and mortality was high in all trees except the largest giant sequoias. The wildfire burned at much lower intensity when it entered an area that had been prescribed burned 10 years earlier.

The effectiveness of different treatments can be tested with computer models. FARSITE (Finney, 1994) is a deterministic, spatial, and temporal fire behaviour model that uses fuels, slope, aspect, elevation, canopy cover, tree height, height-to-live crown base, crown density, and weather as inputs. The input data required by FARSITE is extensive but the model is based largely on physics.

FARSITE was originally developed to predict the behaviour of prescribed natural fires. With the appropriate geographic information system (GIS) resources, managers can predict the behaviour and growth of lightning ignited fires and decide if the fire is within a predetermined prescription. The model has been tested under field conditions (Finney and Ryan, 1995; Finney, 1995). Graphical validations have also been conducted using four prescribed natural fires and one wildfire in Sequoia National Park (Finney, 1995).

The objectives of this study were to model fire behaviour in a mixed-conifer forest and to test the effectiveness of different silvicultural and fuels treatments in reducing the potential for extreme fire behaviour and effects.

2. Simulation area

Fire behaviour was modeled in the North Crane Creek watershed in Yosemite National Park, CA (Fig. 1). The mixed-conifer forest in this area is composed of giant sequoia, sugar pine (*Pinus lambertiana* Dougl.), ponderosa pine (*Pinus ponderosa* Laws), white fir (*Abies concolor* [Gord. and Glend.] Lindl.), incense-cedar (*Calocedrus decurrens* [Torr.] Floren.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), and California black oak (*Quercus kelloggii* Newb.). North Crane Creek originates near the Tuolumne Grove of giant sequoias and elevations in the watershed vary from 1510 to 1900 m. The UTM coordinates of the modeled area are (248,000; 4,185,000), (248,000; 4,183,000), (254,000; 4,185,000), and (254,000; 4,183,000), resulting in an area of 1600 ha for each simulation.

3. Methods

3.1. Simulation and model assumptions

FARSITE uses BEHAVE (Rothermel, 1972, 1983; Andrews, 1986) to model surface fire behaviour. BEHAVE does not use fuels larger than 7.6 cm in diameter when calculating fire behaviour. Large fuels can produce significant ecosystem effects due to long burn-out periods, and the heat produced from the combustion of these fuels can be an important factor in the initiation and spread of crown fires (Rothermel, 1991, 1994). FARSITE also assumes fire spread can be approximated by an elliptical wave (Finney, 1994). Field observations of fire spread patterns have agreed with elliptical predictions (Anderson et al., 1982). BEHAVE does not assume an elliptical fire spread pattern but calculates fire behaviour variables only in the head-fire direction.

BEHAVE is a surface fire model. Modifications in FARSITE have allowed crown fire to be modeled but this area of the model has not been verified as rigorously as the surface fire component. Problems exist in modelling crown fire mainly because of limited quantitative research in the behaviour of these complex events.

FARSITE uses daily maximum and minimum temperatures and humidities and the time that maximum and minimum temperatures occurred to calcu-

