Effects of post-fire logging on forest surface air temperatures in the Siskiyou Mountains, Oregon, USA

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Summary

Following stand-replacing wildfire, post-fire (salvage) logging of fire-killed trees is a widely implemented management practice in many forest types. A common hypothesis is that removal of fire-killed trees increases surface temperatures due to loss of shade and increased solar radiation, thereby influencing vegetation establishment and possibly stand development. Six years after a wildfire in a Mediterranean-climate mixed-conifer forest in southwest Oregon, USA, we measured the effects of post-fire logging (>90 per cent dead tree (snag) removal) on growing season surface air temperatures. Compared with unlogged severely burned forest, post-fire logging did not lead to increased maximum daily surface air temperature. However, dead tree removal was associated with lower nightly minimum temperatures (~1°C) and earlier daytime heating, leading to a 1–2°C difference during the warming portion of the day. Effects varied predictably by aspect. The patterns reported here represent a similar but muted pattern as previously reported for microclimatic changes following clear-cutting of green trees. Effects of microsites such as tree bases on fine-scale temperature regimes require further investigation.

Introduction

Globally, fire management and post-fire rehabilitation are core issues for forestland management. Following high-severity (stand-replacement) fire, the logging of fire-killed trees (salvage) is a common and widespread practice (Lindenmayer et al., 2008). Considerable controversy surrounds this management practice with respect to ecosystem function and resilience (McIver and Starr, 2001; Noss et al., 2006; Lindenmayer et al., 2008). Studies in recent years have reported effects on several ecosystem components including vegetation regeneration (Stuart et al., 1993; Donato et al., 2006; Greene et al., 2006), future fire behaviour (Kulakowski and Veblen, 2007; Thompson et al., 2007) and wildlife (Cahall and Hayes, 2009). In virtually all cases, investigators found strong differences between post-fire-logged and unlogged stands. However, many of these studies were opportunistic and did not directly measure the mechanisms associated with observed differences.

The major feature of post-fire logging is removal of the fire-killed tree (snag) overstorey. Several authors have hypothesized that despite the leafless nature of fire-killed trees, considerable 'dead shade' exists in burned stands and that this shade moderates surface temperatures and/or moisture stress for regenerating vegetation (McIver and Starr, 2001; Hebblewhite et al., 2009). Thus, shifts in temperature regime with snag removal have been posited as a primary mechanism underlying shifts in vegetation establishment and succession. This hypothesis may stem from studies of green-tree logging, which have reported higher maximum and lower minimum temperatures as well as elevated rates of cooling and heating in logged stands (Chen et al., 1993; Brosofske et al., 1997; Devine and Harrington, 2007; Brooks and Kyker-Snowman, 2008). Wider temperature fluctuations were attributed to decreased absorption of solar radiation by canopy foliage during the day and increased losses of long-wave radiation at night. Yet exactly how or whether these patterns translate to the removal of dead trees has not been quantified.

Shade from snags has been suggested to have three main influences relating to surface microclimate: (1) moderation of stand-level ambient surface air temperatures, (2) provision of shade pockets near trees resulting in locally protected microclimates and/or (3) alterations to the soil–plant moisture continuum such as soil water potential and plant moisture stress (Minore, 1971; Donato et al.,

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2009; Hebblewhite et al., 2009). Our objective was to investigate the first influence: stand-level ambient surface air temperatures. Working in severely burned forests 6 years post-fire, we compared the stand-level surface air temperature regime, controlled for aspect, between stands differing only in post-fire logging treatment. We hypothesized that fire-killed trees would increase shading of stands during the day (reducing maximum temperatures) and possibly provide increased insulation at night (increasing minimum temperatures).

Methods

Study area

The study was conducted in the Siskiyou Mountains of southwest Oregon, USA, within the *Abies concolor* (white fir) zone (Franklin and Dyrness (1973). The region is characterized by a Mediterranean-type climate with warm, dry summers (mean maximum July temperature: 27°C) and cool, wet winters (mean minimum January temperature: 2°C; Agee, 1993; Taylor and Skinner, 1998; USDA, 2004). Fire regimes are of mixed severity, with stand-replacement fire effects (≥90 per cent overstorey mortality) occurring as patches within a complex burn mosaic.

