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Microclimate effects of fuels-reduction and group-selection silviculture: Implications for fire behavior in Sierran mixed-conifer forests

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ABSTRACT

Fire suppression and other past management practices in the western USA have led to dense conifer forests with high canopy cover and thick layers of surface fuels, changes likely to alter understory microclimate relative to historical conditions. Silvicultural treatments are used to restore forest resilience, but little is known about their microclimate-mediated effects on fire behavior. We measured fire-related microclimate variables for two years before and after experimental, operational-scale application of fuels-reduction thinning and group selection treatments in a Sierra Nevada mixed-conifer forest. Measurements included air speed, temperature, and relative humidity; soil temperature and moisture; and dead fuel moisture. Wind gust speed increased moderately (average 0.7 m s^{-1} or 31% increase) in thinned forest and sharply (average 2.5 m s^{-1} or 128% increase) in group-selection openings. Surprisingly, treatments did not affect air temperature or humidity. Soil temperatures increased by a mean of 4 °C in group openings but did not increase in thinned stands. Duff moisture in group selection openings was 72% of that in the control stands, but there were no effects on moisture in other fuel particle size classes, or in thinned stands. Soil moisture increased in group-selection openings at depths down to 0.7 m but did not change in thinned stands. Fire spread simulation modeling with FMAPlus indicated that elevated wind speeds could increase the fire rate of spread, but that increases are moderate and largely linear rather than exponential across the observed range of wind gust speeds. In general our results suggest that group selection openings placed in high canopy cover, Sierran mixed-conifer forests are distinct microclimatic environments that will have slightly different fire behavior than the surrounding matrix due to higher surface temperatures and faster wind speeds. Current fuels-reduction thinning practices in dry western forests, however, will have minimal microclimatic-mediated influence on wildfire behavior, and there is little cause for concern about a faster rate of fire spread or drier fuels in such stands.

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1. Introduction

Fire suppression, climate change and past management practices have led to higher densities of small-diameter, shade-tolerant trees than in previous centuries in many western USA forests (North et al., 2007; Collins et al., 2011). This change in forest structure and composition has contributed to altering fire regimes and increasing the amount of high-severity, stand-replacing fires (Miller et al., 2008). Silvicultural treatments currently employed to mitigate fire hazard and restore forests include thinning for fuels reduction (Agee and Skinner, 2005) and group selection, or creation of larger (e.g., 1 ha) openings to foster regeneration of shade-intolerant, fire-resistant tree species (McDonald and Abbott, 1994; Stephens, 1998; York and Battles, 2008; York et al., 2010). Although the effects of these treatments on forest structure are well known, there are few studies on the response of functional characteristics such as understory microclimate. Opening the canopy creates a cascade of interrelated microclimate effects (Ma et al., 2010) which may affect fire behavior.

Fuels-reduction thinning and group selection create strongly contrasting residual stand structures. Fuels-reduction thinning removes both small-diameter trees with dense crowns ('ladder fuels') and larger trees in intermediate and co-dominant crown classes. Taking out the small trees decreases the propensity for torching (conveyance of surface fire to the tree canopy), and taking the larger trees decreases the canopy bulk density making it more difficult for flames to pass from tree to tree. These fuel-reduction treatments are partial cuttings which often leave high and relatively homogeneous residual basal area (Agee and Skinner, 2005). Group selection, in contrast, is a silvicultural system in which aggregates of trees are harvested, leaving scattered openings in the tree canopy sometimes defined as being less than two tree heights in diameter (Smith et al., 1997). To compensate for past overharvesting of large-diameter (e.g., >75 cm DBH) trees in

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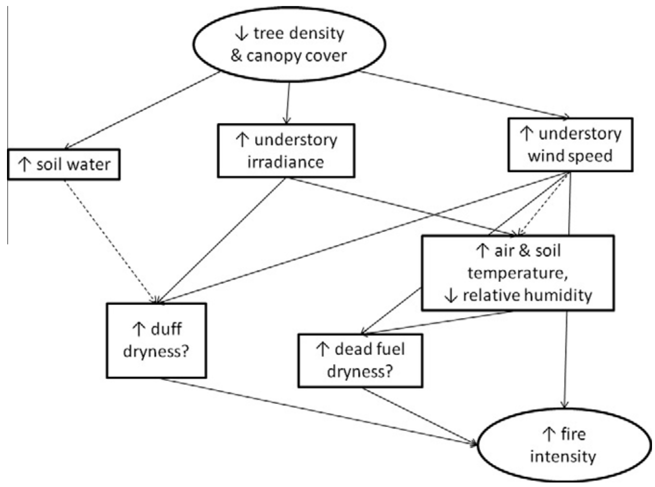

Fig. 1. Conceptual diagram of forest treatment effects on microclimate, and subsidiary effects on fire. Hypothesized effects are positive for solid-line arrows, negative for dotted-line arrows.

western North America, large trees can be retained within group selection openings. Fuels-reduction thinning is in use over larger areas than group selection, but the latter practice is sometimes used in conjunction with the former to increase revenue, enhance regeneration of shade-intolerant species, and create within-stand heterogeneity (e.g., HFQLG, 1998).

These treatments affect fire-related elements of microclimate in diverse ways (Fig. 1). Any canopy-opening treatment may exacerbate fire behavior by increasing wind speed (Albini and Baughmann, 1979) and understory irradiance (Weatherspoon, 1996; Agee and Skinner, 2005). Higher wind speeds provide more oxygen to a fire and make the angle of the flame closer to horizontal, allowing it to pass from one fuel element to the next and spread more rapidly (Fendell and Wolff, 2001). Increased understory irradiance raises the temperature of dead fuels, driving off moisture and bringing the fuels closer to ignition. Potential ameliorative effects of canopy-opening treatments on fire-related microclimate factors include increased soil water and/or higher foliar water status for remaining trees (Sala et al., 2005; McDowell et al., 2006; Zou et al., 2008). Duff as well as mineral soil may be wetter in such cases, making the duff more resistant to combustion. Additionally, open canopies increase the mixing of understory air with the above-canopy atmosphere, providing a cooling effect which may partially counteract the heating effect of canopy opening on understory air temperatures (Meyer et al., 2001).