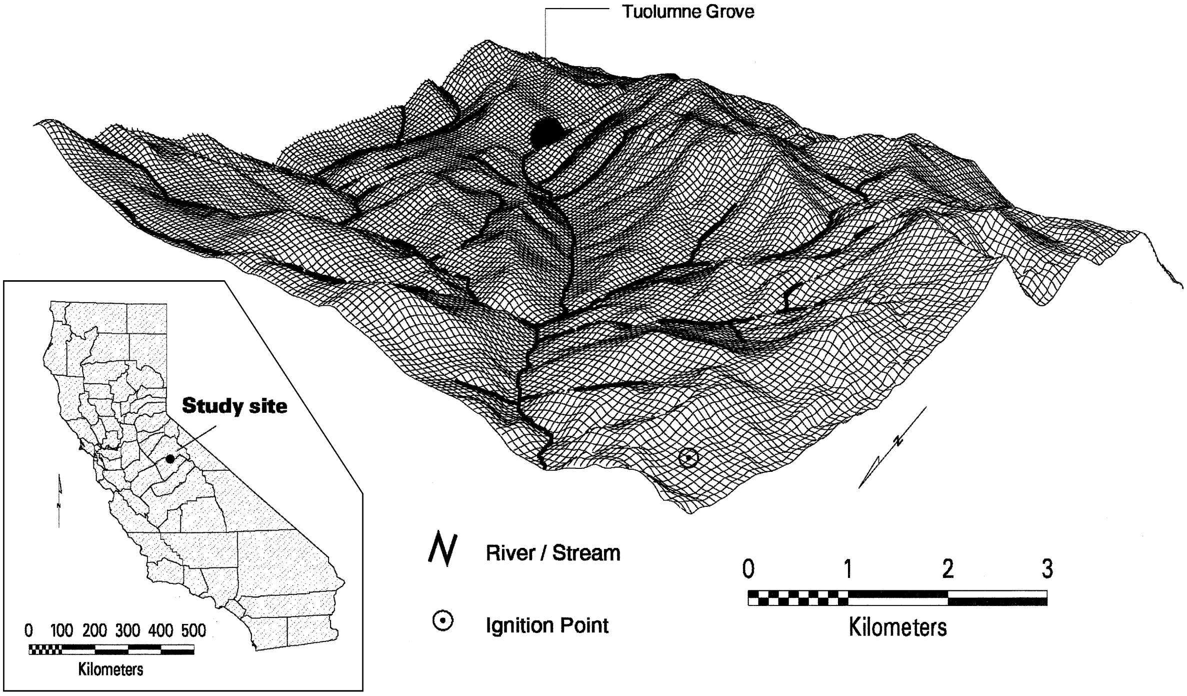

Fig. 1. North Crane Creek fire simulation area, Yosemite National Park, California.

late fuel moisture. This is a simplification of the actual weather stream but was done to reduce data requirements for the simulation.

FARSITE uses raster-based GIS files as inputs. The spatial resolution of the raster files can be set by the user, but once set, the attributes of each cell are constants. In this study, the spatial resolution is 30 m by 30 m and each cell has been assigned a fuel model, aspect, elevation, slope, canopy cover, tree height, crown bulk density, and height-to-live crown base.

The fuel model assumes a homogeneous fuel load within each cell, which is a simplification of the actual landscape because small-scale differences in topography, canopy cover, and fuels will affect fire behaviour. Accurate data for such small differences would be very difficult and expensive to obtain. The simulations also assume a constant height-to-live crown base and crown bulk density (Van Wagner, 1993) for different treatments.

3.2. Fire simulations

FARSITE was used to model the effects of different fuel and silvicultural treatments. The elevation, slope, aspect, fuel model, and canopy cover information was provided by Yosemite National Park research scientist Jan van Wagtendonk (1997, personal communication). Yosemite currently has the most accurate and highest-resolution spatial fuel information in the Sierra Nevada. The fuel map was produced by remote sensing using thermatic mapper images (van Wagtendonk, 1997).

Standard BEHAVE fuel models were assigned to each 30 m by 30 m raster cell in the North Crane Creek watershed. The watershed is dominated by BEHAVE timber fuel models 8, 9, and 10 that were assigned on the basis of overstory density and surface fuel load. Fuel models 2 (grass) and 5 (shrubs) were also assigned in the North Crane Creek watershed but were relatively rare, covering less than 5% of the simulation area. Fuel model 0 (bare ground) was assigned to rock out crops. Tree canopy cover was separated into the following categories: 1–20%, 21–50%, and 50–80% depending on overstory density. Canopy cover is necessary for computing shading, and wind reduction factors for fuels other than the standard 13 BEHAVE models (Finney, 1996).

Each simulation was run in the same area with a common ignition point approximately 6 km northwest of the Tuolumne Grove of giant sequoias (Fig. 1). The duration of each simulation was 24 h beginning at 12:00 PM and ending at 12:00 PM the following day. Weather information at the 95th and 75th percentiles from the Crane Flat lookout was obtained from Yosemite National Park (Jan van Wagtendonk, 1995, personal communication) and is summarized in Table 1. Weather information at the 95th and 75th percentiles describes fire weather conditions that occur, on average, 5% and 25% of the year, respectively. Windspeeds used in FARSITE simulations are 6 m (20-ft) windspeeds.

The ignition point was placed in the lowest region of the North Crane Creek watershed within the park. All fire simulations were unconstrained by suppression activities. Outputs from the simulation include fire line intensity (Byram, 1959), heat per unit area, rate of spread, area burned, and whether spotting and crowning occurred. Scorch height was calculated from fireline intensity and windspeed (Van Wagner,

Table 1
Weather information used in fire simulations of the North Crane Creek watershed

	75th percentile	95th percentile
Maximum temperature (°C)	18	32
Minimum temperature (°C)	7	16
Maximum humidity (%)	60	40
Minimum humidity (%)	20	10
Time of maximum temperature and windspeed (h)	1400	1400
Time of minimum temperature and windspeed (h)	500	500
Maximum/minimum windspeeds (km/h)	9.6/3.2	28.8/19.2
Wind direction (degrees)	285	285

Table 2
Characteristic of custom fuel models used in fire simulations in the North Crane Creek watershed

Model parameter	Model number				
	14	15	16	17	18
1-h fuel load (ton/ha)	2.3	3.4	3.4	0.9	5.6
10-h fuel load (ton/ha)	1.4	0.4	2.3	0.5	10.1
100-h fuel load (ton/ha)	2.3	0.2	5.6	0	12.4
Live fuel load (ton/ha)	0	0	2.3	1.1	0
1-h surface area/volume ratio (ft^{-1})	2000	2500	2000	2000	2000
Live fuel surface area/volume ratio (ft^{-1})	n.a.	n.a.	1500	1500	n.a.
Fuel depth (m)	0.03	0.03	0.15	0.18	0.45
Canopy cover (%)	1–80	1–80	1–80	0	1–80
Extinction moisture content (%)	30	25	25	20	20
Fire rate of spread adjustment factor	0.5	0.5	0.5	0.25	0.5

n.a. = not applicable.

