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Canopy microclimate response to pattern and density of thinning in a Sierra Nevada forest

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ABSTRACT

Restoring Sierra Nevada mixed-conifer forests after a century of fire suppression has become an important management priority as fuel reduction thinning has been mandated by the Healthy Forests Restoration Act. However, in mechanically thinned stands there is little information on the effects of different patterns and densities of live-tree retention on forest canopy microclimate. This study compared gradients of air temperature and vapor pressure deficit (VPD) through the vertical forest profile among an overstory-thin, an understory-thin, an un-thinned control, and a riparian environment in a Sierra Nevada mixed-conifer forest. Temperature and humidity were recorded for a year by 60 data loggers arrayed in 12 trees at 5, 15, 25, 35, and 45 m above the forest floor. Both thinning treatments had significantly more extreme summer daily ranges of temperature and VPD than the control across heights. The overstory-thin resulted in the greatest maximum temperatures, VPDs, and VPD range among all sensors at 5 m, and significantly higher summer maximum temperatures and VPDs than the control in lower strata ($\leq$15 m). The understory-thin also had significantly higher summer maximum temperatures than the control ($\leq$15 m), but these too were significantly less than in the overstory-thin nearest the surface at 5 m. Understory thinning did not alter the mean or range of microclimate as much as overstory thinning. Riparian microclimate had significantly lower minimums and means, and greater daily ranges of temperatures and VPDs than the control. Results suggest that thinning canopy cover significantly increases the extremes and variability of understory microclimate compared to thinning from below and no-thin treatments.

1. Introduction

Following a century of fire suppression, fuels reduction has become an important management priority in western forests. The Healthy Forests Restoration Act [1]of 2003 mandated hazardous fuel reductions to decrease the incidence and extent of stand-replacing crown fires which exceed the historic range of fire regime variability in many western forests. Two commonly used mechanical means of fuel reduction are strategically placed area treatments (SPLATs) and defensible fuel profile zones (DFPZs). The SPLATs thin forests from below, often leaving overstory trees in a grouped pattern characteristic of many western forests (Bonnicksen and Stone, 1982; North et al., 2004). On the other hand, DFPZs are designed to reduce canopy bulk density by thinning overstory trees and leaving retention trees evenly spaced with separated crowns. Although both treatments are being widely used to reduce fuels, there have been few studies of their effects on ecosystem processes and microclimate conditions.

Aggregated (grouped) retention has become a common method of managing forests for both timber and ecological objectives in the Pacific Northwest (Heithecker and Halpern, 2007) where live-tree retention harvests have been mandated on public lands in the range of the northern spotted owl (*Strix occidentalis caurina*) (USDA & USDI, 1994). But even there, no firm consensus has developed as to what pattern or density of live-tree retention best meets management goals of fostering forest ecosystem functions and biodiversity (Chen and Franklin, 1997). Specifically, there is little information on the effects of aggregated *vs.* dispersed live-tree retention on canopy microclimate even though arboreal temperatures and humidities are known to be important for the structure

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[1] http://www.frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_cong_bills&docid=f:h1904enr.txt.pdf.

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and composition of epiphyte communities (McCune, 1993; Sillett and Rambo, 2000) and could influence habitat conditions for invertebrates and small mammals (Dupuis et al., 1995; Danehy and Kirpes, 2000). Poikilohydric epiphytes such as lichens and bryophytes are strongly affected by moisture and temperature regimes (Proctor, 1982; Kershaw, 1985), and particularly sensitive to microclimate changes (Renhorn et al., 1997). The vertical stratification of arboreal epiphyte communities has been well established (e.g., Hale, 1952; McCune et al., 1997; Sillett and Rambo, 2000), and change in composition of epiphytes from one stratum to another generally reflects the sensitivity of individual species to desiccation and their consequent ability to achieve positive net photosynthesis in low-moisture environments (Hosokawa et al., 1964; Tobiessen et al., 1977).

Several studies have looked at the effects of different thinning patterns and densities on surface microclimate parameters up to 2 m height, including the Missouri Ozark Forest Ecosystem Project (Zheng et al., 2000), the Density Management Study (Chan et al., 2004), and the Demonstration of Ecosystem Management Options Study (Heithecker and Halpern, 2006). However, none of these studies examined temperature and/or humidity gradients through the vertical forest profile (however, see Fowells, 1948; Friedland et al., 1992, 2003; Morecroft et al., 1998). The objective of our research was to quantify and describe microclimate gradients in trees from near the forest floor up through the canopy within different treatments. We had two specific goals: (1) to compare air temperatures and vapor pressure deficits across heights within trees among two different fuel reduction thinning treatments and an un-thinned control, and (2) to additionally compare those parameters between upland and riparian-influenced un-thinned forest. Our study is the first to examine forest canopy microclimate in replicate trees in different retention treatments, an information need identified more than a decade ago (SNEP, 1996; Chen and Franklin, 1997).

2. Methods

2.1. Study site

The Teakettle Experimental Forest (36°58′N, 119°02′W) is situated in the Sierra National Forest north of the North Fork of the Kings River, approximately 80 km east of Fresno, California. This 1300 ha old-growth forest spans the red fir (*Abies magnifica*) and mixed-conifer ecotone of the south central Sierra Nevada on the west side of the crest. The mixed-conifer overstory consists of red fir, white fir (*Abies concolor*), incense cedar (*Calocedrus decurrens*), Jeffrey pine (*Pinus jeffreyi*), and sugar pine (*Pinus lambertiana*). Representative understory plants include manzanita (*Arctostaphylos nevadensis* and *A. patula*), bush chinquapin (*Castanopsis sempervirens*), whitethorn (*Ceanothus cordulatus*), and snowberry (*Symphoricarpos mollis*). Warm, dry summers (Fowells and Means, 1990) contrast with much cooler, moist winters. Annual precipitation averages 112 cm and falls mainly as winter snow, which usually persists through May (Berg, 1990). Generally gradual slopes, with an average gradient of 136 m km^{-1} (Keeler-Wolf, 1990), give rise to first and second order perennial streams that run through the experimental plots at elevations from 2000 to 2125 m.

