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Spatial variability in microclimate in a mixed-conifer forest before and after thinning and burning treatments

Siyan Ma [a,*], Amy Concilio [b], Brian Oakley [c], Malcolm North [d], Jiquan Chen [e]

[a] Ecosystem Sciences Division, 137 Mulford Hall 3114, Department of Environmental Science, Policy, and Management, University of California at Berkeley, Berkeley, CA 94720-3114, USA
[b] Department of Environmental Studies, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
[c] Department of Biological Sciences, University of Warwick, Coventry CV4 7AL, UK
[d] US Forest Service, Pacific Southwest Research Station, 1731 Research Park Dr., Davis, CA 95618, USA
[e] Department of Environmental Sciences, The University of Toledo, Toledo, OH 43606, USA

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ABSTRACT

In the western United States, mechanical thinning and prescribed fire are common forest management practices aimed at reducing potential wildfire severity and restoring historic forest structure, yet their effects on forest microclimate conditions are not well understood. We collected microclimate data between 1998 and 2003 in a mixed-conifer forest in California's Sierra Nevada. Air and soil temperatures, relative humidity, photosynthetically active radiation (PAR), wind speed, soil heat flux, and soil volumetric moisture were measured at the center of 18 four-ha plots. Each plot was assigned one of six combinations of thinning and burning treatments, and each treatment was thus given three replications. We found that spatial variability in microclimate, quantified as standard deviations among monthly values of each microclimatic variable across different locations ($n \leq 18$), was significantly high and was influenced primarily by elevation and canopy cover. The combination of thinning and burning treatments increased air temperature from 58.1% to 123.6%. Soil temperatures increased in all thinned plots. Air moisture variables indicated that treatments made air drier, but soil moisture increased in the range 7.9–39.8%, regardless of treatment type. PAR increased in the range 50.4–254.8%, depending on treatment type. Treatments combining thinning and burning increased wind speed by 15.3–194.3%. Although soil heat flux increased dramatically in magnitude in some plots, overall treatment effects on G were not statistically significant. We discussed the significance and implications of the spatial variability of microclimate and the treatment effects to various ecological processes and to forest management.
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1. Introduction

Sierra Nevada mixed-conifer forests, typical of many western U.S. forests, are fire-dependent ecosystems; fire is essential both for nutrient supply and for germination of some species (Kennard and Putz, 2005). Historically, these forests had a frequent (12–20 years), low-intensity fire regime (Miller and Urban, 1999). However, fire has been suppressed for more than 100 years throughout most of the region (McKelvey and Busse, 1996). With such long-term fire suppression, mixed-conifer forests in the region have become denser than analogous historical structures, although the forests still retain a heterogeneous spatial structure consisting of closed-canopy tree groups, shrub thickets, and open gaps (Miller and Urban, 1999; North et al., 2007). Currently, these forests are facing greater risks of fire hazard (NWGC, 2001). From an ecological perspective, high stem densities and canopy cover promote shade-tolerant species (*e.g.*, white fir, incense cedar) but significantly inhibit shade-intolerant species (*e.g.*, ponderosa, Jeffery, and sugar pine) (North et al., 2007; Moghaddas et al., 2008). Current forest management in the Sierra Nevada is aimed at not only reducing stand density but also restoring historic species composition. Mechanical thinning, prescribed fire, or combinations of these are commonly used as restoration/fuel treatments (North et al., 2007). Although the effects of these treatments on many ecological characteristics and processes (*e.g.*, species richness and abundance, forest regeneration, community dynamics, organic matter decomposition, and soil carbon flux) have been addressed (Innes et al., 2006; Wayman and North, 2007; Ryu et al., 2009), the effects of mechanical thinning and prescribed burning treatments on forest structure and microclimate remain poorly understood in our subject forests.

* Corresponding author. Tel.: +1 510 642 2421; fax: +1 510 543 5098.
E-mail address: syma@berkeley.edu (S. Ma).

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Microclimate is important in understanding ecological processes and functions because microclimate determines biophysical environmental conditions or resources (*e.g.*, temperature, water, and light) that in turn determine species composition, plant growth and development, community population, regeneration, soil nutrient cycling, organic matter decomposition, and primary productivity (Zobel et al., 1976; Spies and Franklin, 1989; Chen et al., 1993). However, it remains a challenge to properly evaluate microclimatic conditions under a forest canopy since microclimatic variables are highly dynamic and correlated in space and time (Horne and Scheider, 1995). It is well known that forest management at a stand level can alter vegetation cover and consequently influence forest microclimate (Aussenac, 2000). For example, light levels are directly influenced by the spatial distribution of canopy cover (Lieffers et al., 1999), and forest management practices that affect canopy openness, such as thinning treatments, can increase light levels in the understory (Drever and Lertzman, 2003). Consequently, any changes in radiation could have cascading effects on temperature, water conditions, and energy balance since solar radiation provides primary energy to the ecosystem (Aussenac, 2000). Other forest treatments, such as burning, might have different effects on microclimate, such as increased *albedo* of the forest floor or increased soil temperature and moisture. Although some changes in microclimate due to thinning or burning may be predicable, the two treatment types might interact to produce unexpected patterns, which could vary across the landscape, creating more complicated patterns (North et al., 2007).

We began this study in the Teakettle Experimental Forest (TEF) in 1998 to determine how alternative forest management might affect understory microclimate. We collected below-canopy microclimate data with automated microclimate stations at 18 different locations over 4 years (from before to after our treatment). This long-term, forest-wide microclimate dataset allows us to better examine microclimate variability in pre-treated forests and to quantify the degree of treatment effects. Our objectives were to (1) examine microclimate spatial variability in the fire-suppressed forest (pre-treatment period), and (2) quantify treatment effects on microclimate. We hypothesized that treatment effects on light levels would depend primarily on the degree of canopy removal but that other microclimate variables, such as temperature and moisture, would be affected by additional factors as well (such as forest floor conditions).