1973). This information was used to compare the effectiveness of 12 different fuel treatments.

Differences in treatments were simulated by changing fuel characteristics (total load, load by size class, depth), height-to-live-crown base, canopy cover, and crown bulk density. Crown bulk density values were derived from published work (Brown, 1978). Characteristics of custom (Burgan and Rothermel, 1984) and standard fuel models used in the simulations are summarized in Tables 2 and 3. Custom fuel models were developed and used when the 13 standard BEHAVE fuel models were not applicable. Adjustment factors for fire rate of spread were used to calibrate simulated fire spread to actual conditions (van Wagtendonk and Botti, 1981; Rothermel and Rinehart, 1983) (Table 2).

The 12 treatments simulated are enumerated below.

(1) No treatment, extensive ladder fuels present. Fuel load and vertical fuel continuity are high. Surface fuels consist of unmodified BEHAVE models (Anderson, 1982). Height to live-crown-base set to 1 m to simulate extensive ladder fuels. Crown bulk density of 0.3 kg/m^3 is assigned to all timber fuel models (Brown, 1978). Crown cover of 1–20, 21–50, and 50–80% assigned to fuel models 8, 9, and 10 depending on overstory density; crown cover of 1–20% assigned to fuel model 5.

(2) Prescribed burn. Simulates fuel conditions after a moderate consumption, moderate intensity prescribed burn. Prescribed burn would probably occur in late fall and fireline intensity would be

Table 3
Characteristic of standard fuel models used in fire simulations in the North Crane Creek watershed

Model parameter	Model number					
	2	5	8	9	10	12
1-h fuel load (ton/ha)	4.5	2.3	3.4	6.5	6.8	9
10-h fuel load (ton/ha)	2.3	1.1	2.3	0.9	4.5	31.5
100-h fuel load (ton/ha)	1.1	0	5.6	0.3	11.3	37.1
Live fuel load (ton/ha)	1.1	4.5	0	0	4.5	0
1-h surface area/volume ratio (ft^{-1})	3000	2000	2000	2500	2000	1500
Live fuel surface area/volume ratio (ft^{-1})	1500	1500	n.a.	n.a.	1500	n.a.
Fuel depth (m)	0.3	0.6	0.06	0.06	0.3	0.7
Canopy cover (%)	0	1–20	1–80	1–80	1–80	0
Extinction moisture content (%)	15	20	30	25	25	20
Fire rate of spread adjustment factor	0.5	0.25	0.5	0.5	0.5	0.5

n.a. = not applicable.

moderated by firing pattern and fuel moisture content (Martin and Dell, 1978). Surface fuel load and depth are reduced by 50% in this treatment, and areas originally assigned to fuel models 8, 9, 10, and 5 are reassigned to custom models 14, 15, 16, and 17, respectively. Height-to-live crown base increased to 2 m by burning. No change in crown bulk density or canopy cover occurred because overstory trees were not affected by treatment.

(3) Pile and burn. Ladder fuels are mechanically cut by hand crews and/or machinery. Material is then piled and burned when original surface fuels will not combust, probably after first significant precipitation. Treatment removes ladder fuels but does not alter original surface fuels. Height to live crown base increased to 2 m. No change in crown bulk density or crown cover occurred because overstory trees were not affected by treatment.

(4) Cut and scatter. Ladder fuels are mechanically cut by hand crews and/or machinery. Fuels are lopped and scattered on site, resulting in higher surface fuel load. Height-to-live crown base increased to 2 m. Areas of fuel models 8, 9, and 10 are assigned to custom fuel model 18 to simulate effects on surface fuels. No change in crown bulk density or canopy cover occurred because overstory trees are not affected by treatment.

(5) Thinning and biomass. Ladder fuels and trees of intermediate size are mechanically cut by hand crews and/or machinery. All harvested material is taken off site, original surface fuels unchanged. Height-to-live crown base increased to 2 m, and crown bulk density is reduced by 50% because of removal of overstory trees. Canopy cover originally assigned values of 81–100% changed to 50–80%, all other canopy cover classes remain unchanged because this operation would alter remaining canopy cover classifications.

(6) Thinning and biomass followed by prescribed burn. Ladder fuels and trees of intermediate size are mechanically cut by hand crews and/or machinery. The configuration is identical to no. 5 except surface fuel load and depth are reduced by 50% from burning, and areas originally assigned to fuel models 8, 9, 10, and 5 are reassigned to custom models 14, 15, 16, and 17, respectively.