2.2. Design and analyses

The Teakettle Ecosystem Experiment includes two different forest thinning treatments in plots of 4 ha in area. The overstory-thinned treatment (O-thin) harvested all trees >25 cm diameter at breast height (dbh) except for approximately 22 large trees ha^{-1} that were left regularly dispersed 20–25 m apart (North et al., 2002). The second treatment, understory thinning (U-thin), followed California Spotted Owl Report (CASPO) guidelines (Verner et al., 1992), retaining 40% of live basal area while not harvesting trees ≥76 cm dbh. Although originally designed to reduce impacts to spotted owls, CASPO thinning has become widely used for fuel reduction in the Sierra Nevada. This treatment left an average of 44 trees ha^{-1} with a mean dbh of 91 cm, often aggregated in groups (see also Fig. 1 and Table 1b). To determine stand canopy cover, hemispherical images were taken with a gimbal and tripod mounted digital camera from intersecting points on a 50 m × 50 m grid established within plots, and analyzed using GLA software (Frazer et al., 1999).

Analysis of the Teakettle forest structure determined plot size would need to be approximately 4 ha to include the range of composition and stand variability that characterizes the discontinuous canopy cover of southern Sierra mixed-conifer forest (North et al., 2002). Following pre-treatment data collection, most ecosystem processes and particularly microclimate were found to be significantly different among the three dominant patch types: closed canopy, shrub, and open gap conditions (Ma et al., 2005; North and Chen, 2005). When choosing three trees for study from an O-thin, a U-thin, a no-thin control plot, and a riparian area (12 trees, Table 1a), we selected trees separated by at least one change in patch type to ensure independence of samples. Distance between replicates ranged from a minimum of 35 m (U-thin) to ca. 400 m (riparian). Study trees were further restricted to white firs to avoid any potential confounding effect of differences in transpiration among tree species, and because white firs were the most ubiquitously distributed tree from riparian to upland. Understory-thin study trees were within groups of trees in contrast to the O-thin trees, which were solitary. Because the zone of riparian stream influence at Teakettle is narrowly restricted (<10 m, Rambo and North, 2008), we selected riparian study trees to be within 5 m of a perennial stream.

Shielded Hobo Pro 8 Data Loggers were suspended by brackets on northeast aspects of each study tree bole at 5, 15, 25, 35, and 45 m above the forest floor in September, 2003. These sensors have an accuracy of ±0.2 °C and ±3% relative humidity (±4% in condensing environments). To reduce radiant heating, sensors were enclosed within naturally vented multiplate shields (however, see Nakamura and Mahrt, 2005). Sensors were left in place for a year while recording temperature and relative humidity (RH) every 30 min. The 30 min observations were used to calculate vapor pressure deficit (VPD, kPa), a measure of the drying power of the air more biologically relevant than RH to plant transpiration (Valigura and Messina, 1994) and potential condensation especially important for epiphytic cryptogams and associated invertebrate communities. For practicality, it was assumed that VPD = 0 when temperature was ≤0 °C.

Daily data from sensors in the 5 m stratum of control plot trees were averaged and smoothed using a moving average temperature approach (Liu et al., 1998) to determine starting and ending seasonal thresholds of temperature. Using threshold temperatures of 0 and 10 °C, winter was defined as the time-period when daily mean temperatures were frequently below 0 °C and summer when means were consistently >10 °C (Ma, 2003). Because the transitional seasons of spring and fall are highly variable at this elevation of the Sierra, analyses were focused on the summer season when temperature and humidity extremes are likely to be most biologically important (Danehy and Kirpes, 2000; Welsh et al., 2005), and then compared to winter.

Repeated measures multiple analysis of covariance (MANCOVA) analyses were run among treatments across heights (5, 15, 25, 35, and 45 m) using continuous variables of time and a heat load index based on slope, aspect, and latitude (McCune and Keon, 2002). Response parameters included mean daily minimum,