The goal of this study was to document the effects of fuels-reduction thinning and group selection on fire-related microclimate factors in a mixed-conifer forest. We carried out a replicated, operational-scale experiment with pre- and post-treatment measurements of wind speeds, air temperature and relative humidity, soil temperature, soil moisture, and fuel moisture. A fire spread simulation is used to interpret the observed microclimate effects on fire behavior, the overriding management concern in these forests.

2. Methods

Data were collected in the Meadow Valley area of the Plumas National Forest, in northern California (39°55′N, 121°04′E). The base of the valley (1150 m) is an ancient lake bed. To the west the steep scarp of the Sierra Nevada range rises an additional 900 m, and smaller ridges rise 500 m to the north, south, and east. Soils were primarily Ultic Palexeralfs, which are well-drained loams with >2 m to restrictive bedrock features. The experiment was in Sierran mixed-conifer forests at elevations from 1200 to 1650 m. The forest type is characterized by a mixture of shade-intolerant pines (*Pinus jeffreyi* and *Pinus ponderosa*), mid- to intolerant conifers (*Abies concolor*, *Calocedrus decurrens*, *Pseudotsuga menziesii*, *Pinus lambertiana*), and a shade-intolerant broadleaved oak (*Quercus kelloggii*). A 1915 photograph of one of the study areas suggests that it was clear-cut except for some pine seed-trees, and that it was dominated by a heavy shrub cover (Fig. 2a). Today, skeletons of *Arctostaphylos patula* are prevalent in the understory, implying a typical successional pattern in which shrubs establishing after disturbance are followed and eventually out-competed by the shade-tolerant *A. concolor* (Conard and Radosevich, 1982). Scattered large (e.g., DBH > 75 cm) pines and firs are interspersed with dense, ca. 90 year-old, multi-layered second-growth consisting mainly of *A. concolor* (Fig. 2b).

Treatments were arranged in three experimental units that were treated as statistical blocks, one with south-facing slopes on the northern side of the valley, one with northwest-facing slopes on the southeastern side, and one with north-facing slopes or level areas on the southern ridge (Fig. 3). Maximum distance among sites was 11 km. Each block comprised an untreated control, a lightly thinned stand (50% canopy cover target), a moderately thinned stand (30% canopy cover target), and a single group selection opening. Controls and thinned stands were 9 ha, and the group selection opening was 0.7–0.8 ha. Group selection area was typical for the Plumas National Forest based on the goals of increasing revenue, enhancing the regeneration of shade-intolerant species, and creating within-stand heterogeneity (HFQLG, 1998). The 9-ha size of the fuels treatment was large enough to ensure that units were treated with methods and equipment common to standard fuels reduction operations. In each unit, two sites for thinning were selected in 2003 from areas previously slated by National Forest managers for fuels treatment as part of a defensible fuels profile zone (DFPZ; Weatherspoon and Skinner, 1996) network; moderate and light thin treatments were randomly allocated to these sites. Control sites were selected adjacent to this zone. Criteria for site selection were to find square, ca. 300 × 300 m stands with no maintained roads, large openings, or recent treatments. Measurements took place in the 100 × 100 m core, leaving a 100 m treated buffer on all sides of the measurement area. Group selection sites were selected in 2004 from among ones previously designated for harvest by the National Forest managers and close to the fuels treatment plots.

Prior to treatment, canopy cover was 69% (7% standard deviation) for the treatment plots; controls were 77% (5%); differences were not significant ($p = 0.34$). Canopy cover was measured with a vertical sighting tube; detailed methods are found in Bigelow et al. (2011). In June 2007 trees were cut by a feller-buncher then whole trees were skidded to landings outside the plots and cut to length and/or chipped. There was no subsequent treatment of residual surface fuels. After treatment, mean canopy cover was 57% (6%) in lightly thinned stands, 49% (8%) in moderately thinned stands, and 12% (6%) in the group selection openings. Canopy cover in group selection openings was contributed in part by several large trees that were retained in each opening. Canopy cover for light and moderate thin treatments did not differ statistically, so these were analyzed as a single treatment. Basal area prior to treatment (mean of all plots) was 55 $m^2\ ha^{-1}$; after treatment, basal area varied from 8 in group selection openings to 49 in both lightly and moderately thinned treatments.

2.1. Wind speed, air temperature, and relative humidity

Microclimate measurements were collected on a square, nine-point sampling grid at 50 m spacing in the center of each plot (Fig. 3). One anemometer was placed at a site randomly selected