(7) Salvage harvest operation without slash or landscape level fuel treatment. Simulates a salvage logging operation that removes standing dead trees and leaves the resulting logging slash on site. Surface fuel load will be dramatically increased in the area of the salvage operation, and the remaining landscape will be untreated. The simulation uses a single 30 meter square (raster GIS) opening to represent the area covered by a salvage operation. In most cases, a relatively small group of trees are removed by such salvage operations, and this opening is representative of such a treatment. Six hundred of these openings were randomly placed inside the simulation area and summed together; they cover 2% of the area. Surface fuels in areas outside the salvage operation consist of unmodified models, and height-to-live crown base set to 1 m to simulate extensive ladder fuels. Openings with untreated salvage slash are simulated by fuel model 12 which represents intermediate levels of slash. Crown cover within the openings was assigned a value of 0. Crown bulk density and crown cover remains unchanged in untreated landscape.

(8) Salvage harvest operation with slash treatment but without landscape level fuel treatment. Treatment simulates a salvage logging operation that removes standing dead trees and burns the resulting slash fuels. The configuration is identical to no. 7 except the salvage opening is assigned fuel model 0 which represents bare ground.

(9) Salvage harvest operation with slash and landscape-level fuel treatment. Treatment simulates a salvage logging operation that removes standing dead trees, burns the resulting slash fuels, and treats the remaining landscape with prescribed fire. The configuration is identical to no. 8 except fuel models 8, 9, 10, and 5 are reassigned to custom models 14, 15, 16, and 17, respectively. Height-to-live crown base increased to 2 m by burning. No change in crown bulk density or crown cover occurs in landscape because overstory trees are not affected by treatment.

(10) Group selection harvest operation without slash or landscape-level fuel treatment. Simulates an uneven-aged group selection silvicultural operation that removes all trees within the group and leaves the resulting logging slash on site. Surface fuel load will be dramatically increased in the area of the harvesting, and the remaining landscape will be untreated. Simulation uses five 30 meter square pixels to produce an opening area of 0.45 ha for each group

Table 4
Fuel and canopy characteristics used in fire simulations in the North Crane Creek watershed

Treatment	Fuel models used	Crown density (kg/m^3)	Height-to-live crown base (m)
None	0, 2, 5, 8, 9, 10	0.3	1
Prescribed burn	0, 2, 5 = 17, 8 = 14, 9 = 15, 10 = 16	0.3	2
Pile and burn	0, 2, 5, 8, 9, 10	0.3	2
Cut and scatter	0, 2, 5, 8 = 18, 9 = 18, 10 = 18	0.3	2
Thinning and biomass	0, 2, 5, 8, 9, 10	0.15	2
Thinning and biomass followed by prescribed burn	0, 2, 5 = 17, 8 = 14, 9 = 15, 10 = 16	0.15	2
Salvage without slash or landscape fuel treatment	0, 2, 5, 8, 9, 10, 12	0.3	1
Salvage with slash treatment but without landscape fuel treatment	0, 2, 5, 8, 9, 10	0.3	1
Salvage with slash and landscape fuel treatment	0, 2, 5 = 17, 8 = 14, 9 = 15, 10 = 16	0.3	2
Group selection without slash or landscape fuel treatment	0, 2, 5, 8, 9, 10, 12	0.3	1
Group selection with slash treatment but without landscape fuel treatment	0, 2, 5, 8, 9, 10	0.3	1
Group selection with slash and landscape fuel treatment	0, 2, 5 = 17, 8 = 14, 9 = 15, 10 = 16	0.3	2

selection unit. Six hundred of these openings were randomly placed inside the simulation area and summed together; they cover 10% of the area. Surface fuels in areas outside the salvage operation consist of unmodified models. Height-to-live crown base is set to 1 m to simulate extensive ladder fuels and the openings are simulated by model 12 which represents intermediate levels of slash fuels. Crown cover within the openings was assigned a value of 0. No change in crown bulk density or crown cover occurs in landscape because overstory trees are not affected by treatment.

(11) Group selection harvest operation with slash treatment but without landscape-level fuel treatment. Treatment simulates an uneven-aged group selection silvicultural operation that removes all trees within the group and burns the resulting slash fuels. The configuration is identical to no. 10 except the group selection opening is assigned fuel model 0 which represents bare ground.

(12) Group selection harvest operation with slash treatment and landscape-level fuel treatment. Treatment simulates an uneven-aged group selection silvicultural operation that removes all trees within the group, burns the resulting slash fuels, and treats the remaining landscape with prescribed fire. The configuration is identical to no. 11 except fuel models 8, 9, 10, and 5 are reassigned to custom models 14, 15, 16, and 17, respectively. Height-to-live crown base increased to 2 m by burning. No change in crown bulk density or crown cover occurs in the landscape because overstory trees are not affected by treatment.