All sample areas were mature to old-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) dominated forest prior to stand-replacement fire (for developmental/structural descriptions, see Thornburgh, 1982; Agee, 1993). Study areas were at mid-slope positions on steep terrain (generally >20°) between 1200 and 1300 m elevation on metasedimentary/metavolcanic soils.

Study fire and treatments

The Biscuit Fire burned with mixed severity >200 000 ha of the Siskiyou Mountains in July to November, 2002. Post-fire logging was conducted in limited areas of the burn, largely during the fall–spring of 2004–2005 (2- to 3-year post-fire), in stand-replacement patches ranging from ~4 to >1000 ha. Harvest units ranged from 1 to 70 ha in size (mean = 8 ha). Harvest method consisted of hand felling and either helicopter or cable yarding; logs were limbed and bucked on site. Harvest prescriptions called for varying levels of snag retention; in some units, retained snags were clustered at the edge of units, resulting in a patch of >90 per cent snag removal inside the unit. Harvest intensity in these units reduced basal area by >90 per cent but had a much smaller influence on ground cover (Fontaine *et al.*, 2009). Thus, any differences in temperature regime would most likely be due to the removal of the overstorey.

The sampling period spanned from 22 June to 2 October 2008, which included the warmest portion of the growing season. We measured surface air temperature in each of four pairs (n = 8 sensors total) representing logged and unlogged stands on northwesterly, westerly, southerly and south-southeasterly aspects. All sampled logged stands had experienced >90 per cent snag removal at the scale of several hectares. Study points (no more than one per harvest unit) were located randomly within harvest units and adjacent unlogged areas (>150 m from harvest unit edges). HOBO® temperature sensors (Onset Computer Corporation, Bourne, MA) equipped with naturally ventilated multiplate radiation shields appropriate for air temperature measurements and set to record hourly values were placed parallel to the slope, 0.10 m above soil surface, facing the dominant aspect. Vegetation was absent from the immediate area (0.5-m radius) surrounding the sensors. In the plant associations we sampled, regenerating vegetation was still quite sparse and low-statured, thus having little influence on surface shade. Differences in re-vegetation between logged and unlogged stands were negligible with respect to per cent cover of herbs, litter and bare ground (Fontaine, 2007). Sensors recorded ambient surface air temperature once per hour throughout the sampling period. Prior to and following deployment, temperature sensors were calibrated relative to one another. At constant temperature all sensors were within 0.1°C of one another.

Data analysis

We assessed the influence of post-fire logging on stand-level ambient surface air temperature and its variation with respect to aspect and time of day. We first constructed a number of different metrics to represent differing hypotheses (for a discussion of microclimatic temperature measurements, see Chen et al., 1993). For each entire day, we calculated the mean, maximum, minimum and range of temperature values. Within each day, we also isolated data for three periods, each representing a different phase of the daily temperature regime for which we calculated the mean temperature (12-h daytime: 07.00 a.m. to 06.00 p.m. , 6-h heating period: 09.00 a.m. to 02.00 p.m., 6-h cooling period: 04.00 p.m. to 09.00 p.m.). In addition, we evaluated the variance in daytime temperature to test for the effect of shadow casting by snags.

For statistical analysis, we applied a paired t-test and comparisons of group means and their 95 per cent confidence intervals. All analyses were conducted using R (R Development Core Team, 2008). Confidence intervals of hourly differences and their standard errors were based on n = 8 sample units. Within each experimental unit, mean temperatures and their standard errors were based on n = 102 observations, one for each day of the sampling period. Paired t-tests were applied to all eight temperature metrics, five of which were calculated on a daily basis and three calculated from the mean of hourly measurements for a portion of each day (daytime, heating, cooling periods). We found no evidence for departures from normality when examining probability plots although the limited replication precluded rigorous assessment of variance homogeneity. The modest size of the data set (n = 4 pairs of temperature sensors) did not allow a formal test for an interaction between aspect and treatment. Instead, to demonstrate variation by aspect we present means and standard errors within each aspect, as well as mean hourly temperatures throughout the study period, summarized by aspect for each treatment. We assessed seasonal trends in logging effect by re-running the same analyses using weekly averages and visually examining plots of weekly averages of temperature measurements (mean, maximum, minimum and range) for trends, and also by re-running the above analyses using the weekly averages. None of these differed from comparisons of overall means.