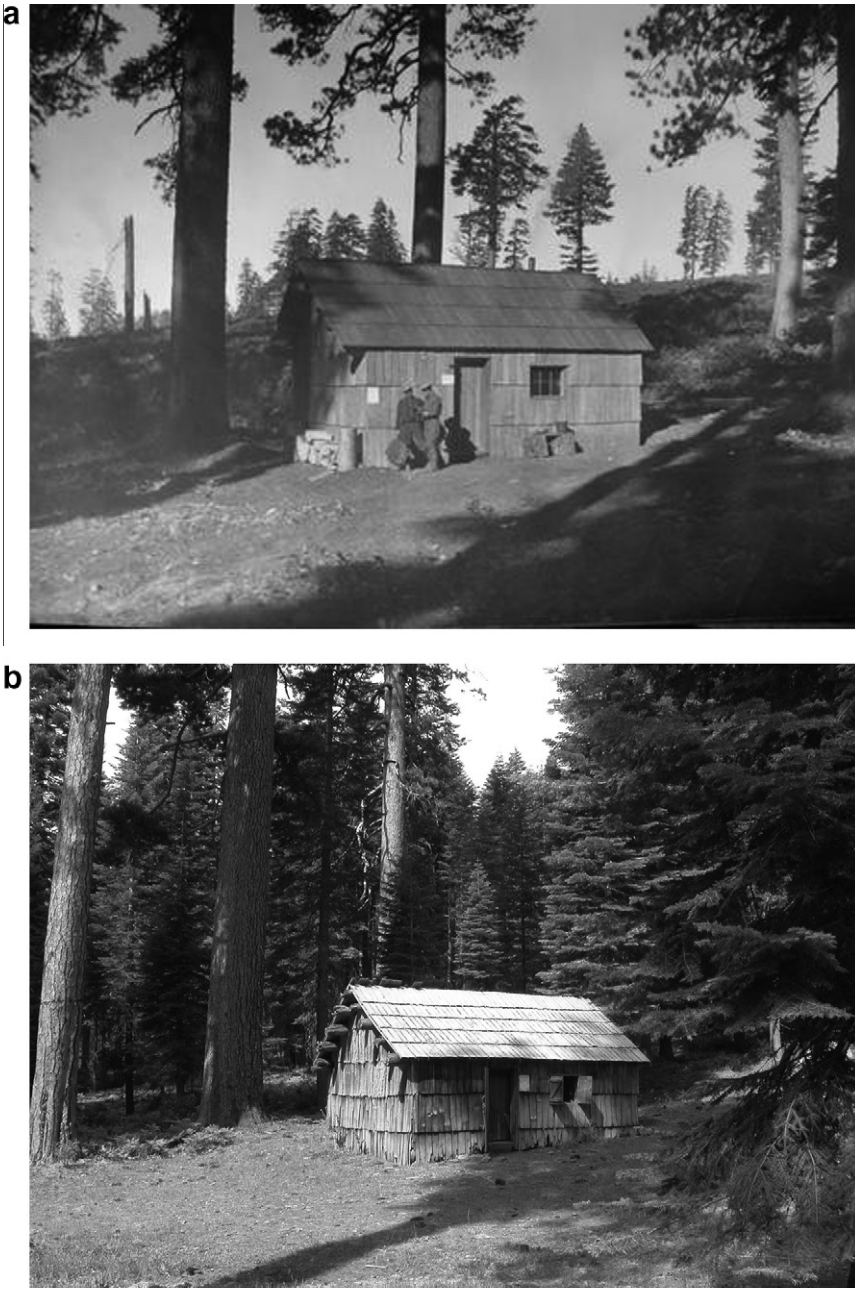

Fig. 2. Guard cabin on the ridge south of Meadow Valley, the southernmost experimental unit of the present study, Plumas National Forest, northern California. (a) Background of ca. 1915 photo shows apparently heavily harvested stand with scattered large firs and pines retained. (b) By 2005 strong recruitment of white fir is apparent.

from among the nine sampling stations at each sample site (total $N = 12$). Wind speed was measured with a 3-cup polycarbonate anemometer (Wind Speed Smart Sensor) at 2.5 m above the ground connected to a data logger (Hobo MicroStation; sensor and logger were from Onset Computer Corporation, Bourne, Massachusetts). Starting threshold was $\leqslant$0.5 m s^{-1}, and accuracy was ±0.5 m s^{-1}. Anemometers were removed from the field and evaluated after each season; any anemometer whose readings were not within 15% of those of a new reference anemometer was replaced. Wind gust speed was the fastest wind speed recorded for any two-second interval during the logging interval. Pre-treatment logging interval was one hour, decreased to 10 min post-treatment.

Relative humidity and air temperature were measured at three places on the nine-point sampling grid, representing minimum, median, and maximum canopy openness as estimated with hemispherical image analysis (Bigelow et al., 2011). Air temperature and relative humidity were logged at 15 minute intervals continuously from June through September from 2004 to 2006 (pre-treatment) and 2007 to 2008 (post-treatment). Temperature and relative humidity were measured with Hobo H8 Pro series integrated humidity chip, thermistor, and logger (Onset Computer Corporation, Bourne, Massachusetts). The H8 integrated sensor and logging system was mounted within a radiation shield and placed at 2 m height on a post. The radiation shield had an eight minute response time to reach 90% in air moving at 1 m s^{-1}. The thermistor was accurate to 0.5 °C over the range of temperatures measured, and the humidity sensor had ±3% accuracy.

2.2. Soil temperature and soil moisture

Soil temperature and moisture were measured at all nine sampling stations per stand at three to four week intervals from