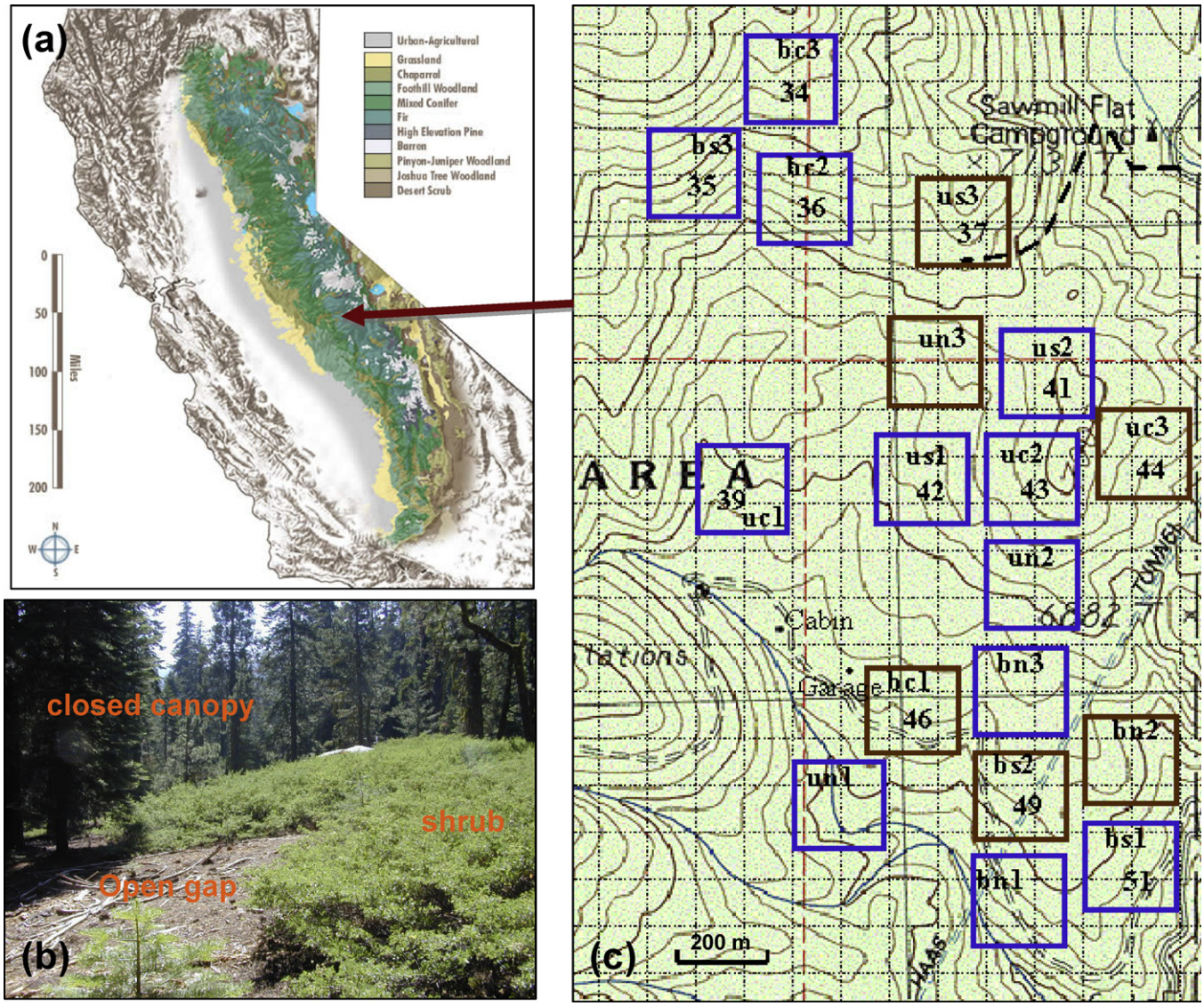

Fig. 1. The Teakettle Experimental Forest in California's Sierra Nevada: (a) site location on California regional map; (b) three dominant mixed-conifer patch conditions: closed-canopy forest, shrub, and open gap; (c) locations of treatment plots, labeled with treatment type (refer to Table 1).

2. Methods

2.1. Study site

The study was conducted in the TEF, located at 36°58′N, 119°2′W, at elevation 1880–2485 m in California's southern Sierra Nevada (Fig. 1a). The mixed-conifer forest is a matrix of tree clusters punctuated with persistent gaps averaging 5–20 m in diameter. Open areas (*e.g.*, canopy gaps) are typically bare ground or have limited shrub cover (Fig. 1b). This mixed-conifer forest contains white fir (*Abies concolor*), sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), Jeffrey pine (*Pinus jeffreyi*), lodgepole pine, and western white pine (*Pinus monticola*). White fir dominates the forest based on tree density and basal area, but sugar pine and Jeffery pine are among the largest diameter and tallest trees. Shrub cover consists primarily of whitethorn ceanothus (*Ceanothus cordulatus*) and green leaf manzanita (*Arctostaphylus patula*).

TEF has a typical Mediterranean climate with hot, dry summers and cold, wet winters. During our study period, the average annual precipitation was 1025 mm, most of which occurred as snow between November and April. Annual mean air temperature was ~18 °C, ranging from 4 °C in winter (January) to 32 °C in summer (July), according to the local weather station at Wishon Dam (WSD), Wishon, CA (http://cdec.water.ca.gov/).

The soils at TEF are generally Humic Haploxerepts (or Xerumbrepts), which are typical of the southwestern slopes of the Sierra Nevada, based on a soil taxonomy survey conducted by US Department of Agriculture staff (2006). The granitic-based soils have a coarse sandy loam texture throughout the relatively shallow profile (75–100 cm) with approximately 18–20% volumetric soil water holding capacity (North et al., 2002).

2.2. Treatment arrangements

Six combinations of thinning and burning treatments – two levels of burning (*i.e.*, burn and no burn) crossed with three levels of thinning (no thin, understory thin, and overstory thin) – were carried out within a total of 18 four-ha (200 m × 200 m) plots, with three replications per treatment combination (Fig. 1c). The 18 plots had similar vegetation composition and structure before treatment based on a vegetation analysis identifying mixed-conifer structure and composition and the scale of stand size (North et al., 2002). Each plot contained an equal mix of the three dominant patch types identified in a cluster analysis: closed-canopy tree groups (characterized by >80% canopy cover and a thick litter layer), patches of ceanothus shrub (>60% cover), and open canopy (herb, shrub, and tree cover <20%).

The thinning treatment was based on California spotted owl (CASPO) guidelines, which aim to minimize impact to spotted owl (*Strix occidentalis*) habitat (Verner et al., 1992). The CASPO guidelines became standard forest practice in the 1990s and are still widely used as a fuel-reduction treatment (USDA Forest Service, 2004). This treatment prescription included removing all trees 25–76 cm DBH while retaining at least 40% canopy cover (leaving 22 regularly spaced large diameter trees per hectare).

The six treatment combinations were randomly assigned to the 18 plots, resulting in three replicates per treatment combination (Fig. 1c). To be consistent with the plot names that have been used in the TEF community since the initial phases of the project, we apply the same naming system here (Table 1): the letter "U" for unburned plots, the letter "B" for burned plots, "C" for the understory thinning treatment, "S" for the overstory thinning; and "N" for the no thinning treatment. As an example, a plot labeled "UC" was not burned but understory-thinned; the three replicate plots with the same treatment type are named as UC1, UC2, and UC3.

Table 1
Labels of restoration and fuel treatments, crossing two types of burning treatment (*i.e.*, no burn and burn) with three types of thinning treatment (no thin, understory thin, and overstory thin).

	No thin—"N"	Understory thin—"C"	Overstory thin—"S"
No burn—"U"	UN (control)	UC	US
Burn—"B"	BN	BC	BS

The thinning treatments were applied in the autumn of 2000 (thin and burn plots) and early spring of 2001 (thin-only plots). Following typical practices, the prescribed fire was lit in the autumn of 2001 after the first substantial autumnal rains (2 cm). The fire was extinguished 1 week later by snow.

2.3. Microclimate stations and field measurements

Microclimate stations were established at the center of each plot. At each microclimate station, we measured air temperature (T_a), relative humidity (Rh), photosynthetically active radiation (PAR), and wind speed (v) at 2 m above the ground. Soil temperature at 0 cm (T_{sf}, buried near the soil surface) and 15 cm depth (T_{s15}), soil heat flux (G), and soil volumetric moisture at 15 cm depth (θ_v) were also measured at each station. T_a and Rh were measured using Model HMP45C sensors installed in radiation shields without aspirators (Campbell Sci., Inc., CSI, Logan, Utah, USA). T_{sf} and T_{s15} were measured with 107 temperature probes (CSI). PAR was measured with Quantum Sensors (LI-190SA). R.M. Young Wind Sentry Anemometers (03101-L) were used for measuring v. Soil heat flux plates (HFT01, CSI) were buried near the soil surface, covered with a thin layer of soil (~0.2 cm). θ_v was calculated by the measurement of soil water potential at 15 cm depth from soil surface using Model 257 Soil Moisture Sensors (CSI).

Six microclimate stations (*e.g.*, BC1, BN2, BS2, UC3, UN3, and US3, see Fig. 1c) were installed in August 1998 and the remaining twelve in July 1999. Sensors were programmed with a CR10(X) datalogger (CSI) and read every 10 s for hourly means. During summer months (June–August), data were downloaded every other week. During winter months, data were downloaded every other month. Each time we visited the microclimate stations, sensors were checked for performance and accuracy, and damaged sensors were fixed or sent back to the factory for re-calibration.