All new models were created and tested using new-model and test-model BEHAVE applications. Table 4 specifies which models were used in each treatment and also gives overstory parameters used in the simulations. Initial fuel moisture contents re-

Table 5
Initial fuel moisture values used in fire simulations in the North Crane Creek watershed

	75th percentile	95th percentile
1-h fuel moisture (%)	6	4
10-h fuel moisture (%)	8	6
100-h fuel moisture (%)	10	8
Live woody fuel moisture (%)	110	90
Live herbaceous fuel moisture (%)	110	90

Table 6
Average results of fire simulations with 75th percentile weather conditions in the North Crane Creek watershed

Treatment	Fireline intensity (kW/m)	Heat/area (kJ/m^2)	Area burned (ha)	Scorch height (m)	Spotting and crowning	Passive crown fire
None	72.81	5241.79	7	6.71	no	no
Prescribed burn	7.94	1750.74	6	1.53	no	no
Pile and burn	65.29	4613.31	24	6.24	no	no
Cut and scatter	84.47	7975.95	33	7.41	yes	no
Thinning and biomass	68.75	4754.09	25	6.46	no	no
Thinning and biomass followed by prescribed burn	6.61	1712.88	6	1.36	no	no
Salvage without slash or landscape fuel treatment	87.59	5389.29	24	7.59	yes	no
Salvage with slash treatment but without landscape fuel treatment	22.75	3294.54	18	3.09	no	no
Salvage with slash and landscape fuel treatment	8.23	1797.45	7	1.57	no	no
Group selection without slash or landscape fuel treatment	114.36	8382.84	26	9.07	yes	no
Group selection with slash treatment but without landscape fuel treatment	85.96	4467.26	17	7.50	no	no
Group selection with slash and landscape fuel treatment	8.34	1721.45	7	1.58	no	no

Table 7
Average results of fire simulations with 95th percentile weather conditions in the North Crane Creek watershed

Treatment	Fireline intensity (kW/m)	Heat/area (kJ/m^2)	Area burned (ha)	Scorch height (m)	Spotting and crowning	Passive crown fire
None	481.67	6204.9	330	23.66	yes	yes
Prescribed burn	38.94	2740.93	25	4.42	no	no
Pile and burn	164.15	4529.19	120	11.54	yes	no
Cut and scatter	1070.82	8699.56	620	40.30	yes	yes
Thinning and biomass	181.34	4531.36	130	12.33	yes	no
Thinning and biomass followed by prescribed burn	37.93	2796.65	20	4.35	no	no
Salvage without slash or landscape fuel treatment	621.37	7824.89	300	28.03	yes	yes
Salvage with slash treatment but without landscape fuel treatment	457.53	6869.00	170	22.86	yes	yes
Salvage with slash and landscape fuel treatment	34.19	2991.67	20	4.06	no	no
Group selection without slash or landscape fuel treatment	1040.12	14141.37	320	39.52	yes	yes
Group selection with slash treatment but without landscape fuel treatment	425.45	8336.16	180	21.78	yes	yes
Group selection with slash and landscape fuel treatment	33.21	2885.78	16	3.98	no	no