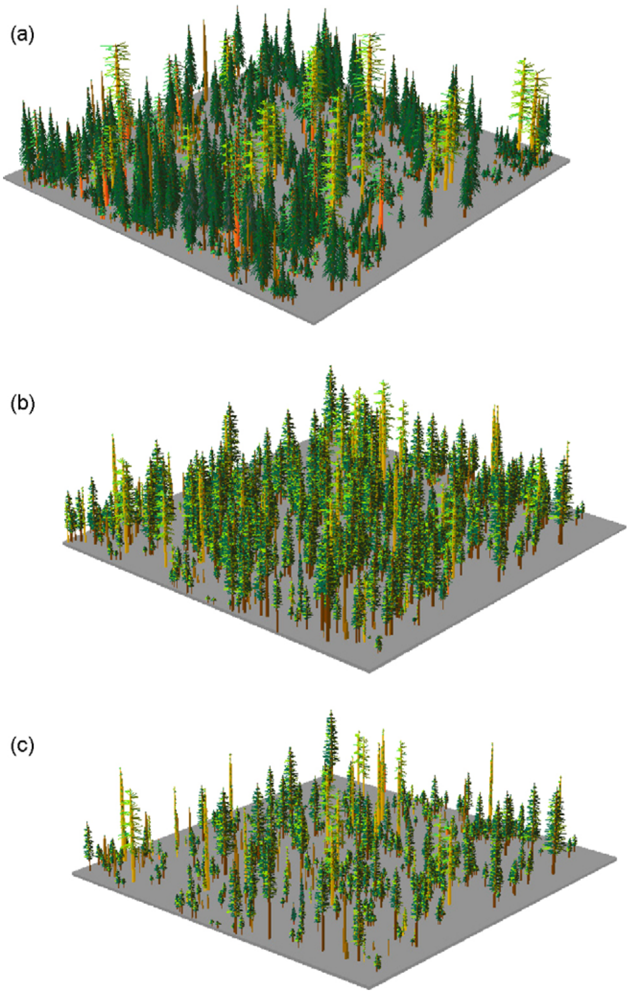

Fig. 1. Stand visualization simulations of Teakettle experimental treatments for (a) an un-thinned control plot, (b) a post-treatment understory-thinned plot, and (c) a post-treatment overstory-thinned plot. Plots are 4 ha (200 m × 200 m); stem locations, species, and sizes were determined from mapped field data.

maximum, and means of temperature and VPD. We also analyzed mean daily ranges in temperature and VPD for each sensor as measures of microclimate buffering. When regression of the response variable with either covariable in MANCOVA was nonsignificant, we used analysis of covariance (ANCOVA) with the remaining significant covariable. When neither covariable had a significant relationship with the response, a simple repeated measures analysis of variance (ANOVA) approach was used. If power transformation of the response variable was not sufficient to achieve homoscedasticity and satisfy assumptions of normality, we used nonparametric rank *F* test analyses. Means were compared via orthogonal contrasts ($P < 0.05$).

3. Results

During the sample period, using the 0 and 10 °C thresholds for the sensors at 5 m on control plot trees, winter was 125 days from 1 November through 4 March and summer 156 days from 29 May through 31 October. Over the summer period, mean daily temperatures ranged from a mean minimum of 11.4 °C (6:30 a.m.) to a mean maximum of 20.8 °C (2:00 p.m.) and daily VPD from a mean minimum of 0.77 kPa (7:00 a.m.) to a maximum of 1.66 kPa (1:30 to 2:00 p.m.). Over winter, temperatures ranged from −3.0 °C (6:30 a.m.) to 3.8 °C (12:00 p.m.) and VPD from 0.10 kPa (9:00 p.m. to 7:00 a.m.) to 0.30 kPa (12:00 p.m.). Mean basal areas (and standard errors) within encompassing circular 0.1 ha plots of control, riparian, U-thin, and O-thin trees were 8.10 (1.33), 5.66 (0.80), 5.65 (2.45), and 1.59 (0.68) m^2, respectively (Table 1a). Riparian trees had less basal area than the control because they faced 180° on gaps over creeks. Thinning treatments significantly reduced density and basal area in the understory (−171 stems and −20.2 m^2 ha^{-1}) and overstory thinning treatments (−192 stems and −33.9 m^2 ha^{-1}) (Table 1b and Fig. 1).

Table 1

(a) Environmental variables by treatment trees: Rip = riparian; U-thin = understory-thinned; O-thin = overstory-thinned; Heat = heat load index; Water = distance to nearest perennial stream; BA = tree basal area in encompassing circular 0.1 ha plot. (b) Post-treatment mean stand structure and composition for the un-thinned (control), understory-thinned (U-thin), and overstory-thinned (O-thin) plots, for all stems ≥5 cm dbh. The riparian did not significantly differ from control conditions.

Tree	Height (m)	DBH (cm)	Elevation (m)	Heat	Water (m)	BA (m^2)
(a)						
Control 1	55	175	2105	1.05	101	6.61
Control 2	50	105	2105	1.01	124	10.75
Control 3	50	106	2122	1.05	72	6.95
Rip 1	58	98	2042	1.02	3	5.12
Rip 2	51	113	2020	0.75	2	7.24
Rip 3	58	127	2009	0.93	3	4.61
U-thin 1	58	136	2055	1.01	59	3.14
U-thin 2	53	113	2062	1.03	87	10.55
U-thin 3	48	123	2083	1.01	122	3.26
O-thin 1	52	103	2068	1.03	59	0.53
O-thin 2	51	130	2076	1.03	96	2.87
O-thin 3	50	117	2091	1.05	134	1.37

Stand-level	Control	U-thin	O-thin
(b)			
Basal area (m^2 ha^{-1})	56.4	41.2	22.7
Density (stems ha^{-1})	469	240	150
Volume (m^3 ha^{-1})	435	398	201
Quadratic mean dbh (cm)	19.6	23.4	21.9
Proportion of fir[a] stems (%)	71	72	68
Canopy cover (%)	79.8	72.5	62.7
Transmitted direct light (mol m^{-2} d^{-1})	24.9	31.8	42.4
Transmitted diffuse light (mol m^{-2} d^{-1})	2.3	3.0	3.9

[a] *Abies concolor* and *Abies magnifica*.

3.1. Riparian

Summer nighttime minimum temperatures and VPDs, and mean diurnal temperatures, were significantly lower in the riparian than in all other treatments at every height (Tables 2 and 3). Mean VPD was significantly the lowest among treatments ≤35 m. As both minimums warmed with height, so did their means, even though maximum temperatures and VPDs decreased. In spite of cooling with elevation, maximum temperatures remained the warmest of all treatments across heights with the exception of the O-thin at 5 m. This made riparian diurnal temperature and VPD ranges statistically the greatest across heights, except for VPD in the O-thin at 5 m.