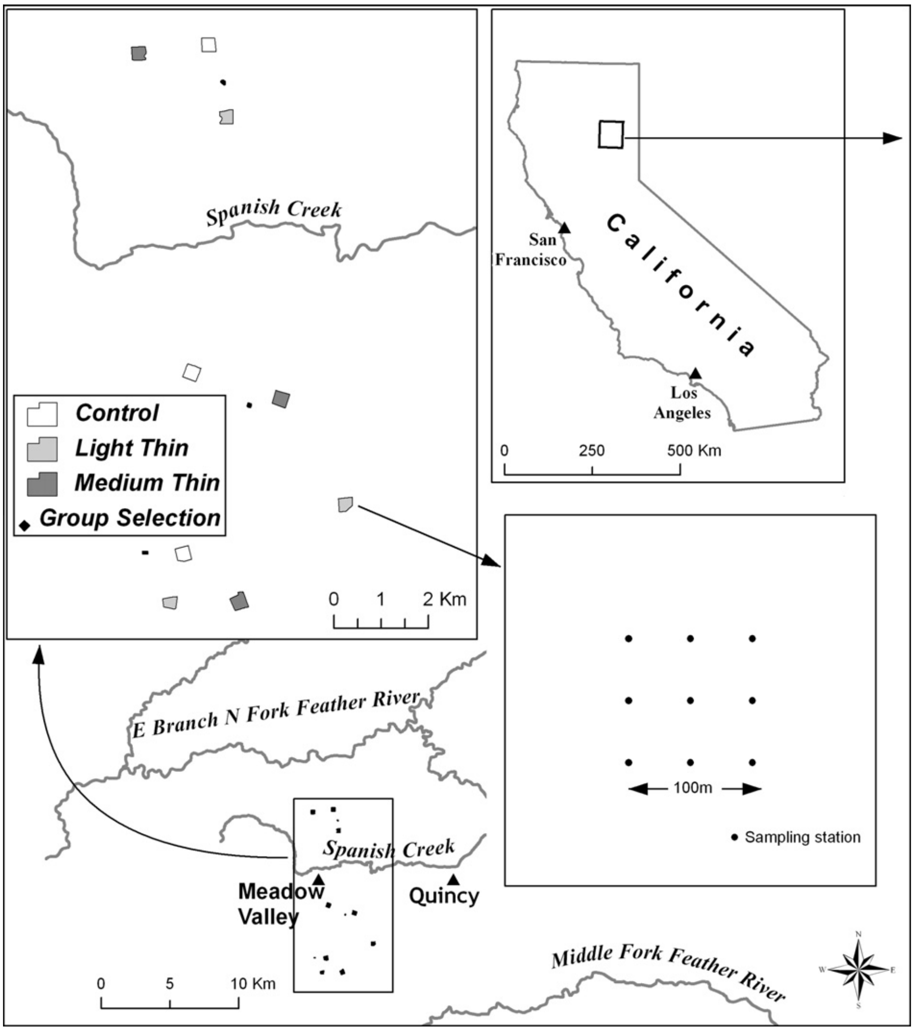

Fig. 3. Study site in Plumas National Forest, with experimental design and layout of sampling stations.

June to September for the pre-treatment years of 2005–2006 and the post-treatment years of 2007–2008 (no measurements were done in June 2007 because treatments were taking place). Soil temperature was measured within 2 h of solar noon using a thermistor probe (Temp 5, Oakton Instruments, Vernon Hills, IL) inserted through the duff layer and 2 cm into the mineral soil. Readings were taken after a constant temperature displayed for >10 s. Readings were taken at two locations within 30 cm at each sampling station. Values were averaged to provide a sampling station mean and then averaged again (nine values) to provide a stand mean.

Soil moisture was measured with a time-domain reflectometry (TDR) system comprising a cable-tester (TDR100; Campbell Scientific Instruments, Logan, UT) connected to a data-logger (CR1000) and portable 12 V power supply. Three pairs of stainless-steel rods traversing soil depths from 0 to 15, 0 to 40, and 0 to 70 cm were inserted vertically into the ground at each sampling station. Two centimeters of rod protruded above the surface for attachment of a cable via alligator clips. Volumetric soil water content (m^3 water per m^3 soil) was calculated using the Topp et al. (1980) equation. Soil moisture was calculated for the 0–15, 15–40, and 40–70 cm portions of the soil profile by converting volume water contents for the three rod lengths to water depth equivalents, subtracting as appropriate (e.g., water equivalent depth from 15 to 40 equals depth from 0 to 40 minus 0 to 15 cm), and converting back to volume water content.

2.3. Fuel moisture

Fuel moisture was measured on fuels in the duff, 10- (6–25 mm), 100- (25–76 mm), and 1000-h (>76 mm diameter) moisture time-lag classes. Fuel moisture was measured at the same monthly interval as of soil temperature and soil moisture; 100- and 1000-h fuel moistures were measured before 12:00 h, and duff and 10-h fuel moistures were measured between 12:30 and 15:30 h. Fuel moisture was measured at nine stations per plot, except for the 10-h time-lag class which was estimated at three stations per plot. Ten-hour fuel moisture was estimated with dowels of Douglas-fir weighed with a portable measuring scale (Ben Meadows Co., Janesville, WI). Duff moisture, expressed as g water per g dry duff, was measured with gravimetry: duff samples were sealed into tins, weighed the same day, heated for 48 h at 70 °C, and reweighed. Fuel moisture in the 100- and 1000-h time lag classes was estimated with a resistance meter (BD-10, Delmhorst Instrument Co., Towaco, NJ). Two pieces of woody debris from each appropriate time lag class were labeled at each sampling site. The resistance meter was inserted to a depth of 6 mm in undecayed, bark-free wood, in two locations. Wood samples were exchanged for fresh ones once they became decayed.

2.4. Data analysis and statistical modeling

Each variable required a slightly different approach to data preparation. For wind speed (one sensor per plot), the three

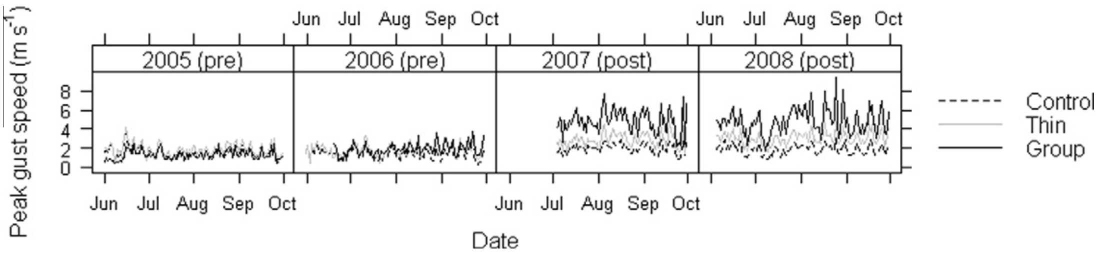

Fig. 4. Maximum wind gust speed (mean of three highest per day) before and after fuels-reduction thinning and group selection in lower montane mixed-conifer stands, Plumas National Forest, northern California. Data are means of three replicate blocks.

highest gust speeds were averaged to produce a single daily datum for each plot from June through September for the years 2005 through 2008. The values were then averaged by month, retaining only months with >15 d of observations. For soil temperature, observations at nine stations per plot were averaged to provide a single value for each plot at each survey date. Months in which >1 survey occurred were averaged to provide a single monthly value. Soil moisture and fuel moisture data were prepared in the same way as of soil temperature. Duff was log-transformed prior to analysis because the ability of organic matter to retain many times its mass in water led to a strongly right-skewed frequency distribution.