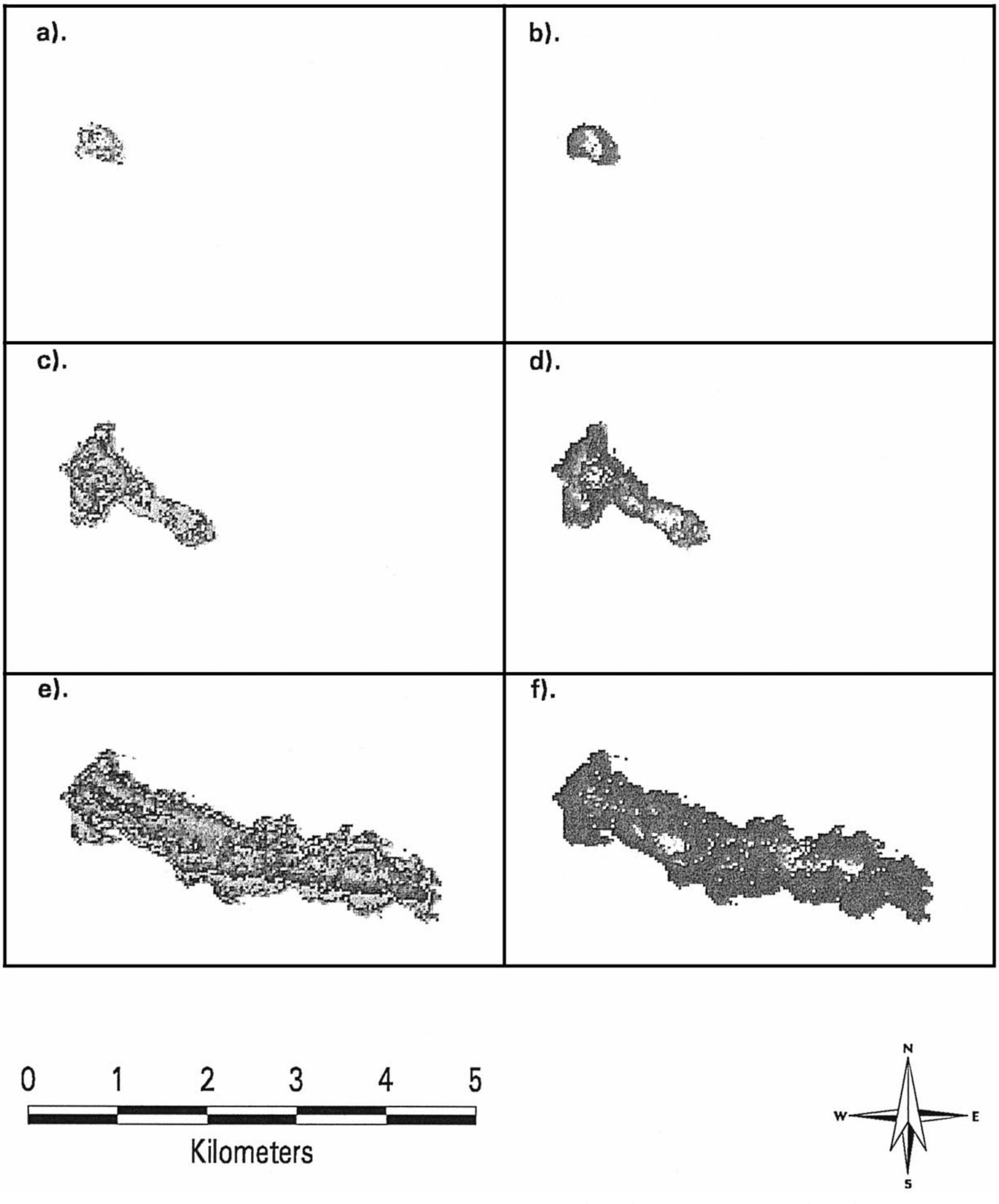

Fig. 2. GIS output files at 95th percentile weather conditions. Heat per unit area (a, c, e) and fireline intensity (b, d, f) for prescribed burn, biomass, and the untreated forest, respectively.

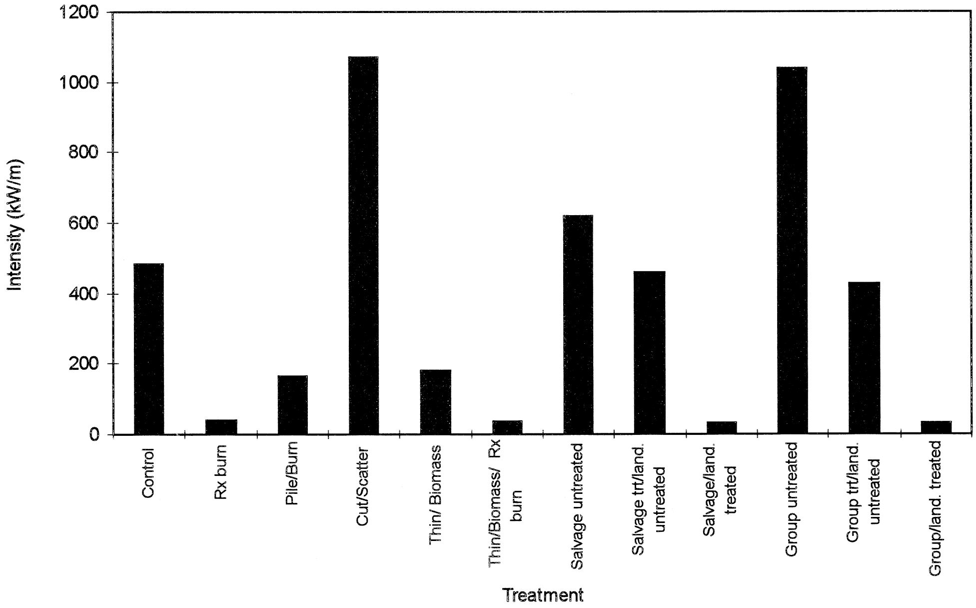

Fig. 3. Average fireline intensity at 95th percentile weather conditions, Crane Creek watershed, Yosemite National Park. Rx = prescribed fire; trt = treatment; land = landscape.

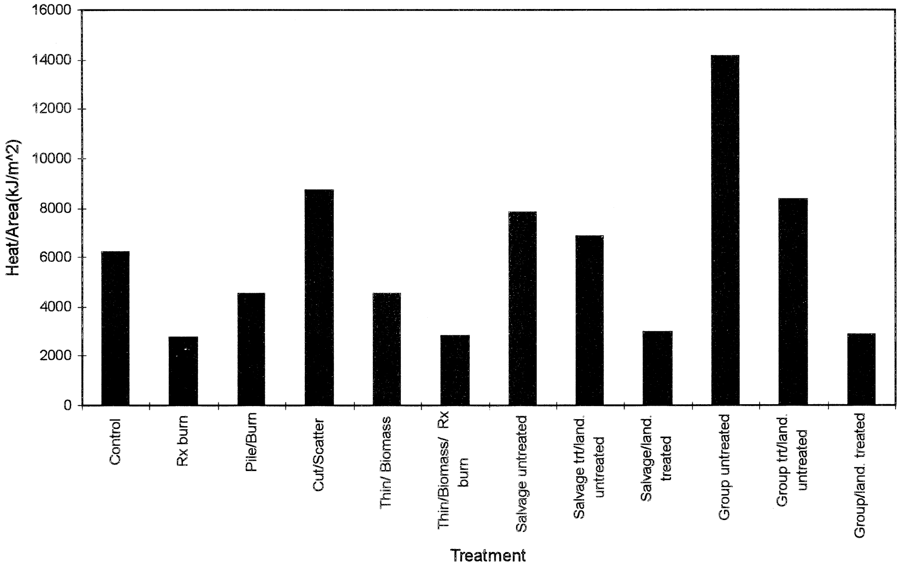

Fig. 4. Average heat per unit area at 95th percentile weather conditions, Crane Creek watershed, Yosemite National Park. Rx = prescribed fire; trt = treatment; land = landscape.

quired for the simulations are summarized for 75th and 95th percentile conditions in Table 5 and are representative of actual fuel moisture during prescribed burns (Stephens, 1995).