A hemispheric image was taken at each station using a hemispheric lens (Sigma 8 mm F4, Sigma Corporation, Tokyo, Japan) mounted on a digital Nikon camera (Nikon Corporation, Tokyo, Japan) before sunrise and after sunset during cloud-free days in the summers of 2000 and 2002. The camera was installed on a 1.2-m tripod, and the top of the photo was oriented to true north. The lens was leveled before each shot. Afterward, canopy cover was calculated for each point using a Gap Light Analyzer (Frazer et al., 1999). The Universal Transverse Mercator (UTM) coordinates of microclimatic stations were measured with the GPS Pathfinder® Pro XRS receiver (Trimble Navigation Limited, Sunnyvale, CA, USA). Elevation, slope, and aspect were derived from digital electron model (DEM) images with 30-m resolution from the United States Geological Survey (USGS). In addition, throughout the 18 four-ha plots, all trees ≥5 cm DBH were tagged and mapped using a Criterion 4000 survey laser station (North et al., 2007).

2.4. Data analyses

2.4.1. Determining forest structure around microclimate stations

Forest structure around each microclimate station was identified by tree density (TD, stems ha^{-1}) and basal area (BA, m^2 ha^{-1})

Table 2
Characteristics of topography and forest structure, including elevation, slope, aspect, canopy cover, tree density (TD), stand basal area (BA), and diameter at breast height (DBH), around microclimate stations before and after treatments. Plot names refer to Table 1. Sub-mean and sub-STD are mean and standard deviation of three plots for each treatment type. Mean and STD are mean and standard deviation of all 18 plots.

Plot	Elevation (m)	Slope (°)	Aspect (°)	Pre-treatment				Post-treatment			
				Canopy coverage (%)	TD (stems ha^{-1})	DBH (cm)	BA (m^2 ha^{-1})	Canopy Coverage (%)	TD (stems ha^{-1})	DBH (cm)	BA (m^2 ha^{-1})
BC1	2036.5	9.2	192.1	89.1	631.8	23.8	30.8	65.1	295.4	22.1	26.6
BC2	2147.9	10.1	59.4	76.3	560.5	26.7	65.1	47.8	61.1	46.3	43.7
BC3	2219.7	18.3	37.8	62.9	183.4	44.8	29.9	56.3	50.9	42.8	20.1
sub-Mean	2134.7	12.6	96.4	76.1	458.6	31.8	41.9	56.4	135.8	37.1	30.2
sub-STD	92.3	5.0	83.5	13.1	240.9	11.4	20.1	8.7	138.3	13.1	12.2
BN1	1995.1	20.5	49.6	68.0	290.4	26.3	24.7	67.0	213.9	31.6	24.7
BN2	1996.4	14.2	302.5	82.1	560.5	31.6	54.2	79.0	427.8	34.5	54.2
BN3	2046.0	8.0	85.8	78.8	341.4	38.1	14.1	79.0	285.2	42.5	14.1
sub-Mean	2012.5	14.2	146.0	76.3	397.5	32.0	31.0	75.0	309.0	36.2	31.0
sub-STD	29.0	6.3	136.7	7.4	143.5	5.9	20.8	6.9	108.9	5.6	20.8
BS1	2004.3	11.3	228.4	75.2	463.7	33.0	41.4	74.8	40.7	38.8	15.2
BS2	2024.6	12.3	25.6	65.1	321.0	37.0	36.7	35.6	76.4	35.3	11.8
BS3	2178.7	17.8	72.1	68.7	417.8	25.3	31.2	50.2	66.2	48.6	22.7
sub-Mean	2069.2	13.8	108.7	69.7	400.8	31.8	36.4	53.5	61.1	40.9	16.6
sub-STD	95.4	3.5	106.2	5.1	72.8	5.9	5.1	19.8	18.4	6.9	5.6
UC1	2070.6	3.8	121.9	81.7	310.8	34.2	43.7	40.3	219.0	35.6	38.3
UC2	2139.8	16.0	40.1	79.7	422.9	29.8	37.6	64.7	244.5	30.1	26.0
UC3	2127.4	14.0	76.9	83.4	570.7	28.1	61.0	69.8	336.1	27.4	50.6
sub-Mean	2112.6	11.3	79.6	81.6	434.8	30.7	47.5	58.3	266.5	31.0	38.3
sub-STD	36.9	6.5	40.9	1.9	130.3	3.2	12.1	15.8	61.6	4.2	12.3
UN1	2013.9	9.3	6.9	76.9	183.4	41.5	32.2	73.3	183.4	41.5	32.2
UN2	2096.7	5.5	192.7	86.8	861.1	22.6	63.7	83.8	861.1	22.6	63.7
UN3	2112.7	3.8	79.8	69.7	346.5	38.9	63.7	70.7	346.5	38.9	63.7
sub-Mean	2074.4	6.2	93.1	77.8	463.7	34.4	53.2	75.9	463.7	34.4	53.2
sub-STD	53.0	2.8	93.6	8.6	353.7	10.2	18.1	6.9	353.7	10.2	18.1
US1	2091.0	5.0	201.1	83.2	346.5	41.9	52.0	67.2	132.4	32.5	17.7
US2	2124.4	11.0	67.5	80.2	351.6	40.4	64.7	61.4	168.1	28.4	38.1
US3	2142.5	11.5	132.2	87.4	749.0	27.9	60.9	62.9	183.4	25.4	21.4
sub-Mean	2119.3	9.2	133.6	83.6	482.4	36.7	59.2	63.8	161.3	28.8	25.7
sub-STD	26.1	3.6	66.8	3.6	231.0	7.7	6.5	3.0	26.1	3.6	10.9
Mean	2087.1	11.2	109.6	77.5	439.6	32.9	44.9	63.8	232.9	34.7	32.5
STD	67.1	5.0	81.7	7.8	184.2	7.0	16.1	13.4	193.2	7.9	16.7

within a 25-m radius (R) based on the stem mapping database of the 18 plots (Table 2).

$$\mathrm{BA} = \frac{\sum_i^n ((1/2)\mathrm{DBH}_i)^2}{R^2 \times 10,000}) \quad (1)$$

where i is the ith tree within the sampling area; n refers to the total number of trees within the same sampling area with a radius of R.

2.4.2. Determining spatial variability in microclimatic variables

Spatial variability in microclimatic variables is defined here as the mean difference in a microclimatic variable across sampling stations. The mean difference was represented by the standard deviation (σ) across sampling microclimate stations at any given moment. For example, to calculate the spatial variability in a specific microclimatic variable (x) at noon on Day 120 in 2000, we pooled measurements at that specific time but at different locations (x_i) and calculated the standard deviation of the dataset:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

where $\bar{x}$ is mean of x_i; $n \leq 18$. The advantage of σ is that spatial variability at any given time retains the same unit as the microclimatic variable of interest. Here, we present monthly and yearly means or sums, providing general features of spatial variability.

2.4.3. Standardizing microclimatic variables

Microclimatic data were first screened by quality control criteria, and missing data due to failures of sensors or batteries were excluded from further computing. For daily averages, a minimum of 20 sample hours were logged within a 24-h period; monthly averages are calculated from a minimum of 24 days per month. For yearly averages or sums, data were considered valid only if >10 sample months were available.

To quantify effects of thinning and burning treatments, we calculated standardized values for each variable for two reasons. First, the sampling size for each treatment type was rather small for reliable ANOVA tests. Second, if we compared raw data with ANOVA tests, a significant result could have been due to treatment effects, but it also could have been due to natural spatial variability in microclimate that had existed in the pre-treated forest. Thus, we computed standardized monthly values of each microclimatic variable and then performed ANOVA tests with repeated measures including not only post-treatment but also pre-treatment data. In this way, sampling size was extended for each treatment type with monthly repeated measures, excluding the controls.