Most response variables were summarized monthly from June to September, 2005–2008, and analyzed using a mixed model (Proc Mixed; SAS Institute, 1999) specifying treatment, year, and month as fixed effects and block as a random effect. A term for an interaction between treatment and year was included because treatment effects were only expected after treatments had occurred. There was also a quadratic polynomial term (*month* · *month* · *year*) because many response variables showed a curved trajectory during the 4-month measurement period each year. The resulting statistical model was *treatment* + *year* + *treatment* · *year* + *month* + *month* · *month* · *year*. Potential covariance in repeated measurement residuals was modeled with a spatial power model based on the number of months elapsed since January 2005. This model was used because the eight-month gaps between data collected in successive years created an irregularly spaced time series. Air temperature (maximum and minimum) and relative humidity were summarized at weekly rather than monthly intervals, and *week* was substituted for *month* in the statistical model.

To establish treatment effects on a given response variable, we compared the difference between treatment and control plots *after* treatments were applied (in May–June 2007) to the difference *before* treatments were applied. An 'estimate' statement in SAS compared 2005–2006 means with 2007–2008 means. Student's *t*-test was applied to establish whether the estimate was significantly different than zero, using $\alpha = 0.05$ probability of making a type I error.

2.5. Modeling wind effects on predicted fire behavior

We explored the sensitivity of fire behavior metrics to changes in the wind speed under simulated conditions similar to those at the study site using FMAPlus (Carlton, 2005), a fire spread simulator based on the Rothermel (1972) fire spread model. We selected the 'TL05' fuel model which assumes that fine fuels are made up mainly of conifer litter. We ran simulations with mid-flame wind speed varied between 0 and 7 m s^{-1} (15.6 mph), a range that covered most of the observed wind speeds at our site. Response variables were rate of spread and flame length. These derived variables are used in computations of a wide variety of fire behavior indices including crowning index, torching index, surface fire intensity, and scorch height (Scott and Reinhardt, 2001; but see critique by Cruz and Alexander, 2010).

3. Results

3.1. Wind speed

Mean gust speed prior to treatment was 1.8 m s^{-1} (3.8 mph; Fig. 4). There were no seasonal trends in gust speed ($p > 0.79$ for *month* and *month*^{2} · *year* terms in the statistical model). The mean gust speed increased significantly after treatments were applied. Mean gust speed was slightly higher (a difference of 0.7 m s^{-1} or 1.5 mph) in the thinned stands than in the controls, and considerably higher (a difference of 2.5 m s^{-1} or 5.6 mph) in group selection openings than in controls (Table 1). Corrected for pre-treatment differences relative to controls, these values represent a 31% increase in thinned forest and a 128% increase in

Table 1
Estimates of pre- vs. post-treatment difference (multiple microclimate variables) between untreated controls and fuels-reduction thinning or group-selection treatments.

Response variable	Units	Thinned			Group selection		
		Est.	S.E.	95% C.I.	Est.	S.E.	95% C.I.
Wind gust	m s^{-1}	0.67*,[a]	0.33	0.01 to 1.33	2.52***	0.37	1.77 to 3.26
Air T. max.	°C	0.26	0.76	−1.23 to 1.74	0.50	0.76	−0.99 to 1.98
Air T. min.	°C	0.09	1.01	−1.89 to 2.08	−0.21	1.01	−2.19 to 1.78
Rel. hum.	%	0.61	2.46	−4.22 to 5.44	0.04	2.46	−4.63 to 5.04
Soil T.	°C	1.38	1.09	−0.77 to 3.54	4.12***	1.09	1.96 to 6.28
θ,[b] 0–15 cm	m^3 m^{-3}	0.021	0.019	−0.016 to 0.58	0.056**	0.019	0.019 to 0.093
θ, 15–40 cm	m^3 m^{-3}	0.008	0.015	−0.021 to 0.038	0.055***	0.015	0.025 to 0.084
θ, 40–70 cm	m^3 m^{-3}	0.026	0.030	−0.033 to 0.086	0.073*	0.030	0.013 to 0.133
w,[c] duff	ln(g)(ln(g))$^{-1}$	−0.29	0.149	−0.58 to 0.004	−0.329*	0.149	−0.62 to −0.03
w, 10-h	%	−0.49	0.94	−2.34 to −1.36	−0.97	0.96	−2.88 to 0.94
w, 100-h	%	−0.05	1.13	−2.18 to 2.29	0.21	1.13	−2.02 to 2.44
w, 1000-h	%	−0.36	1.22	−2.79 to 2.06	−0.16	1.22	−2.27 to 2.58

[a] Type I error probabilities: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.
[b] Volume soil moisture: m^3 of water per m^3 of soil.
[c] Mass moisture: mass of water per dry mass of duff or wood.

group selection openings. Relative differences remained consistent even on windy days. For example, peak gust speeds on September 3, 2007 (the day a major wildfire, the 260 km^2 Moonlight fire, began nearby) were 2.6 m s^{-1} (5.8 mph) in control stands, 3.8 m s^{-1} in (8.5 mph) thinned stands, and 6.3 m s^{-1} (14 mph) in group selection openings. The highest single gust observed was 16.8 m s^{-1} (37.5 mph) in a group selection opening, August 25, 2008; elsewhere on that day maximum gusts were 7.2 m s^{-1} (16.1 mph) in thinned stands and 4.2 m s^{-1} (9.4 mph) in untreated stands.

3.2. Air temperature and relative humidity

Treatments had no significant effect on relative humidity or maximum and minimum air temperatures. All specific contrasts of pre- vs. post-treatment control-impact differences were non-significant ($p > 0.49$). The general seasonal pattern of humidity and temperature variables was similar between treatments. Relative humidity trended downward over the summer season, reaching a minimum in July or August, and increasing through the end of September. Maximum and minimum temperatures followed the opposite pattern. The time-related variables year, week, and the interaction between year and the squared week term were highly significant ($p < 0.001$). No block effect (i.e., placement of experimental units within the Meadow Valley landscape) was detected but the covariance term was highly significant ($p < 0.001$), indicating a high degree of consistency among successive measurements made in individual plots.