Winter minimum, maximum, and mean daily temperatures were the lowest among treatments throughout the vertical forest profile. In synchrony with temperatures, minimum, maximum, and mean daily VPDs were also the lowest among treatments across heights, except for minimum VPD in the U-thin at 5 m. Means and maximums for both temperature and VPD increased with height, while minimum temperatures decreased. Diurnal ranges in VPD were statistically the smallest among treatments up to 45 m, while temperature ranges were only the least at 5 m.

Table 2

Daily means of temperature (°C) parameters by season, treatment, and elevation above the forest floor. Different superscript numbers within a row and season indicate significant differences among the means ($P < 0.05$). Bold numbers are the most extreme values in a row by season: Cont = control; Rip = riparian; U-thin = understory-thin; O-thin = overstory-thin.

	Winter				Summer			
	Cont	Rip	U-thin	O-thin	Cont	Rip	U-thin	O-thin
45 m								
Min	-1.6^{1}	$-\mathbf{3.4}^{2}$	-2.9^{23}	-2.2^{13}	13.2^{1}	$\mathbf{10.1}^{2}$	11.0^{3}	12.2^{4}
Max	$\mathbf{4.4}^{1}$	4.0^{2}	4.3^{3}	4.0^{2}	19.7^{1}	$\mathbf{20.2}^{2}$	20.0^{2}	19.6^{3}
Mean	1.2^{1}	$-\mathbf{0.3}^{2}$	0.3^{3}	0.7^{4}	$\mathbf{16.4}^{1}$	14.8^{2}	15.3^{23}	15.8^{3}
Range	6.0^{1}	$\mathbf{7.4}^{2}$	7.2^{2}	6.3^{3}	6.4^{1}	$\mathbf{10.1}^{2}$	9.0^{3}	7.4^{4}
35 m								
Min	-1.8^{1}	$-\mathbf{3.7}^{2}$	-3.0^{23}	-2.6^{13}	12.9^{1}	$\mathbf{9.6}^{2}$	10.8^{3}	11.6^{4}
Max	$\mathbf{4.4}^{1}$	4.0^{2}	4.3^{13}	4.2^{3}	20.1^{12}	$\mathbf{20.6}^{2}$	20.3^{12}	20.0^{1}
Mean	1.1^{1}	$-\mathbf{0.5}^{2}$	0.2^{3}	0.5^{4}	$\mathbf{16.3}^{1}$	14.7^{2}	15.3^{3}	15.6^{3}
Range	6.2^{1}	$\mathbf{7.7}^{2}$	7.3^{23}	6.8^{3}	7.3^{1}	$\mathbf{10.9}^{2}$	9.4^{3}	8.4^{4}
25 m								
Min	-2.2^{1}	$-\mathbf{3.8}^{2}$	-3.2^{23}	-2.9^{13}	12.1^{1}	$\mathbf{9.1}^{2}$	10.3^{3}	10.8^{4}
Max	4.3^{1}	3.8^{2}	4.2^{1}	$\mathbf{4.7}^{3}$	20.3^{1}	$\mathbf{21.0}^{2}$	20.7^{12}	20.6^{12}
Mean	0.7^{1}	$-\mathbf{0.7}^{2}$	-0.1^{3}	0.4^{4}	$\mathbf{16.0}^{1}$	14.6^{2}	15.2^{23}	15.4^{3}
Range	6.5^{1}	$\mathbf{7.6}^{2}$	7.4^{3}	$\mathbf{7.6}^{2}$	7.9^{1}	$\mathbf{11.6}^{2}$	10.1^{3}	9.5^{4}
15 m								
Min	-2.5^{1}	$-\mathbf{4.0}^{2}$	-3.4^{3}	-3.3^{3}	11.9^{1}	$\mathbf{9.0}^{2}$	10.2^{3}	10.5^{4}
Max	4.0^{1}	3.2^{2}	4.1^{3}	$\mathbf{4.9}^{4}$	20.6^{1}	$\mathbf{21.3}^{2}$	21.2^{3}	21.0^{4}
Mean	0.4^{1}	$-\mathbf{1.0}^{2}$	-0.3^{3}	0.1^{4}	$\mathbf{15.8}^{1}$	14.4^{2}	15.1^{23}	15.3^{3}
Range	6.5^{1}	7.2^{2}	7.5^{2}	$\mathbf{8.2}^{3}$	8.7^{1}	$\mathbf{12.2}^{2}$	11.0^{3}	10.5^{4}
5 m								
Min	-2.9^{1}	$-\mathbf{4.2}^{2}$	-3.6^{3}	-3.6^{3}	11.5^{1}	$\mathbf{8.6}^{2}$	9.8^{3}	10.0^{3}
Max	3.8^{1}	2.5^{2}	3.7^{1}	$\mathbf{5.1}^{3}$	21.1^{1}	21.7^{2}	21.6^{3}	$\mathbf{22.3}^{4}$
Mean	0.0^{1}	$-\mathbf{1.4}^{2}$	-0.6^{1}	-0.2^{1}	$\mathbf{15.6}^{1}$	14.1^{2}	15.0^{3}	15.3^{13}
Range	6.8^{1}	6.7^{1}	7.3^{2}	$\mathbf{8.7}^{3}$	9.6^{1}	13.1^{2}	11.8^{3}	12.2^{4}

Table 3

Daily means of vapor pressure deficit (kPa) parameters by season, treatment, and elevation above the forest floor. Different superscript numbers within a row and season indicate significant differences among the means ($P < 0.05$). Bold numbers are the most extreme values in a row by season: Cont = control, Rip = riparian, U-thin = understory-thin, O-thin = overstory-thin.