To calculate standardized values, we first computed monthly averages or sums of microclimatic variables for each plot. Then, these monthly averaged values were divided by a standard value calculated as the average of a microclimatic variable measured from the three control plots (y_c) at any given time. A microclimatic variable measured at a treated plot (y), was standardized against y_c as follows:

$$y_{\%} = \frac{y}{y_c} \times 100\% \quad (2)$$

or

$$\Delta y_{\%} = \frac{y - y_c}{y_c} \times 100\% \quad (3)$$

where $y_{\%}$ is the standardized value (%), and $\Delta y_{\%}$ is defined as the relative percentage value; y represents a microclimate variable of interest averaged over the treatment type; y_c is the same variable averaged over the control plots. For interpretation, $y_{\%} = 100\%$ or $\Delta y_{\%} = 0\%$, when $y = y_c$. These relative values were then compared to determine treatment effects because all pre- and post-treatment values were standardized according to the control plots to account for both background spatial variability and intra- and inter-annual variability. During the pre-treatment period, differences in the ratios of a microclimatic variable between plots directly indicated natural spatial variability. By considering the natural spatial variability, effects of treatment on microclimate could be determined as the difference in the ratios of a microclimatic variable between the pre- and post-treatment period.

2.4.4. Statistical analyses

We applied analysis of variance (ANOVA) to test for spatial variability in microclimatic variables, effects of forest structure and topographic factors, and treatment effects on microclimate. We assumed that microclimate variables were randomly sampled and spatially independent since the 18 microclimate stations were at least 200 m apart (North et al., 2002).

First, we tested spatial variability in microclimatic variables. Our null hypothesis was that a microclimatic variable (y) is similar at different locations (*i.e.*, *site*) in the forest. We tested this hypothesis using a one-way ANOVA model: $y = f(site)$ by month. The monthly means of microclimatic variables within the pre-treatment period (1998–2000) were compared.

Second, we examined which forest structure and topographic factors might affect natural spatial variability. Forest structure factors included TD, BA, and canopy cover, and topographic factors included elevation, slope, and aspect. The hypothesis was tested with multiple regression models with monthly repeated measures. Again, the monthly means of microclimatic variables within the pre-treatment period (1998–2000) were compared.

Third, we tested treatment effects using the standardized values of each microclimatic variable. Our null hypothesis was that each microclimatic variable (*e.g.*, $y_{\%}$) would be similar before and after thinning and burning treatments. We tested this hypothesis with a one-way, repeated ANOVA model: $y_{\%} = f(period)$, where *period* represents two treatment periods––pre-treatment and post-treatment period. Monthly standardized values of microclimatic variables during 1998–2003 were applied in this test.

All statistical calculations were done using the GLM procedure of the standard statistical software package SAS (Version 9.1, SAS Institute Inc., Cary, NC, USA). Missing values were not included in any analyses.

3. Results

The 18 stations fairly represented the majority of topographical and forest structure conditions in TEF (Table 2), compared to a

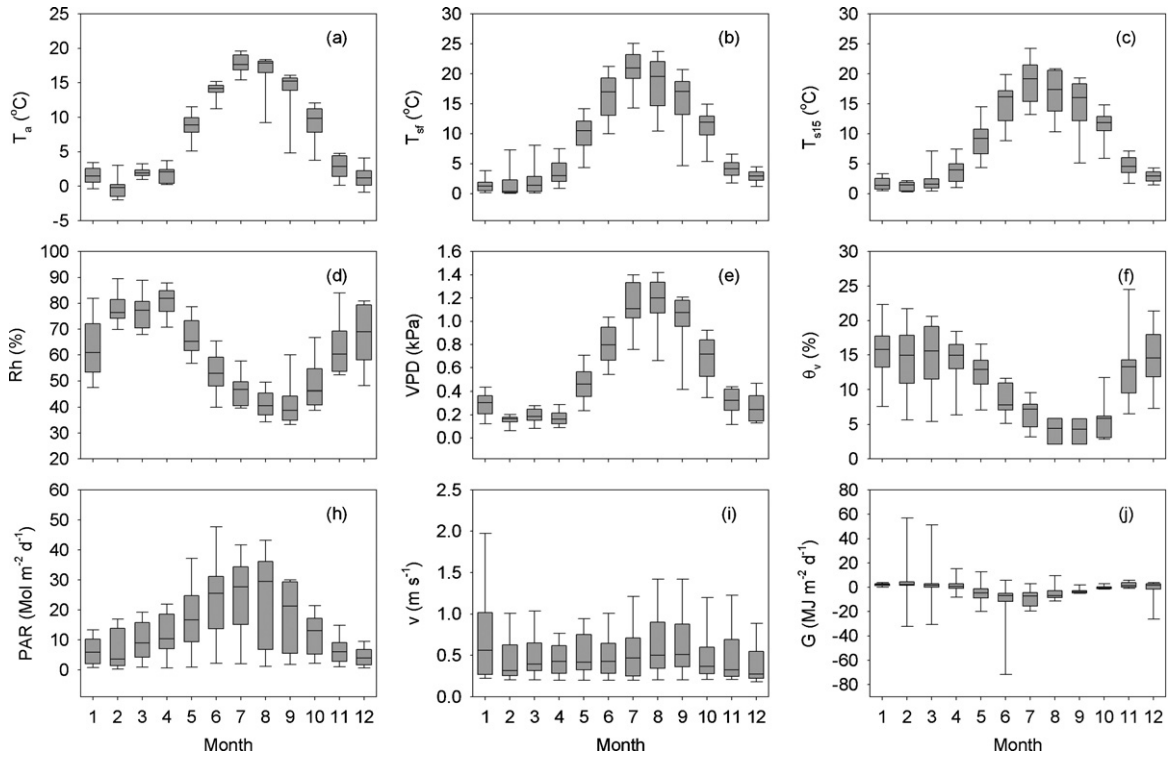

Fig. 2. Variation in microclimatic variables across sampling stations at a given month of the year: (a) air temperature (T_a), (b) soil surface temperature (T_{sf}), (c) soil temperature at 15 cm depth (T_s), (d) relative humidity (Rh), (e) vapor pressure deficit (VPD), (f) soil volumetric moisture (θ_v), (h) photosynthetically active radiation (PAR), (i) wind speed, and (j) soil heat flux (G). Each box-plot represents data distribution at a given hour ($n \leq 18$). The line within the box marks the median of the data set; the top and bottom boundaries of the box indicate the 75th and 25th percentiles, respectively; error bars above and below the box indicate the 90th and 10th percentiles, respectively.

more comprehensive analysis reported by North et al. (2007). Mean elevation, slope, and aspect of the 18 stations were 2087.1 ± 67.1 m, 11.2 ± 5.0°, and 109.6 ± 81.7°, respectively. Prior to the treatments, canopy cover was 77.5% on average, ranging from 62.9% (Plot BC3) to 89.1% (Plot BC1). In comparison, mean canopy cover was decreased to 63.8% after treatments. The lowest canopy cover recorded was 35.6% in Plot BS2. Tree density was decreased from 439.6 to 232.9 stems ha^{-1}; stand basal area from 44.9 to 32.5 m^2 ha^{-1}, while treatments increased DBH from 32.9 to 34.7 cm. Based on data from the 18 stations, thinning treatments decreased canopy cover, tree density, and stand basal area ~20%, ~65%, and ~59%, respectively.

3.1. Spatial microclimate variability before treatment

Prior to the treatments, microclimatic variables showed high variation across sampling stations on a monthly scale (Fig. 2). Boxplots in Fig. 2 represent the data distribution of each microclimatic variable at a given month ($n \leq 18$). The ranges roughly illustrate differences among different locations, indicating that this fire-suppressed mixed-conifer forest naturally had high spatial variability in microclimate, a variability that tended to differ by time of year. In general, greater spatial variation occurred in summer months for most variables.