Results

Daily mean temperatures ranged from 9.1°C (1 September) to 27.5°C (18 August). Aspect effects on temperature in unlogged stands were typical for northern temperate forests, with southerly and south-southeasterly aspects recording the highest daily means and northwesterly aspects showing the lowest maximum temperatures (Figure 1, Table 1).

Daily mean and maximum temperatures were not significantly related to post-fire logging (Table 2). In general, daily temperature profiles in logged *vs* control stands were characterized by similar maximum temperatures (Figure 1). However, daily minimum temperature was significantly lower in logged stands by ~1°C (Table 2, Figures 1–2). Daily temperature changes in logged *vs* control stands were characterized by earlier and accelerated heating periods in the morning and early afternoon, followed by accelerated cooling rates in the evening/night (Figures 1–2). Thus, temperatures in logged stands were significantly warmer by 1–2°C during the heating period (09.00 a.m. to 02.00 p.m.) (Table 2, Figure 2). The cooling period also showed 0.5 –1.5°C differences between logged and control stands (Figure 2) which was characterized by a smaller, but significant, effect size (Table 2). During the 12 daylight hours (07.00 a.m. to 06.00 p.m.), overall mean temperatures did not differ (Table 2); however, the magnitude of increased morning heating tended to exceed the difference in afternoon temperatures (Figure 2), suggesting greater overall daytime heating of logged *vs* unlogged stands. Despite generally higher temperature variance in unlogged stands (Table 1), we found no statistical support for the hypothesis of higher variance in temperature in control stands due to tree shadows passing over temperature sensors (Table 2). Effects of post-fire logging varied in size by aspect with the NW aspect generally showing the largest differences (Figure 1).

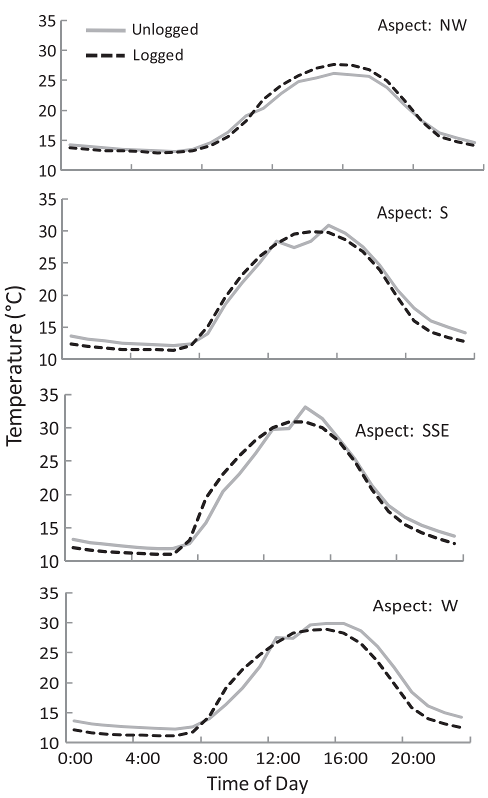

Figure 1. Mean daily temperature profiles (by hour) of all four sampled aspects (NW, S, SSE, W). The post-fire logging treatment was characterized by lower minimum temperatures and earlier warm up/cool down, but similar maximum temperatures.

Discussion

Our results suggest a similar, but muted, change in temperature pattern when compared with previous studies of microclimate in mature *vs* recently clear-cut green forests (Chen et al., 1993), consistent with our original hypotheses. Studies contrasting mature forest with recently clear-cut forests have reported post-harvest microclimates with higher maximum temperatures (1–5°C), lower minimum temperatures (1–3°C) and increased rates of cooling/heating relative to mature green forests (Chen et al., 1993; Brosofske et al., 1997). The effect sizes measured in this study are low (~1°C) relative to green-tree studies but almost certainly reflect similar mechanisms.