	Winter				Summer			
	Cont	Rip	U-thin	O-thin	Cont	Rip	U-thin	O-thin
45 m								
Min	$\mathbf{0.11}^{1}$	0.02^{2}	0.05^{2}	0.08^{1}	$\mathbf{0.73}^{1}$	0.49^{2}	0.56^{3}	0.63^{4}
Max	$\mathbf{0.46}^{1}$	0.37^{2}	0.42^{3}	0.43^{3}	1.65^{1}	1.70^{2}	$\mathbf{1.71}^{2}$	1.68^{3}
Mean	$\mathbf{0.25}^{1}$	0.12^{2}	0.17^{23}	0.21^{13}	$\mathbf{1.17}^{1}$	1.00^{2}	1.06^{2}	1.14^{1}
Range	0.36	0.34	**0.37**	0.35	0.92^{1}	$\mathbf{1.21}^{2}$	1.14^{3}	1.05^{4}
35 m								
Min	$\mathbf{0.09}^{1}$	0.02^{2}	0.04^{23}	0.06^{3}	$\mathbf{0.71}^{1}$	0.46^{2}	0.54^{3}	0.61^{4}
Max	$\mathbf{0.44}^{1}$	0.35^{2}	0.40^{3}	0.43^{1}	1.70	**1.73**	1.72	1.70
Mean	$\mathbf{0.23}^{1}$	0.10^{2}	0.15^{1}	0.19^{1}	$\mathbf{1.16}^{1}$	0.98^{2}	1.05^{3}	1.09^{13}
Range	0.35^{1}	0.33^{2}	0.35^{13}	$\mathbf{0.36}^{3}$	0.99^{1}	$\mathbf{1.28}^{2}$	1.17^{3}	1.09^{4}
25 m								
Min	$\mathbf{0.08}^{13}$	0.01^{2}	0.04^{1}	0.05^{3}	$\mathbf{0.66}^{1}$	0.43^{2}	0.53^{3}	0.57^{4}
Max	$\mathbf{0.44}^{1}$	0.30^{2}	0.38^{3}	$\mathbf{0.44}^{4}$	1.72	**1.78**	1.77	1.77
Mean	$\mathbf{0.21}^{1}$	0.08^{2}	0.14^{3}	0.18^{1}	$\mathbf{1.14}^{1}$	0.96^{2}	1.05^{3}	1.09^{13}
Range	0.34^{1}	0.28^{2}	0.33^{1}	$\mathbf{0.38}^{3}$	1.07^{1}	$\mathbf{1.35}^{2}$	1.24^{3}	1.20^{4}
15 m								
Min	$\mathbf{0.06}^{1}$	0.01^{2}	0.02^{3}	0.03^{4}	$\mathbf{0.63}^{1}$	0.40^{2}	0.49^{3}	0.52^{4}
Max	0.39^{1}	0.25^{2}	0.35^{1}	$\mathbf{0.44}^{1}$	1.74^{1}	1.80^{2}	$\mathbf{1.83}^{3}$	1.82^{4}
Mean	$\mathbf{0.19}^{13}$	0.06^{2}	0.11^{1}	0.16^{3}	$\mathbf{1.11}^{1}$	0.94^{2}	1.03^{3}	1.06^{13}
Range	0.33^{1}	0.24^{2}	0.33^{1}	$\mathbf{0.40}^{3}$	1.11^{1}	$\mathbf{1.39}^{2}$	1.33^{3}	1.30^{3}
5 m								
Min	$\mathbf{0.05}^{1}$	0.02^{2}	0.00^{2}	0.02^{2}	$\mathbf{0.60}^{1}$	0.36^{2}	0.46^{3}	0.48^{3}
Max	0.36^{1}	0.18^{2}	0.30^{1}	$\mathbf{0.42}^{3}$	1.80^{1}	1.85^{1}	1.89^{12}	$\mathbf{1.98}^{2}$
Mean	$\mathbf{0.15}^{1}$	0.04^{2}	0.09^{3}	0.13^{1}	$\mathbf{1.09}^{1}$	0.90^{2}	1.02^{13}	1.06^{3}
Range	0.31^{1}	0.17^{2}	0.28^{3}	$\mathbf{0.40}^{4}$	1.20^{1}	1.49^{2}	1.43^{3}	$\mathbf{1.51}^{4}$

3.2. No-thin control

Summer maximum temperatures in the control were significantly cooler than in other treatments ≤15 m, which in turn led to the coolest maximum VPDs (Tables 2 and 3). At the same time, mean daily temperatures and minimum temperatures and VPDs were significantly greater than in other treatments across heights (except for O-thin mean temperature at 5 m). These latter three responses and minimum temperatures increased with height above the forest floor, while maxima and ranges of temperature and VPD decreased. Warmer minimum and cooler maximum temperatures resulted in both temperature and VPD diurnal ranges that were statistically the smallest of all treatments across heights.

Winter minimum and mean temperatures and mean VPD values were higher than in other treatments and increased with increasing height from 5 m. Where temperatures were lowest near the forest floor, so were maximum VPDs and their diurnal ranges, both of which also increased with height. Daytime maximum temperatures were somewhat intermediate among treatments until becoming the warmest ≥35 m. Moderate maximum temperatures and warmer minima gave the control significantly smaller diurnal ranges than other treatments throughout the vertical profile (except the riparian at 5 m).

3.3. Overstory-thin

Summer O-thin minimum temperatures and VPDs were significantly lower than in the control throughout the vertical profile (Tables 2 and 3). At the same time, maximum temperatures and corresponding VPDs were significantly greater than in the control ≤15 m. The O-thin had the single greatest temperature and VPD maxima of all treatments and heights at 5 m.