We used standard deviations of monthly microclimatic variables across sampling stations to quantify an average spatial variability in microclimate (Table 3). Spatial variability of monthly T_a ranged from 0.4 to 2.6 °C, with an annual mean spatial variability of 1.2 °C. Monthly T_{sf} and T_{s15} showed greater spatial variability than T_a (Table 3). In terms of air moisture, spatial variability of Rh was low in spring and summer months (*e.g.*, 4.9% in June) and high in winter months (*e.g.*, 15.7% in October), while VPD showed an opposite trend: high spatial variability in spring and summer months (*e.g.*, 0.23 kPa in April) and low spatial variability in the winter months (*e.g.*, 0.13 kPa in January). The spatial variability in soil moisture tended to be larger in the spring months and lower in the summer months. For PAR, spatial variability was larger in the summer months and lower in the winter months. Wind speed showed similar spatial variability throughout most of the year, while the highest value was measured in July. Spatial variability of G tended to be high in the autumn months.

Monthly spatial variability of each microclimatic variable is an average spatial variance among sampling stations. However, if we compared monthly values between a pair of individual stations, the absolute difference in a microclimatic variable could be much larger than the average spatial variability. For example, monthly mean T_{sf} was 16.3 °C in June at Station BC3, while T_{sf} was much lower at Station UN2 (5.0 °C) during the same month. Thus, the absolute difference in monthly mean T_{sf} between these two stations was 9.3 °C, which is likely to be highly significant for many ecological processes.

To understand the primary factors driving such significant spatial variability in microclimate, we compared three topographic factors (*i.e.*, elevation, slope, and aspect) and forest structure (*i.e.*, canopy cover, TD, DBH, and BA). We found that topographic factors played more important roles than forest structure factors in driving spatial variability in microclimate, and elevation was the most important topographic factor (Table 4). Indeed, elevation significantly affected almost all of variables with the exception of *G*. Canopy cover was the secondary factor directly influencing understory light conditions (PAR), soil temperature (T_{sf}, T_{s15}), and moisture (θ_v), but canopy cover appeared to be more important within a stand when variations in elevation are ignorable.

3.2. Treatment effects

Applying monthly values of each microclimatic variable (see Section 2) in ANOVA tests with repeated measures, including not only post-treatment but also pre-treatment data, we found that monthly values of all microclimatic variables were significantly different before and after treatments, with the exception of *G* (Table 5).

We computed the mean and standard error of standardized values by treatment type within the pre-treatment period (although treatment had not been performed in this period) to compare with those from the post-treatment period (Fig. 3). Within the pre-treatment period, standardized values indicated the degree to which a group-averaged microclimatic variable was different from the standard value (by percent change), suggesting that microclimate was different among station groups, similar to comparisons among all individual microclimate stations. In contrast, standardized values within the post-treatment period also indicated variations among groups, but such variations combined natural spatial variability and treatment effects.

The differences between pre- and post-treatment values indicated the degree of treatment effect (Table 6). After treatments were applied, T_a increased 123.6% and 58.1% in thin-and-burn plots (BC and BS), respectively, but decreased 8.1% in burn-only plots (BN). Effects of thin-only treatments on T_a were not consistent, with increased T_a (+31.1%) in US plots and

Table 3
Spatial variability (*e.g.*, standard deviation) in monthly mean air temperature (T_a), soil surface temperature (T_{sf}), soil temperature at 15 cm depth (T_{s15}), relative humidity (Rh), water vapor deficit (VPD) of air, soil volumetric moisture at 15 cm depth (θ_v), daily-sum of photosynthetically active radiation (PAR), wind speed (v), daily-sum of soil heat flux (G) across sampling stations (n).

Month	n	T_a (°C)		T_{sf} (°C)		T_{s15} (°C)		Rh (%)		VPD (kPa)		θ_v (%)		PAR (mol m^{-2} d^{-1})		V ($m s^{-1}$)		G (MJ m^{-2} d^{-1})	
1	12	0.6		0.8	*	0.9	*	5.3	*	0.13		2.1	*	2.3	*	0.1	*	0.5	*
2	11	0.5		0.6	*	0.6	*	6.2	*	0.14	**	2.8	*	3.4	*	0.1	*	0.5	*
3	10	0.4		0.7		0.6		6.0	**	0.17	*	3.9	*	5.2	*	0.2	*	0.7	*
4	10	1.1		2.1		1.8		3.7	*	0.23	**	6.0	*	7.6	*	0.2	*	0.7	
5	9	0.7		3.1	**	1.9	*	3.4	*	0.21		5.3	*	10.0	**	0.2	**	0.7	
6	15	1.0	*	3.0	*	2.3	*	4.9	*	0.21	*	2.3		12.0	*	0.2	*	0.6	**
7	17	2.6	*	3.5	*	2.7	*	4.9	*	0.41	*	1.9		12.9	*	0.4	*	0.6	*
8	17	0.9	*	3.0	*	2.4	*	4.6	*	0.17	*	2.4	*	12.6	*	0.2	*	0.4	
9	16	1.0	*	1.9	*	1.8	*	3.8	*	0.13	*	2.4	**	9.4	*	0.1	*	1.6	*
10	10	2.7	**	2.4	*	2.0	*	15.7	**	0.16	**	4.9	*	6.4	*	0.2	**	0.3	
11	11	1.6		1.8	**	1.8	**	10.8	*	0.12		2.7		3.9	*	0.1	*	0.7	*
12	10	1.2	na	0.8	na	1.2	na	13.3	na	0.16	na	2.9	na	3.4	na	0.2	na	0.7	na
mean		1.2		2.0		1.7		6.9		0.19		3.3		7.4		0.2		7.4	

"na" indicates no analysis performed due to missing data.
* Significance at level 0.05.
** Significance at level 0.1.

Table 4
Repeated ANOVA tests for effects of topographic and forest structure factors on microclimatic variables. Independent variables include monthly mean air temperature (T_a), soil surface temperature (T_{sf}), soil temperature at 15 cm depth (T_{s15}), relative humidity (Rh), water vapor deficit (VPD) of air, soil volumetric moisture at 15 cm depth (θ_v), daily-sum of photosynthetically active radiation (PAR), wind speed (v), daily-sum of soil heat flux (G). Dependent variables include elevation, slope, aspect, tree density (TD), stand basal area (BA), and diameter at breast height (DBH).

Independent variable	Statistical value	Dependent variable					
		Elevation	Slope	Aspect	TD	BA	DBH
T_a	$F_{(1,168)}$	5.7001	0.0071	1.0540	1.9666	1.0280	0.1843
	p-value	0.0181*	0.9328	0.3061	0.1627	0.3121	0.6683
T_{sf}	$F_{(1,161)}$	6.2925	0.4783	2.1796	1.4477	1.4387	0.1380
	p-value	0.0131*	0.4902	0.1418	0.2307	0.2321	0.7107
T_{s15}	$F_{(1,162)}$	6.6789	0.1645	0.8933	0.7968	0.7650	0.0017
	p-value	0.0106*	0.6856	0.3460	0.3734	0.3831	0.9673
Rh	$F_{(1,154)}$	34.0373	0.9033	0.3958	0.8289	0.2789	0.4662
	p-value	<0.0001*	0.3434	0.5302	0.3640	0.5982	0.4958
VPD	$F_{(1,154)}$	2.1078	0.9085	0.6753	1.6126	0.0063	0.0752
	p-value	0.1486	0.3420	0.4125	0.2060	0.9369	0.7842
θ_v	$F_{(1,126)}$	6.7484	1.6434	0.2037	0.0037	0.0015	0.9878
	p-value	0.0105*	0.2022	0.6525	0.9517	0.9695	0.3222
PAR	$F_{(1,168)}$	3.3225	0.5712	0.6723	0.1350	0.2851	4.1E−4
	p-value	0.0701**	0.4508	0.4134	0.7138	0.5941	0.9949
v	$F_{(1,161)}$	13.9729	0.1722	0.0160	1.2321	2.1163	1.0935
	p-value	0.0003*	0.6787	0.8995	0.2687	0.1477	0.2973
G	$F_{(1,159)}$	0.0347	2.8E−4	0.0149	2.2980	1.6516	0.4842
	p-value	0.8524	0.9958	0.9031	0.1315	0.2006	0.4875