In contrast to minimum temperature, we found no evidence for increases in maximum near surface stand temperature between logged and unlogged post-fire stands suggesting that snags are not intercepting a great deal of shortwave radiation. Thus, we conclude that snags likely intercept little direct shortwave radiation, with most of it reaching the surface. We also found no evidence for increased daily temperature ranges in logged stands, despite similar maximum temperature and different minimum temperatures. The elevated rates of heating we observed in logged stands may be a consequence of increased wind speed and convective heat transfer from soil during the morning transition because of lower stand-scale heterogeneity. Similarly, higher wind speeds (and thus air mixing) in logged stands may be responsible for limiting maximum temperatures. Changes in surface albedo with logging may also play a role. In a relevant study in sparse canopy conditions (semi-arid juniper woodland, leaf area index 0.7, 128 trees ha^{-1}), Anthoni et al. (2000) found that albedo (reflectivity) of the soil was 0.13 and the canopy was 0.10. Albedo of charred trees is likely very low, and a low albedo combined with low evapotranspiration can lead to local warming from partitioning of a larger amount of available

Table 1: Mean (standard error) temperatures (°C) of logged and unlogged stands by aspect for eight measurements of microclimate for the entire study period (June to October 2008) in the Siskiyou Mountains, OR, USA

	Northwesterly		Southerly		South-southeasterly		Westerly	
Aspect	Unlogged	Logged	Unlogged	Logged	Unlogged	Logged	Unlogged	Logged
Mean (24 h)	18.2 (0.4)	18.4 (0.4)	19.2 (0.3)	18.7 (0.3)	19.2 (0.3)	19.0 (0.3)	19.1 (0.3)	18.2 (0.3)
Max (24 h)	26.9 (0.5)	28.4 (0.5)	31.1 (0.5)	30.6 (0.5)	33.5 (0.5)	31.6 (0.5)	31.0 (0.5)	29.5 (0.4)
Min (24 h)	12.2 (0.3)	11.6 (0.3)	11.3 (0.3)	10.1 (0.3)	10.9 (0.3)	9.7 (0.3)	11.4 (0.3)	9.9 (0.3)
Range (24 h)	14.6 (0.3)	16.7 (0.3)	19.8 (0.4)	20.4 (0.3)	22.5 (0.4)	21.9 (0.3)	19.6 (0.4)	19.6 (0.3)
Mean (day*)	21.5 (0.5)	22.2 (0.5)	24.1 (0.4)	24.4 (0.5)	24.8 (0.4)	25.4 (0.5)	23.7 (0.4)	23.6 (0.4)
Variance (day*)	25.7 (1.4)	35.4 (1.8)	42.8 (1.7)	40.7 (1.7)	47.2 (1.8)	34.9 (1.3)	48.2 (2.1)	38.0 (1.5)
Mean (heating*)	21.5 (0.5)	22.1 (0.5)	25.0 (0.5)	26.1 (0.5)	27.1 (0.5)	28.1 (0.5)	23.8 (0.4)	24.9 (0.5)
Mean (cooling*)	15.4 (0.4)	15.0 (0.4)	15.0 (0.3)	13.4 (0.3)	14.3 (0.3)	13.2 (0.3)	15.0 (0.3)	13.2 (0.3)

* Daytime period was defined as the 12-hourly measurements spanning 07.00 a.m. to 06.00 p.m., heating as 09.00 a.m. to 02.00 p.m. and cooling as 04.00 p.m. to 09.00 p.m.

Table 2: Mean difference, standard error, 95% confidence intervals and paired *t*-test results of comparisons of eight temperature metrics for surface air temperatures of stands with and without post-fire logging, Siskiyou Mountains, OR, USA

Comparison (logged *vs* unlogged)	Mean difference (°C)	Standard error	95% confidence interval	*t*-value	*P*-value
Mean (24 h)	−0.3	0.2	−1.1, 0.4	−1.47	0.24
Max (24 h)	−0.6	0.7	−2.9, 1.8	−0.80	0.48
Min (24 h)	−1.1	0.2	−1.7, -0.5	−6.09	0.009
Range (24 h)	0.6	0.6	−1.2, 2.4	0.98	0.40
Mean (day*)	0.4	0.2	−0.2, 1.0	2.24	0.11
Variance (day*)	−3.7	5.0	−19.5, 12.1	−0.75	0.51
Mean (heating*)	1.0	0.1	0.6, 1.4	7.66	0.005
Mean (cooling*)	−1.3	0.3	−2.2, -0.3	−4.19	0.025

* Daytime period was defined as the 12-hourly measurements spanning 07.00 a.m. to 06.00 p.m., heating as 09.00 a.m. to 02.00 p.m. and cooling as 04.00 p.m. to 09.00 p.m.