With lower minimums and higher maximums (≤25 m) than the control, every height also had significantly greater temperature and VPD ranges that steadily decreased with elevation.

Winter daily minimum temperatures and VPDs were significantly lower than those in the control ≤15 m, and steadily increased with height. At the same time, maximum temperatures and VPDs were significantly greater than in the control ≤25 m, and decreased with height. As in summer, the winter O-thin had significantly greater diurnal temperature ranges than the control throughout the vertical profile, and VPD ranges that were significantly greater ≤35 m. These diurnal fluctuations in temperature and VPD were the greatest among all treatments nearest the forest floor (≤15 and ≤35 m, respectively).

3.4. Understory-thin

Summer nighttime minimum temperatures and VPDs in the U-thin were significantly lower than in the control across all heights (Tables 2 and 3). At the same time those responses were significantly lower than in the O-thin ≥15 m, but significantly higher than the riparian across all heights. Maximum temperatures were significantly higher than the control and significantly lower than the riparian ≤15 m. However, the maximum temperature nearest the forest floor at 5 m was also significantly cooler than the most extreme maximum of the O-thin. While minimum temperatures and VPDs increased with height, maximums decreased, and consistent with other treatments, summer daily ranges in temperature and VPDs also decreased with height. Both ranges were significantly greater than in the control and O-thin across heights except nearest the forest floor.

Winter minimum and mean temperatures in the U-thin warmed with increasing height, but were significantly cooler than in the control. At the same time, where U-thin conditions were coolest ($\leq$15 m), minimum temperatures were still warmer than in the riparian. Maximum temperatures increased with height above the floor similar to the control but opposite the O-thin pattern. Diurnal temperature ranges were significantly greater than in the control throughout the vertical profile and significantly less than in the O-thin $\leq$25 m. At 25 m and above, U-thin ranges became greater relative to the O-thin whose maximums were decreasing while those of the U-thin remained constant.

Winter mean and maximum VPDs in the U-thin were lower than in the control and O-thin treatments across elevations, but higher than in the riparian. Understory-thin means were significantly less than in the O-thin and the control $\leq$25 m ($P = 0.0798$ at 15 m), and nearest the forest floor at 5 m, the U-thin maximum was significantly less than in the O-thin. While maximums in the U-thin increased with height, those in the O-thin remained relatively constant through the vertical profile, resulting in U-thin VPD ranges that were only significantly less than in the O-thin $\leq$25 m. At the same time, U-thin ranges were only significantly less than in the control at 5 m.

4. Discussion

4.1. Riparian: unique microclimate

As zones of transition between aquatic and terrestrial environments, riparian areas have a microclimate strongly influenced by the aquatic system (Gregory et al., 1991; FEMAT, 1993; Meleason et al., 2003) that can be further modified by local topography (Barnes et al., 1998; Chen et al., 1999; Naiman et al., 2000; Geiger et al., 2003). The riparian areas in this study were narrowed by steeper slopes, which decrease direct solar radiation, thereby reducing summer heat load (Moore et al., 2005; Rykken et al., 2007).

In summer, steep slopes also cause drainages to be warmer than ridge tops from upslope winds in daytime and cooler at night due to downslope flow of cold air from surrounding higher terrain. As a result, accumulation of cold air at night can result in a local temperature inversion in drainages (Barnes et al., 1998). This phenomenon acts in conjunction with stream influence, which directly cools air temperature and indirectly supplies water for daytime evaporative cooling via plant transpiration (Naiman et al., 2000). Transpiration and soil evaporation bolstered by the hyporheos can be major contributors to air moisture content in forests (Danehy and Kirpes, 2000), decreasing VPDs. In dense forests, transpiration is the greater component of evapotranspiration (Barnes et al., 1998). However, in more open forests such as in this study (North et al., 2004), evaporation from the forest floor plays a larger role (Barnes et al., 1998; Geiger et al., 2003). The combination of these factors gives the riparian zone overall cooler daily mean temperatures. The riparian extreme temperature and VPD ranges were greatest in proximity to the stream (the drainage low point) where diurnal fluxes in cold and warm air create more variable temperature fluctuations than occur more upland or at greater height above the forest floor.

In winter, temperature inversions are not restricted to nighttime. Low-lying headwater drainages act as perpetual winter cold sinks, holding down both nighttime minimum and daytime maximum temperatures and VPDs. Temperatures become warmer (and VPDs greater) with height when low-angle winter sun warms the forest canopy and temperature inversion occurs above the cold sink of the forest floor.

While winter humidity was enhanced, and its fluctuation dampened throughout the vertical profile, riparian temperature ranges were only buffered relative to other treatments near the stream. In spite of continual snow cover on the forest floor throughout the season, these headwater streams remained unfrozen and ran openly. The buffering influences of water and surrounding snowpack on temperatures nearer the forest floor act with winter temperature inversion to create less variability in temperature regimes throughout the day near the forest floor than higher in the forest canopy (Rambo and North, 2008).