$F_{(n\text{-df, d-df})}$: F value with the numerator degrees of freedom (n-df) and the denominator degrees of freedom (d-df) in bracket.
* Significance at level 0.05.
** Significance at level 0.1.

decreased T_a (−13.4%) in BN plots. T_s and T_{sf} increased in all cases except BN plots. Decreased Rh and increased VPD indicated that air became drier after treatments. In contrast, soil moisture and PAR increased by 7.9–39.8% and 50.4–254.8%, respectively, for all treatment types. Like T_a, wind speed increased in BC, BS, and US, but decreased in BN and UC. Although G increased dramatically in magnitude in some plots, overall treatment effects on G were not statistically significant.

As expected, changes in microclimatic variables (especially PAR) corresponded to the intensity of tree removals, as a function of BA (Fig. 4). For example, after treatments, BA decreased, but PAR increased (Fig. 4g). Similar relationships were also observable for other variables. In addition, the greatest value for each microclimatic variable more likely occurred after treatments, indicating that the thinning and burning treatments induced extreme microclimate conditions.

Table 5
Comparison of microclimatic variables measured during pre- and post-treatment periods by one-way repeated ANOVA. Data applied in this test are standardized monthly mean air temperature (T_a), soil surface temperature (T_{sf}), soil temperature at 15 cm depth (T_{s15}), relative humidity (Rh), water vapor deficit (VPD) of air, soil volumetric moisture at 15 cm depth (θ_v), daily-sum of photosynthetically active radiation (PAR), wind speed (v), daily-sum of soil heat flux (G).

Microclimatic variable	n-df	d-df	F value	p-value
T_a	2	4	382.3440	<0.0001*
T_{sf}	2	4	104.1758	0.0004*
T_{s15}	2	4	143.8668	0.0002*
Rh	2	4	2414.6829	<0.0001*
VPD	2	4	422.2917	<0.0001*
θ_v	2	4	261.2838	<0.0001*
PAR	2	4	34.6769	0.0030*
v	2	4	25.6933	0.0052*
G	2	4	2.3722	0.2093

n-df: The numerator degrees of freedom; d-df: the denominator degrees of freedom.
* Significance at level 0.05.

4. Discussion

We found that this mixed-conifer forest has considerably high spatial variability in microclimate in comparison with other forests in the USA. For example, one study in California reported that the difference in T_{sf} between open and canopy-covered areas was 8 °C in August (Dunlap and Helms, 1983), while the maximum difference in August at our site was over 10 °C. Comparing our data with a study in a west-coast old-growth Douglas-fir forest (Chen and Franklin, 1997), we found that the maximum difference in T_a was over 10 °C at our site, while the maximum difference in T_a along a 200-m transect was only 2.7 °C during the summer months (July–September) in the Douglas-fir forest. Furthermore, the maximum difference in T_{sf} at our site was up to 30 °C, which is much greater than variation in T_{sf} (5.9 °C) in the old growth Douglas-fir forest. A study of soil temperature in a deciduous forest in the northern Wisconsin showed that the difference in daily T_{sf} along a transect 3820 m long was about 4.2 °C during the months of July and August (Saunders et al., 1998), which is just one-tenth of the difference in daily T_{sf} that we observed in the same summer months in this mixed-conifer forest. In terms of spatial variability, soil temperature in an oak forest in the southeastern Missouri Ozarks, with similar canopy cover as our forest, showed a range similar to what we found (Xu et al., 1997). As our results demonstrate, mountainous locations and heterogeneous canopy cover can cause high spatial variability in microclimate, distinguishing this mixed-conifer forest from others.

High spatial variability of microclimate in the mixed-conifer forest is essential for many ecological processes that have been studied in this forest. For example, greater species diversity and richness are associated with high spatial variability of microclimate in the mixed-conifer forest because heterogeneous microclimate provides favorable biophysical conditions for seed germination, seedling establishment, and successful recruitment of a variety of understory species and tree species (Gray et al.,

2005; North et al., 2005). In turn, diversity of vegetation structure and distribution produces different environmental conditions for many below-canopy or belowground ecological processes, such as soil nutrients (Erickson et al., 2005), soil respiration (Ma et al., 2005), and soil arthropods (Marra and Edmonds, 2005). All of these processes could be affected when any type of disturbance (human-induced or not) occurs, and microclimate would be changed accordingly or consequently.

Our study confirms that thinning and burning treatments significantly affect microclimate, in agreement with numerous studies (*e.g.*, Liechty et al., 1992; Tang et al., 2005; Heithecker and Halpern, 2006). Thinning decreases canopy cover and results in