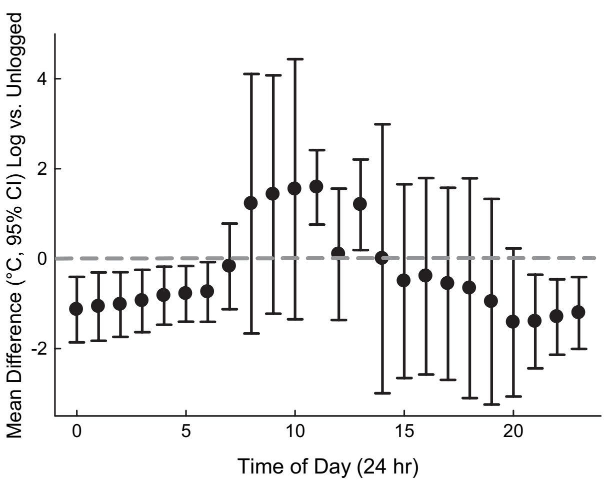

Figure 2. Mean (95% confidence intervals) effect size, in degrees C, of post-fire logging treatment on temperature for each hour of the day across the entire study period relative to unlogged control stands. Post-fire logging increased temperatures by ~1–2°C during mid-day (heating period: 09.00 a.m. to 02.00 p.m.) and decreased temperatures by ~1–2°C in the evening (cooling period: 07.00 p.m. to 01.00 a.m.). These effects reflect the increased rates of warming/cooling in logged stands rather than differences in maximum and minimum temperatures.

energy into sensible rather than latent heat. Thus, it is possible that albedo of charred trees offset any stand-level effects of shading. The potential effects of changes in wind speed and albedo require future investigation.

In summer–drought Mediterranean climate regimes, changes in growing-season moisture stress can strongly influence competitive dynamics (e.g. favouring of broadleaf sclerophyllous species), but the small changes in mean stand-level temperature due to post-fire logging may not be of sufficient magnitude to significantly affect soil moisture or leaf transpiration. Fine-scale microclimate may play a larger role, for example as observed in Mt St Helens reforestation efforts (Winjum, 1984). Moreover, the observed differences between logged and unlogged stands may not persist beyond ~15–20 years when snags become fragmented and have less influence on stand-level microclimate and post-fire vegetation regeneration is well underway. We measured stands 6 years post-fire, by which time snags have begun to lose some fine twigs and branches from their canopies. This study measured ambient surface air temperature (0.1 m above the ground) in four pairs of temperature sensors grouped by aspect 6 years following fire and 3 years following post-fire logging. The data presented here allow us to make inference to microclimatic conditions at the stand scale with respect to post-fire logging of the Biscuit Fire in the Siskiyou Mountains, Oregon, USA. While we sampled across a range of aspects and logging units, we were limited to four treatment pairs which additionally limits inference. Other forest types with more gentle terrain, continental climatic regimes and different understorey development patterns could show different microclimatic responses to post-fire logging. It should be noted that these data represent near surface air temperature and not shallow soil temperatures. Potentially high soil temperatures could exist in exposed environments which may impact vegetation development (i.e. conifer seedling survival and growth). More work is required to investigate additional metrics such as soil moisture, soil temperature, relative humidity and wind.

Management of post-fire forests often includes planting of commercially valuable species such as conifers. Declines in conifer seedling densities following post-fire logging (Donato et al., 2006; Greene et al., 2006) have been attributed to a number of mechanisms, including elevated daytime temperatures and/or altered thermal regimes. Our results suggest that stand-scale temperatures do not appear to be elevated by post-fire logging, suggesting that variation in fine-scale microclimate (temperature, radiation and moisture) may be a more important factor (e.g., near the base of snags: Devine and Harrington, 2007). Importantly, the sampling approach employed in this study was stand scale, with four pairs of temperature sensors placed at random locales to assess ambient surface temperatures; we did not assess fine-scale variation in microclimate. For example, it is possible that stable shady microsites exist at the base of large snags, and this may alter growing conditions more significantly in localized pockets. Previous studies have shown the importance of microsites such as stumps and logs for conifer seedling survival (Minore, 1986). While we were unable to detect any effects of shade-casting by snags (as measured by temporal variance in surface temperature), further study is required. Higher fine-scale heterogeneity in unlogged stands relative to logged stands may play an important role in vegetation development following fire.

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Conflict of Interest Statement

None declared.

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