4. Results

The prescribed burn, thinning and biomassing followed by prescribed burn, and salvage or group selection with slash and landscape fuel treatments resulted in the lowest average fireline intensities, heat per unit area, rate of spread, area burned, and scorch height in 24 h for both the 75th and 95th percentile weather conditions (Tables 6 and 7). GIS output files for a subset of the simulations at 95th percentile weather conditions are given in Fig. 2. Fireline intensity and heat per unit area at 95th percentile weather conditions varied by a factor of 10 and 5, respectively, depending on treatment (Figs. 3 and 4).

Passive crown fires were not produced at 75th percentile weather conditions and spotting and torching occurred only when high amounts of slash were produced during the cut and scatter, salvage without slash and landscape fuel treatments, and group selection without slash or landscape fuel treatments (Table 6). This is in contrast to fire behaviour at 95th percentile weather conditions where the only treatments that did not produce spotting, torching, and passive crown fires were the prescribed fire, biomass followed by prescribed fire, and salvage or group selection with slash and landscape fuel treatments.

Crowning and spotting were produced in all other treatments at 95th percentile weather conditions and passive crown fires were produced in the untreated forest, cut and scatter, salvage without slash or landscape fuel treatment, salvage with slash treatment but without landscape fuel treatment, group selection without slash or landscape fuel treatment, and group selection with slash treatment but without landscape fuel treatment (Table 7).

5. Discussion

The GIS layers used in this work incorporated many landscape features that have a significant effect on fire behaviour such as rock outcrops, changes in topography, and changes in fuels. The fuel map also has fine spatial resolution and is much more representative of the actual landscape than a conventional vegetation map.

Maximum fire size in 24 h at 75th percentile weather conditions was only 33 ha (Table 7). The cut and scatter treatment and group selection/salvage operations without slash or landscape fuel treatment produced the highest fireline intensity, heat per unit area, rate of spread, area burned, and scorch height because these treatments increased surface fuel load.

None of the fires simulated under the 75th percentile weather conditions would pose much of a threat to the surrounding ecosystems because their moderate behaviour. Maximum scorch height was approximately 9 m, with the majority of treatments producing scorch heights of 1.5–6 m. Few trees would be killed at 75th percentile weather conditions because of low scorch height and limited fire spread. Most fires with this type of behaviour are currently suppressed by wildfire agencies (Husari and McKelvey, 1996), which over time, increases fuel load and fuel continuity in mixed-conifer ecosystems.

Torching and spotting occurred in the majority of the simulations using 95th percentile weather conditions with the exception of the prescribed burn, thinning and biomass followed by prescribed fire, and salvage or group selection with slash and landscape fuel treatments. These treatments all produced similar values for fireline intensity, heat per unit area, area burned, and scorch height in 24 h. Fire behaviour was relatively moderate and fires burning under these conditions would not kill many trees because of limited scorch heights (Stephens, 1995).

This is in contrast to the no treatment, cut and scatter, and salvage or group selection treatments that do not reduce surface fuel load within the landscapes, they produced fireline intensities over 10 times greater than the prescribed burn, thinning and biomass followed by prescribed burn, or salvage and group selection treatments that include slash and landscape fuel treatments at 95th percentile weather conditions. These fires burned into the Tuolumne Grove of giant sequoias during the 24-h simulation period, a distance of approximately 6 km. Scorch height varied from 22 to 40 m and the resulting overstory damage would kill many large trees, including giant sequoias (Stephens, 1995). Torching, spotting, and passive crown fires were also common in these simulations. Multiple spot fires were produced, making it very difficult to contain and control these high-intensity events. Most fires with this type of behaviour cannot be suppressed by wildfire agencies because of their extreme behaviour. A change in weather is needed before suppression activities would normally be successful.

The cut and scatter and salvage/group selection treatments that do not treat the slash and adjoining landscape resulted in more extreme fire behaviour than the control treatment (untreated forest). This occurred because surface fuel load was increased. Removing large, standing dead trees will not reduce fire hazard in these ecosystems. Salvage or group selection operations that treat only the slash produced during the harvesting operation will not substantially reduce the potential for extreme fire behaviour since they treat only a small percentage of the landscape.