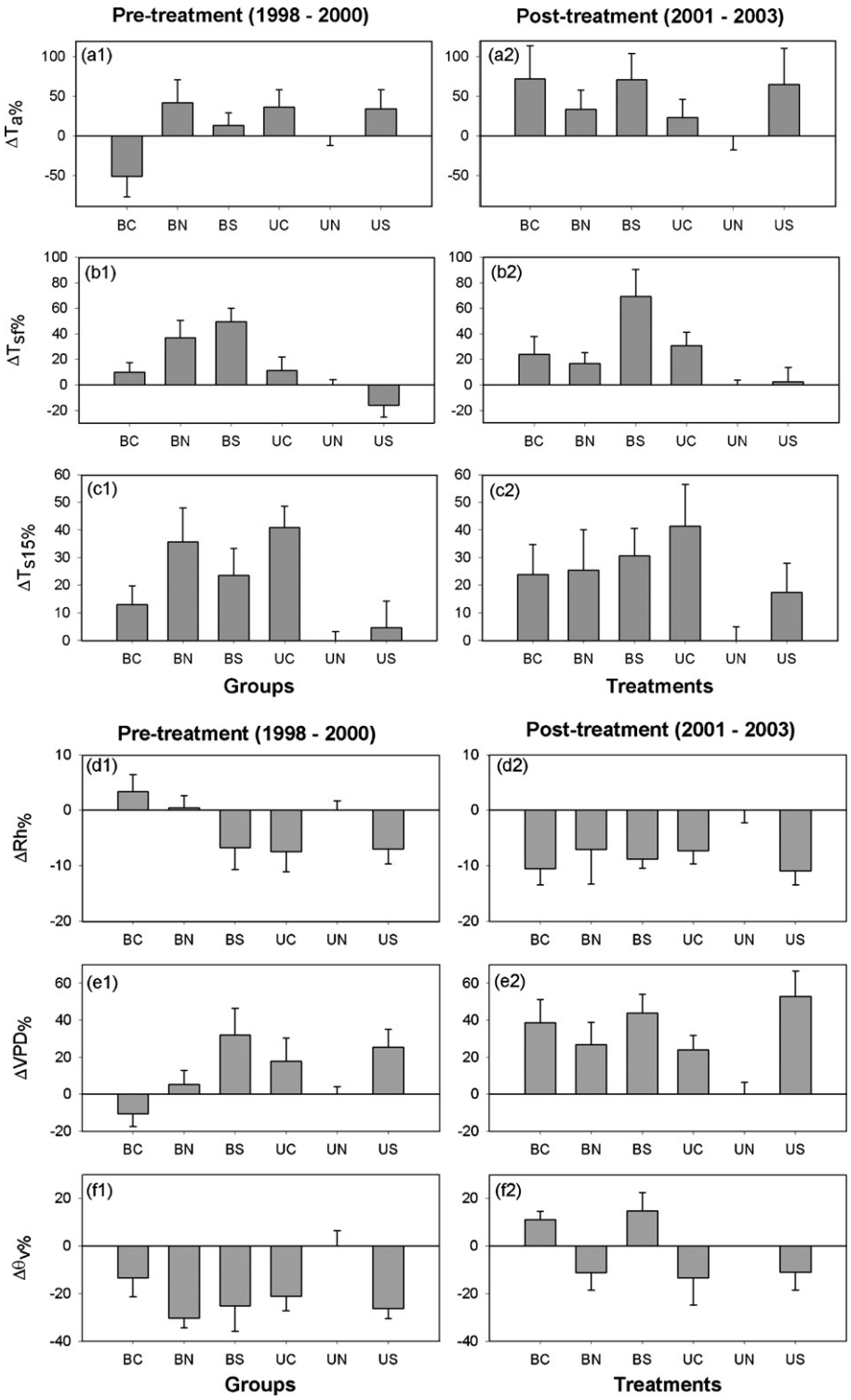

Fig. 3. Percent differences in microclimatic variables between treatment plots and mean of control plots during pre-treatment period (1998–2000) and post-treatment period (2001–2003) separately. Microclimatic variables are (a) air temperature (T_a), (b) soil surface temperature (T_{sf}), (c) soil temperature at 15 cm depth (T_s), (d) relative humidity (Rh), (e) vapor pressure deficit (VPD), (f) soil volumetric moisture (θ_v), (h) photosynthetically active radiation (PAR), (i) wind speed, and (j) soil heat flux (G). Panels are label "1" for the pre-treatment period, and "2" for the post-treatment period.

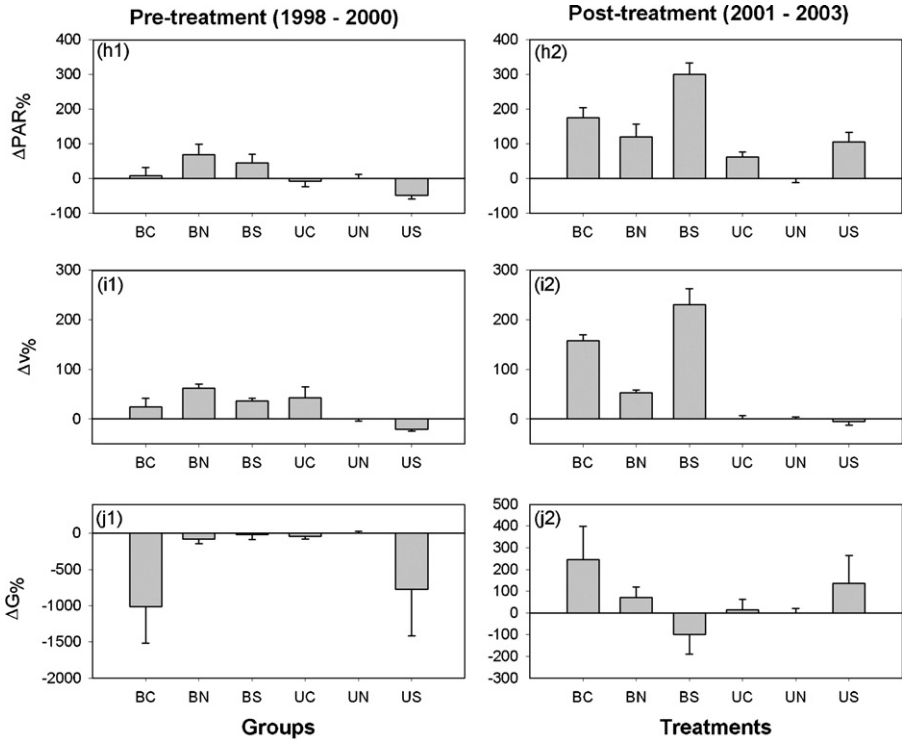

Fig. 3. (*Continued*).

more open areas (Platt and Strong, 1989; Hale, 2001, 2003). In these open areas, more direct sunlight reaches the forest floor, heating up the atmosphere near the forest floor, and transferring heat to deeper soil layers. Thus, T_a, T_{sf}, and T_{s15} increased in general in our experiment (Liechty et al., 1992; Kirschbaum, 1995; Zheng et al., 2000; Tang et al., 2005). If prescribed fire is carried out following thinning treatments, the burning enhances the effects of the thinning treatment on microclimate by disturbing the forest floor. After thinning, slash, logs, and snags are often left behind on the forest floor, which can then become fuels for ground fire. However, they may or may not be burned completely because of differences in fuel quantity and quality (Innes et al., 2003). After burning, soils appear as a patchwork of dark and light colors (due to ash, char, and unburned soil patches). These different colors result in changes in the *albedo* of the ground surface to solar radiation. Darker surfaces absorb more solar radiation; consequently, soils with darker surfaces may be heated more than patches with lighter surface. In contrast, large, unburned slash can reduce incident radiation and prevent heat from being transferred from the forest floor surface down to the mineral soil. These practical realities illustrate how different treatment combinations can affect microclimate in different ways.

This mixed-conifer forest experiences a typical Mediterranean climate—wet, cold winters and dry, hot summers. Water conditions therefore often become a critical limitation to many ecological processes and functions (Royce and Barbour, 2001a). When a canopy is opened with thinning treatments, the near-ground atmosphere in the forest becomes drier, but soils become wetter due to the interaction between microclimate and vegetation. Thinning reduces canopy cover and decreases canopy interception of water from rain and snow events. At the same time, removal of trees and shrubs reduces the physiological water demand from plants (*i.e.*, less transpiration). At the same time, hotter and drier air due to increased solar radiation through the canopy opening may increase evaporation, which could decrease soil moisture. This process typically only occurs during the late spring and beginning of summer, so the period of high evaporation is usually short (Ma et al., 2005). Temperature increases sharply at the end of spring, and a high evaporation rate dries the surface of the forest floor extremely fast establishing a dry surface layer that can prohibit further evaporation from deeper layers and soils (Aussenac, 2000). Because of these combined effects, soil moisture increased after our treatments, regardless of treatment type.

Increases in temperature, water, and light levels associated with changes in canopy cover and forest floor conditions have many implications for forest management practices in this ecosystem. These implications might include managing forests for carbon sequestration, species diversity, nutrient cycling, or other ecosystem services or functions. Increased soil moisture can provide better water supplies for seed germination (Moghaddas

Table 6
Percent of changes ($\Delta y_{\%}$) in microclimate after treatments. Microclimatic variables include air temperature (T_a), relative humidity (Rh), soil surface temperature (T_{sf}), soil temperature at 15 cm depth (T_{s15}), photosynthetically active radiation (PAR), wind speed (v), soil heat flux (G), and soil volumetric moisture at 15 cm depth (θ_v) before and after treatments.