4.2. No-thin control: buffered stability

Direct solar radiation is the primary driver of air and soil heating (Anderson et al., 2007), and forest canopy directly influences understory microclimate by reducing solar radiation through interception by leaf surface area (Aussenac, 2000). Summer control mean temperatures were the warmest of all treatments, even though the intact forest canopy dissipated much solar radiation influx (Holbo and Childs, 1987) and shaded the understory. It is likely for these reasons that summer maximum temperatures (daytime highs) in the control were kept cooler. In winter, maxima were intermediate among treatments from the ground up to where low-angle winter sunlight warmed the canopy foliage and radiative longwave energy had its greatest warming effect within the crown. Summer nighttime temperatures were also kept warmer because overstory canopy insulates the understory environment from longwave radiative losses (Holbo and Childs, 1987; Moore et al., 2005) and decreases advective mixing with cooler downslope flowing air from outside the forest (Valigura and Messina, 1994). Wind penetrates the trunk space beneath the canopy with greater force than in the canopy where wind is buffered (Raynor, 1971). At the same time, solar radiation intercepted and absorbed by the canopy is re-radiated as longwave heat energy by canopy biomass and tree boles. At night, longwave radiation given off from forest canopy partially compensates radiation losses from surface soil and vegetation (Mahrt, 1985) to reduce cooling of the understory. The combination of relatively cool daytime maximums and warm nighttime minimums gave the intact control significantly more dampened diurnal temperature and VPD ranges than all other treatments.

4.3. Overstory-thin: microclimate extremes

It was somewhat surprising that mean temperatures were cooler in the O-thin treatment than in the control. However, the O-thin drastically opened the forest canopy, leaving solitary trees, which increases the loss of longwave heat radiation from the ground and vegetation, leading to increasingly cooler nighttime air temperatures (Mahrt, 1985). Moreover, open sky is cold relative to forest canopy and consequently emits less longwave radiation downwards towards the surface (Groot and Carlson, 1996). In the absence of intact canopy, the O-thin had no insulating blanket to protect the understory environment from radiative heat loss to the cold, open atmosphere. Consequently, the O-thin had significantly lower morning minimum temperatures than the control, where nighttime temperatures were kept more buffered from the open atmosphere by intact canopy.

At the same time, removal of shading overstory allowed largely unrestricted shortwave solar radiation to warm the O-thin forest floor by day, giving it greater temperature and VPD maxima than the control $\leq$15 m, and the highest across all treatments and heights at 5 m. Summer soil surface temperatures in gaps at this site exceeded 50 °C for several hours daily while temperatures beneath adjacent clumps of trees remained at 28 °C (Ma, 2003). Warming of the soil to this degree in turn contributes considerable longwave radiative energy to elevate near-surface daytime air temperatures.

Summer daytime advective mixing of air did not appear to have an influence on the steepness of O-thin vertical temperature and VPD gradients in comparison to the control. In more dense and closed-canopy forests of the Pacific Northwest, thinning increases permeability of stands to air circulation, leading to greater advective mixing of air and reducing variation in temperature and relative humidity regimes through the vertical profile (Chen et al., 1993; Heithecker and Halpern, 2007). However, our O-thin gradients were actually steeper than those in the control, which we attribute to the extreme surface daytime heating and greater nighttime cooling in the O-thin. Raynor (1971) points out that wind and temperature structure found in one forest type may not be applicable to another. It may be that in less dense and more patchy forests typical of Sierra mixed-conifer (Bonnicksen and Stone, 1982; North et al., 2004) there is greater turbulent exchange initiated by the rougher canopy surface, which mixes and homogenizes air and temperature vertically (Lee, 1978). Most downward air flow occurs in canopy openings (Raynor, 1971).

Our near-surface (<25 m) results extend at-surface (≤1 m) results of other investigators. Groot and Carlson (1996) found that early summer minimum air temperatures in Ontario decreased as forest opening increased, with an average difference between forest and clear-cuts of nearly 3 °C (6 °C on clear nights). In western Washington, Heithecker and Halpern (2006) observed increases in mean and maximum air temperatures as the amount of live-tree retention decreased. Temperatures were significantly greater at 0 and 15% retention than in their un-thinned control. In the same region, dispersed live-tree retention treatments studied by Barg and Edmonds (1999) had significantly higher summer maximum air temperatures than intact forest, and maximum temperatures in shelterwood cuts in the central Sierra Nevada were 5–8 °C warmer than in an uncut control (Dunlap and Helms, 1983). Lastly, in western Oregon, Anderson et al. (2007) found that mean air temperature maximums were 1–4 °C higher in thinned than un-thinned stands. They cited penetration of low-angle solar radiation into and beneath tree canopies as an important factor for surface warming in thinned stands, while being relatively unimportant in closed canopy forest.

It was less surprising that diurnal swings between highs and lows of summer and winter temperature and VPD were significantly more extreme than the control and decreased with height. Forest surface radiation balances are dominated by the presence or absence of canopy, and large, rapid changes in radiative flux are characteristic of forest surfaces that have had their overstory removed (Holbo and Childs, 1987). Overstory thinning results in a greater daytime influx of solar radiation with higher near-surface maximum temperatures and VPDs, and a greater nighttime loss of longwave radiation with lower near-surface temperatures and VPDs. This in turn results in more extreme diurnal swings in both parameters. The single greatest daily range in VPD among treatments at any height was in the O-thin at 5 m.

The lower winter surface minimum temperatures and VPDs of the O-thin are consistent with results from Baker et al. (1992). In a long-term comparison of winter days with and without snow cover, they found surface mean minimum and maximum air temperatures were cooler (8.4 °C) when snow-covered. This was attributed to the albedo of snow acting in combination with a reduction in soil-emitted longwave radiation that was instead absorbed by snow. The deeper the blanket of insulating snow, the less radiation can escape, and in the absence of overstory canopy to contribute longwave radiative energy, there is a daily net loss of radiative energy from the understory (Geiger et al., 2003). It follows that the O-thin with widely dispersed live trees and a deeper more uniform snow pack would be expected to have cooler minimum and maximum surface temperatures than under intact canopy where much snowfall is intercepted and melted. However, in contrast to the other treatments, winter maximum temperatures were significantly greater ≤25, and decreased with increasing height. At 5 m and above, the effect of albedo on immediate surface temperature may not be as important in outweighing the warming influence of direct solar radiation unimpeded by canopy. Control maximums became higher than in the O-thin above 25 m where longwave radiative energy emitted from the canopy likely played a role in warming air temperatures.