The thinning and biomass and pile and burn treatments produced similar results. Both of them produced moderate fire behaviour but both still produced spotting and torching. The resulting fuel structures are an improvement over the control in terms of potential fire behaviour at 95th percentile weather conditions, but both still produce enough fireline intensity to kill many large trees (Stephens, 1995). Neither of these treatments burned into the Tuolumne Grove of giant sequoias within the 24-h period.

The most effective treatments for reducing fire behaviour in mixed-conifer ecosystems are the prescribed burn, thinning and biomass followed by prescribed fire, and salvage or group selection treatments with slash and landscape fuel treatments. These treatments resulted in fuel structures that will not produce extreme fire behaviour at 95th percentile weather conditions.

Further evidence that most low and medium intensity fires are suppressed is provided by a recent review on the subject (Husari and McKelvey, 1996). Nationally, only 2% of fires under the jurisdiction of the National Forest System required large-scale suppression efforts in 1994. Only the most extreme fires burn because suppressing these fires is almost impossible, given high fuel loads coupled with extreme fire weather. In 1994, 94% of the total burned acres on National Forest System lands resulted from 2% of the fires (Husari and McKelvey, 1996). This gives further testimony that only the largest, most intense fires are currently playing a significant role in ecosystem processes.

Fires that occurred prehistorically in the Sierra Nevada burned in a variety of sizes, severities, intervals, and to a lesser extent, seasons (Swetnam et al., 1992). The resulting diverse ecosystem structures, in turn, produced the conditions necessary for future diverse fires. Fire suppression has changed the prehistoric fire regimes by suppressing most low and moderate-intensity events. This fundamental change has reduced pyrodiversity (Martin and Sapsis, 1991), the variety in intervals between fires, seasonality, and fire characteristics at the micro, stand, and landscape scales in mixed-conifer ecosystems of the Sierra Nevada.

This study supports the conclusions reached by other researchers (van Wagtendonk, 1996; Weatherspoon and Skinner, 1996). van Wagtendonk (1996) used FARSITE on an artificial landscape to test the effectiveness of different fuel treatments. Results indicate that prescribed burning is the most effective treatment followed by a biomass/burn treatment in reducing fire behaviour at 95th percentile weather conditions. This study also examined the effectiveness of fuel breaks in the Sierra Nevada and found them to be ineffective at 95th percentile weather conditions.

Weatherspoon and Skinner (1996) recommend a landscape-level strategy for fuels management in the Sierra Nevada. Defensible fuel profile zones would be created on the landscape in this approach, and prescribed fire would be used to restore natural processes, where appropriate. Individual land management goals would also be used to create the fuel profiles since no one prescription is appropriate for the diverse ecosystems and ownerships of the Sierra Nevada.

The costs of implementing a large-scale fuel treatment plan will have to be investigated. Areas with high fire risk and hazard could be given higher priority in a fuel reduction program. Integration of independent assessments of fire hazard (fuel load, fuel continuity, topography), fire risk (ignitions from lightning, accidents, arson, weather), and ecosystem values (‘old-growth’ forests, wildlife habitat, structures, watersheds, timber) can be used to prioritize areas for fuel treatments. Historic fire patterns have been analyzed on National Forest System lands within the Sierra Nevada (McKelvey and Busse, 1996) and could be used to in the development of fire risk.

Mechanical treatments such as group selection and salvage operations with landscape-level fuel treatments can be applied to reduce fuel loads in mixed-conifer ecosystems. In other areas, prescribed fire may be the only appropriate tool that can be applied to reduce fuel loads and fuel continuity. Prescribed burns are increasingly being used in ecological restoration and vegetation management but the effects of such fires must be carefully considered (Johnson and Miyanishi, 1995).

Fuel will accumulate after treatments are administered. After long periods of fire exclusion, several repeated prescribed burns, perhaps every 5 to 8 yrs, may be required to sufficiently reduce the existing volume of crown material in the understory (Kilgore and Sando, 1975). After this initial modification, treatment frequency could be designed to duplicate the prehistoric disturbance frequency in these ecosystems.

6. Conclusion

The prescribed burn, thinning and biomassing followed by prescribed burn, and salvage or group selection with slash and landscape fuel treatments resulted in the lowest average fireline intensities, heat per unit area, area burned, and scorch heights. Cut and scatter, salvage or group selection treatments that do not treat slash and adjoining landscapes will make the fire situation more severe.

The simulations demonstrate that salvage or group selection harvesting operations must also include a landscape fuel treatment to be effective in reducing the potential for large, high-intensity wildfires. Removing only large, standing dead trees will not reduce fire hazard in these ecosystems.

If these ecosystems are not managed to reduce fire hazard, large, intense wildfires will continue to occur in the future. Ecologically, high-intensity fires produce significant impacts because of their effects on plants, soils, nutrients, and by the modification of habitat. Large, high-intensity fires lack pyrodiversity and are expensive to suppress. Fires of this type also pose a great risk to firefighters and to the public.

Combinations of prescribed fire and/or mechanical treatments can be used to reduce fuel loads and fuel continuity in mixed-conifer ecosystems. Restoration of mixed-conifer ecosystems must include an analysis of how silvicultural and fuels treatments will affect potential fire behaviour.

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