Treatment	$\Delta T_{a\%}$	$\Delta T_{sf\%}$	$\Delta T_{s15\%}$	$\Delta Rh_{\%}$	$\Delta VPD_{\%}$	$\Delta\theta_{v\%}$	$\Delta PAR_{\%}$	$\Delta v_{\%}$	$\Delta G_{\%}$
BC	123.6	13.9	10.8	−13.9	49.3	24.4	167.8	133.7	1257.9
BN	−8.1	−20.5	−10.3	−7.4	21.6	18.9	50.4	−9.7	149.0
BS	58.1	19.7	7.0	−2.1	11.8	39.8	254.8	194.3	−79.1
UC	−13.4	19.5	0.5	0.2	5.9	7.9	69.4	−42.5	58.9
US	31.0	18.3	12.8	−3.9	27.3	15.2	153.2	15.3	910.3

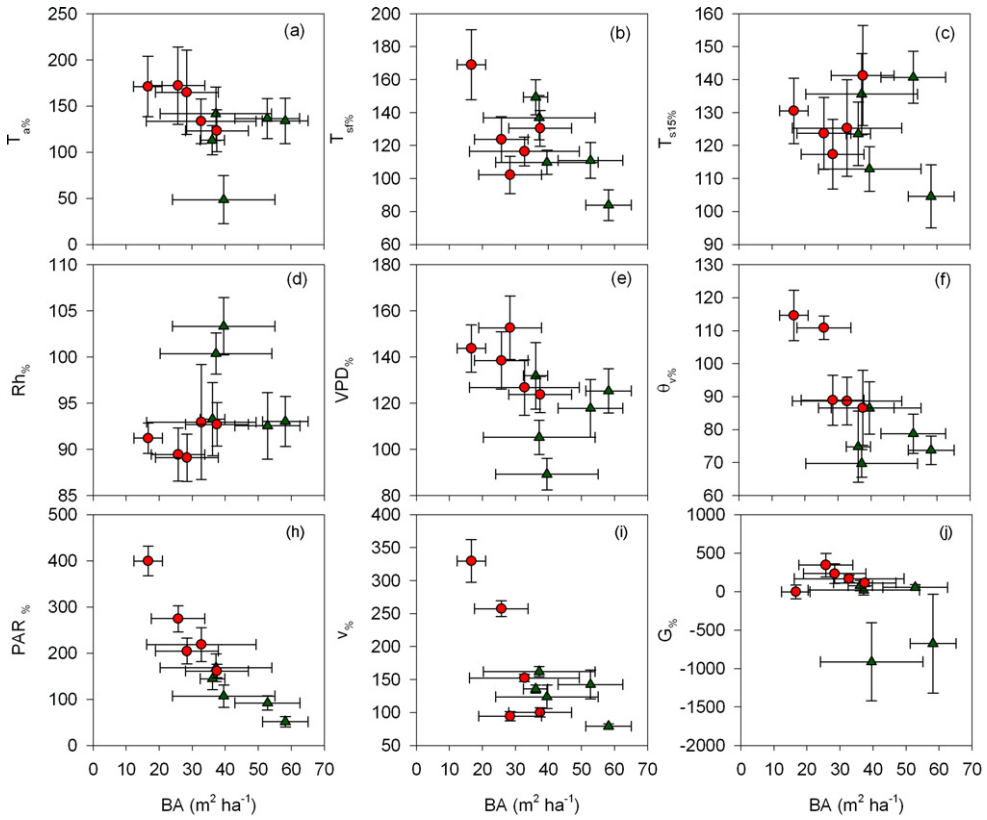

Fig. 4. Relationships between relative microclimatic variables and basal area (BA) across pre- and post-treatment periods: (a) air temperature ($T_{a\%}$), (b) soil surface temperature ($T_{sf\%}$), (c) soil temperature at 15 cm depth ($T_{s\%}$), (d) relative humidity ($Rh_{\%}$), (e) vapor pressure deficit ($VPD_{\%}$), (f) soil volumetric moisture ($\theta_{v\%}$), (h) photosynthetically active radiation ($PAR_{\%}$), (i) wind speed ($v_{\%}$), and (j) soil heat flux ($G_{\%}$). Horizontal error bars indicate standard deviations of BA within three plots of each treatment type, and vertical error bars indicate standard deviations of each microclimatic variable measured at three plots of each treatment type. Triangles refer to values during pre-treatment period; circles refer to values during post-treatment period.

et al., 2008) and tree seedling establishment (Dunlap and Helms, 1983; van Mantgem et al., 2006; Zald et al., 2008; Moktan et al., 2009) and can provide for increases in diversity of plant species (Godefroid et al., 2006; Dodson et al., 2008). Soil respiration, related to litter and soil organic decomposition and CWD decomposition, is increased in hotter and wetter conditions (Concilio et al., 2005; Innes et al., 2006), raising concerns about forest carbon loss. On the other hand, increased decomposition may improve nutrient supplies for seedling establishment and growth (Moghaddas et al., 2008). In addition, treatments also create gaps and enhance edge effects in the forest, which could be important to forest community dynamics (Spies and Franklin, 1989) because resource availability changes along a gradient from gaps, edges, and canopy-covered areas (Chen et al., 1993; York et al., 2003).

This study also indicates that treatments generated extreme microclimatic responses in overstory-thinned plots. This result agrees with a prior microclimate study in forest canopies (Rambo and North, 2009). Extreme microclimatic conditions could be referred to measurements of temperature, water, or light levels that exceed long-term records. However, extreme microclimatic conditions could also be determined when temperature, water, or light levels exceed favorable or tolerable environments of certain species that have occupied there before canopy removal. A study on tree growth showed that maximum air temperatures (~21 °C) were favorable to radial stem growth, and minimum air temperatures above −4 °C or +2.5 °C were necessary for leader growth for *Pinus* and *Abies* species, respectively (Royce and Barbour, 2001b). If more extreme conditions, such as hotter temperatures in the daytime (or summer months) and cooler ones in the nighttime (or winter months), exceed these thresholds, growth of these tree species is affected. Moreover, if extreme conditions exceed tolerance thresholds for certain species, growth patterns and species compositions will likely be altered (Coates, 2000; Harper and Macdonald, 2002; Wayman and North, 2007).

Although we presented monthly and annual means here, we recognize that the temporal scale of our data could have a different biophysical significance depending on the specific ecological processes or functions involved (Chen et al., 1999; Godefroid et al., 2006). Furthermore, relating biological significance to microclimate might differ if hourly, daily, monthly, or annual means or sums are presented. We decided to present monthly and annual values of microclimatic variables because monthly values allowed us to assess seasonal patterns, which are meaningful for many ecological processes, and annual values allow us to understand overall microclimate conditions. However, it is worth noting that spatial variability of microclimate would become greater if microclimate data were organized on a finer temporal scale (*e.g.*, hourly or daily scales), and other factors become important influences on spatial variability when data are organized on a finer temporal scale. For example, not only elevation but also slope and aspect become important for understanding variability in hourly or daily values of many microclimatic variables when ecological processes are examined on these finer temporal scales (Lieffers et al., 1999). In addition, we did not discuss inter-annual variability of climate directly in this study although we did account for this issue in our data processing. A data set from a longer time period would be necessary to evaluate inter-annual trends or influences. Long-term ecological data in future studies would be valuable for better understanding the effects of restoration and fuel treatments on forest microclimate and ecological processes in a changed climate.

Our results suggest that many microclimatic variables are predictable when topographic and forest structure data are available. The most predicable microclimate condition appears to be below-canopy light levels (Drever and Lertzman, 2003; Heithecker and Halpern, 2006), which are tightly correlated to canopy cover or stand basal area (Fig. 4g). Our preliminary analysis shows that BA alone could capture 83% of variation in PAR. Moreover, many of the microclimate variables were highly correlated to PAR, suggesting that PAR could be a promising predictor of microclimate in general. By deriving relationships from commonly collected field data, effects of treatments on microclimatic conditions could be estimated before treatments are applied. This kind of information could be useful for forest managers because they could take into account potential ecological consequences and tradeoffs of different management activities (*e.g.*, planting seedlings, thinning for fuels reductions, etc.) before actually applying any treatments (Drever and Lertzman, 2003; Heithecker and Halpern, 2006).

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