3.3. Soil temperature

Midday soil temperature was higher in group selection treatments compared to control and thinned stands (Fig. 5). There was a marked curved trend in temperature over the progression of each summer season and into early fall; *month* and $month^2 \cdot year$ terms of the statistical model were significant at $p < 0.001$). On average, soil temperatures in group selection openings were 4.1 °C (95% confidence interval 2.0–6.3) warmer than in controls (relative to pre-treatment differences). Mean soil temperatures in thinned stands were 1.4 °C warmer than in controls (corrected for pre-treatment), but the difference was not statistically significant ($p = 0.2$). The highest soil temperature observed over the course of the study was 54.8 °C.

3.4. Fuel moisture

Duff in stands treated with group selection was drier than in control stands (Fig. 6). For group selection openings, the decrease of −0.3291, which is log-transformed, indicates that duff moisture in the openings was 0.72 = *exp*(−0.3291) times the moisture in controls. Typical mid-summer values of duff moisture in dense untreated stands were 0.18 g g^{-1} (18%), compared to 0.13 (13%) in group selection openings. Late-season duff moisture (ratio of water mass to dry duff mass) averaged 0.10 g g^{-1} (0.034 standard deviation) and varied by year. Treatments did not affect moisture in fuels in the 10- (dowels), 100- (25–76 mm diameter), or 1000-h (>76 mm diameter) time-lag classes. There was weak correlation among successive measurements for the 100- and 1000-h fuels ($p < 0.05$), and none for duff and 10-h fuels. Strong seasonal desorption (drying-down) and absorption (rewetting; $p < 0.001$) and inter-annual variation ($p < 0.01$) occurred in all fuel time-lag classes.

3.5. Soil moisture

Soil moisture in thinned stands did not differ from that in controls, but group selection openings had significantly higher soil moisture than controls at all soil depths. The mean increase in volumetric soil moisture in group-selection openings was 0.05–0.07 $m^3\ m^{-3}$, depending on depth (Fig. 7). Soil dried down substantially over the course of each season in surface soil and deep soils (*month* effect was highly significant: $p < 0.001$), but not at the intermediate depth (Table 1). After the initial more rapid dry-down in the early season, soil moisture tended to stabilize between 0.1 and 0.2 $m^3\ m^{-3}$. There were significant differences among years.

3.6. Wind speed effects on predicted fire behavior

As simulated wind speed was increased from 0 to 7 m s^{-1} using the FMAPlus software, simulated rate of spread (based on the TL05 fuel model) increased non-linearly from 0 to 0.12 m s^{-1} and simulated flame length increased from 0 to 1.4 m (Fig. 8). In terms of mean gust speeds observed in the experimental plots, with a mean pre-treatment gust speed of 1.8 m s^{-1}, and a 0.7 m s^{-1} increase after treatment (as in the thinned stands), predicted rate of spread increases from 0.02 to 0.03 m s^{-1}. In group selection openings, the mean wind speed increase of 2.5 m s^{-1} increases predicted fire spread rate to 0.05 m s^{-1} (0.1 mph). Predicted flame length under mean gust speeds in controls was 0.60 m, compared to 0.72 m in thinned stands and 0.99 m in group selection openings (Fig. 8).

4. Discussion

The experimental treatments changed forest structure substantially and we expected to detect the effects on most microclimate variables. Group selection openings displayed a range of effects including higher wind speeds, soil moisture, and

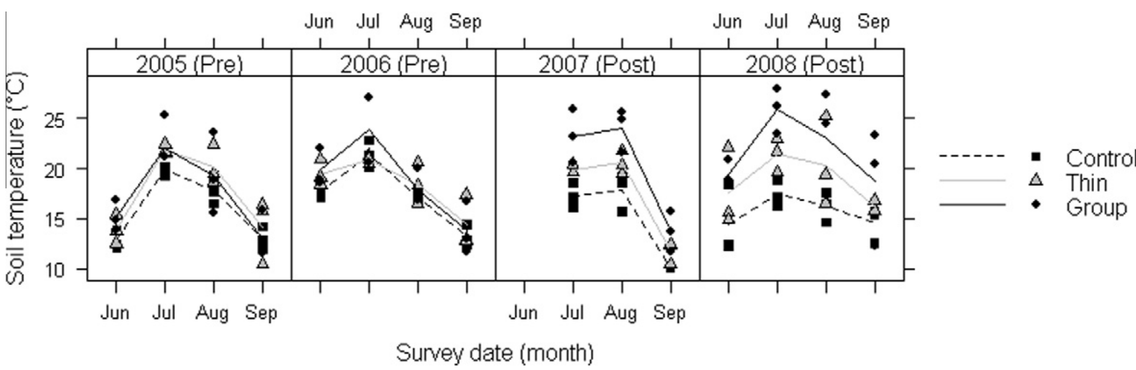

Fig. 5. Soil temperature (2 cm below surface of mineral soil) in lower montane mixed-conifer stands, Plumas National Forest, northern California, before and after fuels-reduction thinning or group selection treatment in May–June 2007 (no measurements were done while treatments were taking place).

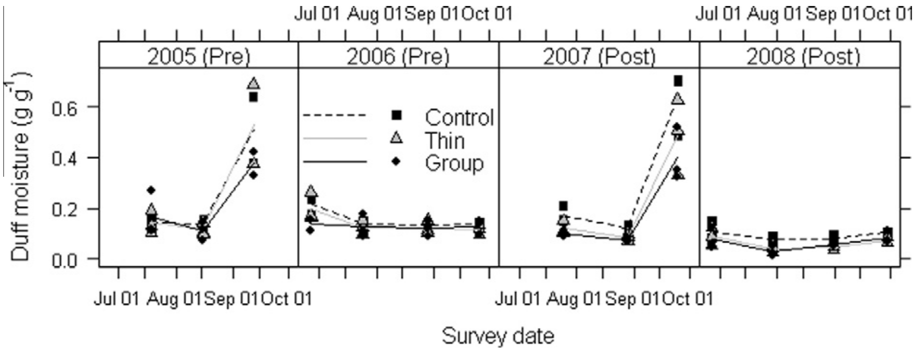

Fig. 6. Duff moisture (water mass over oven-dried duff mass) before and after fuels-reduction thinning and group selection treatment in lower montane mixed-conifer stands, Plumas National Forest, northern California.