4.4. Understory-thin: intermediate conditions

Understory-thin results were expected to be intermediate between those of the O-thin and control, and they frequently were. However, they were often intermediate between the O-thin and riparian or the control and riparian. In spite of the care taken to select U-thinned study trees that were removed from the perennial stream (≥59 m, Table 1) running through that plot, the results appear to be confounded by this treatment's low-lying topographic position that was physically closer to the riparian than the more upland control and O-thin environments. For this reason, a heat load index for each study tree was included as a significant covariable in analyses to help separate the influences of these confounding effects and make *P*-values more indicative of the thinning treatment. However, mean values remained skewed towards the riparian environment.

The confounding is exemplified by the U-thin's summer daily minimum temperatures and VPDs, which were generally lower than in the control and O-thin, but higher than the riparian. This likely reflects the net effect of an insulating partial overstory of the U-thin on the cooler near-riparian microclimate. Of the temperature parameters, the daily minimum would be most influenced by downslope flow of nighttime cold air near the riparian drainage. Maximum temperatures were intermediate between the control and riparian, but also significantly cooler than in the O-thin nearest the forest floor at 5 m. There, the grouped remnant trees of the U-thin left a more shaded and insulated understory microenvironment than the O-thin. Diurnal temperatures and VPD ranges were both intermediate between the riparian and control and between the riparian and O-thin. The relatively high-diurnal temperature fluctuations in the U-thin can again be attributed to its lower topographic position than the control and overstory treatments, and its consequent proximity to nocturnal cold air flow and accompanying low-minimum temperatures. The exception was at 5 m where the extreme exposed conditions of the O-thin outweighed any riparian influence on the U-thin, giving the former significantly greater daily ranges.

Winter patterns of responses were similarly confounded and share the same probable explanations. Morning minimum temperatures, and maximum and mean VPDs in the U-thin were generally less than in the control or O-thin, but greater than the riparian because of proximity to the cold air sink of the riparian drainage. Below 25 m, maximum temperatures, mean VPDs, and VPD ranges were lower relative to the O-thin, and the patterns of increasing temperature and VPD maxima with height were similar to those of the control and dissimilar to the U-thin. In addition to the potential riparian influence, moderate thinning left sufficient canopy to reduce solar radiative influx to the understory, which would depress maximum temperatures and diurnal ranges at lower heights below those of the severely thinned overstory treatment. Removal of forest cover increases solar radiation at the surface and in the understory, elevating daytime air temperatures (Heithecker and Halpern, 2006). At the same time, with increasing height into the canopy, U-thin maxima were warmed by longwave radiative input and buffered from advective mixing of air relative to conditions within the exposed solitary crowns of the O-thin.

In comparison to the O-thin, the U-thin opened the forest canopy more conservatively, leaving study trees within groups of remnant trees that dampened thinning effects on microclimate gradients. While summer U-thin maximum temperatures and temperature and VPD diurnal ranges were significantly greater than in the control nearest the forest floor at 5 m, their departures from control conditions were significantly less than the extremes seen in the O-thin. The U-thin left a more shaded and relatively cooler environment in study trees that was more similar to that of the control than the O-thin.

5. Management implications

Both the overstory- and understory-thin treatments in this study altered summer microclimate gradients within trees from those found in the control. However, of the two treatments, the U-thin left microclimate conditions within trees more similar to conditions within un-thinned forest trees. Microclimate directly influences most ecological and physiological processes in both plant and animal communities (Xu et al., 1997; Chen et al., 1999; Zheng et al., 2000), and summer is when temperature and humidity are most likely to be biologically important as limiting environmental factors for organisms that require cooler or more moist environments. Canopy and bole temperature and VPD environments are important for sustaining arboreal epiphyte communities and their associated invertebrate and small mammal populations. In this study, understory thinning left the microclimate environments those organisms may be dependent upon less altered than overstory thinning. However, whether the statistically significant differences in microclimate variables we found are great enough to be ecologically significant to arboreal organisms is an important question that remains to be addressed in future research.

The confounding effect of topographic position on the understory treatment influence on microclimate was in itself informative. It suggests that to maintain within-tree vertical microclimates after thinning, it may be beneficial to retain larger groups of trees on sites with harsher microclimate conditions. When reducing fire ladder fuels, it may be possible to thin stands more aggressively where milder slopes and proximity to cold air drainages make arboreal microclimate environments more resistant to thinning disturbance than in more upland stands. Canopies can exert more control on the distribution of microclimate energy than topographic variables such as either site slope or aspect (Holbo and Childs, 1987). When thinning, care should be taken to avoid compromising the distinct microclimate regime and plant and wildlife habitat heterogeneity of riparian environments that make them such diverse and complex terrestrial ecosystems (Naiman et al., 1993, 2000). Our results lend support to the argument put forth by North et al. (2004) suggesting that lack of natural regeneration of both shade-tolerant and -intolerant species in southern Sierra Nevada forest gaps may in part be due to an unrealized minimum canopy cover threshold below which high temperatures and transpiration demands severely limit tree establishment.

Finally, even though the stand conditions and treatments in this experiment are typical of many Westside Sierra Nevada forests and their management practices, broader inferences must be drawn with caution as they are necessarily limited by the lack of site-level replication.

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