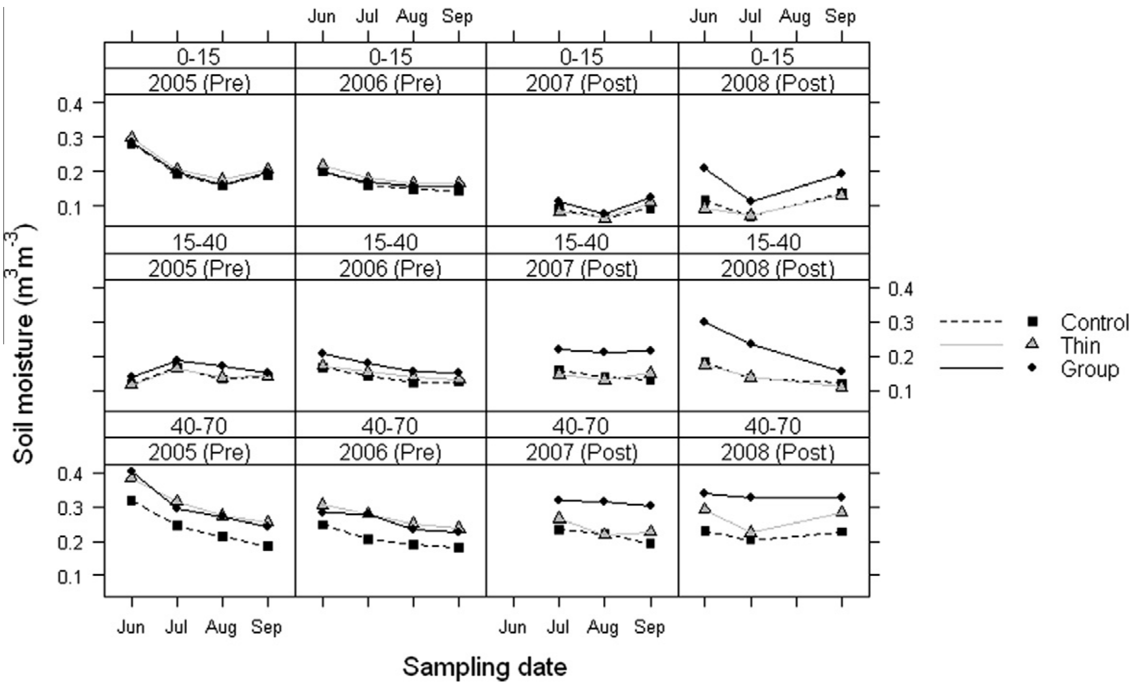

Fig. 7. Mean volume soil moisture ($m^3\ m^{-3}$) at three depths (0–15, 15–40, and 40–70 cm) in lower montane mixed-conifer forest before and after fuels-reduction thinning and group-selection treatments.

surface temperatures, but we found no effects of thinning other than a minor increase in understory wind speeds. For the most part, concerns about treatments causing drier fuels (Van Wagtendonk, 1996; Weatherspoon, 1996; Agee and Skinner, 2005) were unwarranted; only duff in group selection openings was drier than in control stands. Air temperature and relative humidity were unaffected by the treatments even in group selection openings. We acknowledge that the moderate thinning treatment did not reduce canopy cover to the planned level (30%), and greater microclimate differences would probably have been detected if the moderate thinning treatment had achieved its canopy cover target. Nevertheless, the thinnings represent an accurate portrait of fuels-reduction thinning as currently implemented in the northern Sierra Nevada. Similarly, the group selection opening treatment was representative of current practice on the National Forests of the area, i.e., placement of ca. 1 ha openings at low density within a matrix of thinned and unthinned stands.

4.1. Group selection opening

Landscape-level modeling of wildfire spread in mixed-conifer forests has highlighted the vulnerability of planted group selection openings, ostensibly because the low height of the young trees allows fire to pass readily from the surface to their crowns (Moghaddas et al., 2010). Clearly, microclimate factors in these openings are also important. Our measurements indicated that wind gust speeds will be two to four times higher in group selection openings than in untreated forest, and such increases will influence a wide range of fire behaviors including surface fire intensity, flame length, scorch height, and probability of passive or active crown fire (Scott and Reinhardt, 2001). Stand density effects on understory wind speeds (Albini and Baughmann, 1979) are incorporated in many fire behavior modeling frameworks (Reinhardt et al., 2003; Carlton, 2005), but other fire-relevant microclimate factors are less routinely captured in models. For example, we detected elevated temperatures (mean of 4 °C) at 2 cm below the mineral soil surface in group selection openings, and forest floor surface temperatures would have been considerably higher. Elevated surface temperatures decrease the heat input required for fuel ignition (fuel volatilization begins at ca. 200 °C; Nelson, 2001), so our soil temperature measurements suggest there may be an elevated risk of accidental ignitions (e.g., due to sparks from heavy machinery) in group-selection openings.

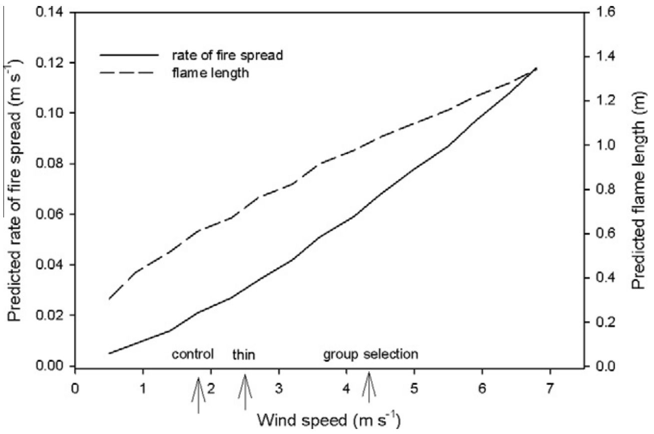

Fig. 8. Simulated rate of fire spread and flame height under wind speeds of 0.5–7 m s^{-1}, using a fuel model representing heavy fuel loads with fire primarily carried by conifer litter (fuel model TL05). Arrows show a mean gust speed for control and treated stands in 2007 and 2008.

The dry duff detected in group selection openings merits notice because moisture content affects duff consumption in fires (Brown et al., 1991), and duff consumption is linked to ecosystem phenomena such as large tree mortality (Stephens and Finney, 2002; Varner et al., 2007); timing, content, and distribution of smoke emissions (Tan et al., 1992); and establishment of understory plant species (Laughlin et al., 2004). Although duff moisture values were higher in control and thinned stands than in group selection openings, by mid-summer all values were below the 20–60% duff moisture range in which the amount of duff consumed in a fire is highly sensitive to duff moisture (Miyanishi, 2001). We therefore expect that there is little practical importance of the fuel moisture differences detected between treatments. There should be very high rates of duff consumption regardless of canopy cover if prescribed burns are done in mid-to-late summer before any fall rains have wetted up fuels (e.g., Fig. 6; 2007 panel), particularly since duff and litter fuels appeared horizontally continuous.

Not all microclimate effects of group selection openings predisposed to more intense fire behavior. Elevated moisture in the upper 70 cm of soil should allow increased water uptake and foliar moisture in plants within and immediately surrounding the opening (Sala et al., 2005). We did not measure live fuel moisture but increased water status if present would enhance resistance to ignition of plants including large reserve trees (Keyes, 2006). In general, however, microclimate effects imply that group openings are likely to serve as loci of increased fire behavior in dry western USA conifer forests. Such increased fire behavior should not exclusively be viewed negatively, because hotter burns may enhance heterogeneity in many forest attributes such as understory plant diversity (Wayman and North, 2007). Group selection openings are distinct microclimatic environments that will behave qualitatively differently from the surrounding forest with respect to fire.

4.2. Fuels-reduction thinning

Many researchers have emphasized the need to carefully weigh benefits that may accrue from thinning to reduce crown fire potential against the dangers of increased surface fire behavior in dry western USA forests (Countryman, 1956; Weatherspoon, 1996; Agee and Skinner, 2005; Keyes and Varner, 2006; Reinhardt et al., 2008). Increased wind speed and fuels dryness are the factors cited as being of concern for surface fire behavior, yet our study and others suggest that such changes in microclimate will be minor. Heavily thinned stands in the southern Sierra Nevada exhibited a 15% mean wind speed increase (Ma et al., 2010), a change on the same order of magnitude as the 31% increase (average increase in gust speed was 0.7 m s^{-1} due to thinning) in thinned stands observed in our study. The increase in rate of spread and flame length predicted from these increases in the wind speed is inconsequential (Fig. 8) and unlikely to pose a problem for suppression efforts. Indeed, if understory wind speeds are only slightly elevated, they may assist prescribed burning because light winds can help prevent crown scorch by dissipating heat (Biswell, 1989; Gould et al., 1997).

If increased wind speed is unlikely to be a problem for fire behavior in thinned stands, what about dryness of dead fuels? Concerns about increased fire effects due to drier fuels in thinned stands have often been voiced (Van Wagtendonk, 1996; Weatherspoon, 1996; Agee and Skinner, 2005) yet our study and that of Faiella and Bailey (2007) found similar fuel moisture in treated and untreated stands. Fine dead fuels (small-diameter branches and conifer needles) are sensitive indicators of the atmospheric environment (as indicated by time-lag nomenclature; 1-h fuels, etc.), and the similar dead fuel moisture between treated and untreated stands is unsurprising given the lack of air temperature and relative humidity differences in treated and untreated stands in this and other studies (Meyer et al., 2001). The slightly increased winds that accompany opening of the canopy signify increased stand ventilation and mixing with the above-canopy air, which may inhibit gradients in air temperature and relative humidity from establishing despite increased understory irradiance. We conclude that there is little cause for concern about fuels dryness and increased fire behavior in thinned stands under microclimatic conditions similar to those of our study.

5. Conclusions

Reducing the forest canopy with silvicultural manipulations to decrease fire behavior or achieve restoration goals affects not only forest structure but also microclimate. Concerns have been expressed that some of the microclimate effects may counteract the main or subsidiary goal of protecting against wildfire. Our study suggests, however, that some microclimate effects may cancel others out, as when faster winds in more open stands allow better mixing of below and above canopy air. This mixing may forestall potential increases in air temperature and decreases in relative humidity, consequently resulting in no difference in fuel moisture compared to denser stands. Overall our research suggests fuels-reduction thinning of high canopy-cover Sierran mixed-conifer forests will not lead to significant shifts in microclimate or fuels drying. Group-selection openings, which are one to two orders of magnitude larger than the largest openings produced in fuels reduction thinnings, present a different case. These openings may not differ in air temperatures and humidity compared to untreated forests, but greatly increased wind speeds and higher surface temperatures mean that they are at risk for more severe fire behavior. This should be of particular concern when group selection openings are embedded within fuels-reduction thinned stands that form part of a network for rapid access by fire-fighting personnel (Moghaddas et al., 2010). Vegetation within such openings, however, may be slightly more resistant to ignition if higher soil moisture results in better canopy foliage water status. Even with more detailed observations on microclimate, fire spread models are limited in their ability to predict what will happen under various silvicultural treatments. Progress will be made by augmenting model estimates with empirical comparisons of fire behavior, fuel combustion, and microclimate in paired treated and untreated forests as they burn.

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