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Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation

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Abstract

Soil temperature influences many processes in young forest stands including growth and phenology of trees, water uptake, and nutrient mineralization. Effects of harvest residue management and other site preparation techniques on soil and air temperatures have previously been reported at the treatment level, but there is little information on temperature patterns in the various microsites created by these treatments. This study examines the effects of bole-only harvesting with and without vegetation control (BO + VC; BO − VC) and total-tree harvesting plus removal of legacy woody debris with vegetation control (TTP + VC) on microsite temperature in a young Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) plantation. Hourly soil temperatures were recorded at a 10-cm mineral soil depth for 5 years post-planting, and near-ground (25 cm) air temperatures were recorded for 1 year. In the TTP + VC treatment, mean soil temperature and diurnal range in soil temperature during the growing season differed by microsite surface condition in the following sequence: exposed mineral soil > intact forest floor > decaying wood over soil > shade of stumps. In the BO treatments, soil temperature differences among microsites were smaller, and only the stump-shade microsite differed significantly from the others. Near-ground air temperature did not differ by microsite. A sine-wave model showed that diurnal warming of soil beneath decaying wood occurred more slowly than for other microsites. Total annual soil degree-day accumulation was 25–37% greater in the TTP + VC treatment than in the BO + VC treatment; the greatest difference occurred in the year with the warmest spring air temperature. Vegetation control treatments had little effect on soil temperature in the BO harvest treatment. The reduced microsite variability and diurnal fluctuation in soil temperature in the BO harvest treatment may be beneficial where summer temperature extremes are a concern. Alternatively, the warmer spring and early summer soil temperatures of the TTP harvest treatment may be advantageous for early seedling development.
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Keywords: Microclimate; Microsite; Soil temperature; Harvest residue; Vegetation

1. Introduction

In young forest stands, soil and near-ground air temperatures directly or indirectly influence numerous processes including seedling shoot and root development (Heninger and White, 1974; Lopushinsky and Max, 1990), phenology (Lavender et al., 1973; Sorensen and Campbell, 1978), hydraulic conductivity and water use (Lopushinsky and Kaufmann, 1984; Carlson and Miller, 1990) and mineralization of soil nutrients (Van Cleve et al., 1990; Gonçalves and Carlyle, 1994). The soil temperature regime may be influenced by forest management practices such as harvest method, harvest residue management, and vegetation control which may affect irradiance and albedo at the soil surface (Hermann, 1963), alter soil physical properties (Cochran, 1969) or insulate the soil surface with organic materials (Proe et al., 2001).

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Presence of overstory or understory vegetation typically causes a decrease in the amplitude of diurnal soil temperature fluctuation during summer (Davies-Colley et al., 2000; Porté et al., 2004; Maher et al., 2005). Daily maximum and daily mean temperatures also are lower, as vegetation absorbs a significant fraction of short-wave radiation before it reaches the soil surface (Coates et al., 1991; Pierson and Wight, 1991; Johnson-Maynard et al., 2004). Conversely, summer minimum soil temperatures are often slightly greater beneath vegetation due to reduced nighttime loss of long-wave radiation (Childs and Flint, 1987; Spittlehouse and Stathers, 1990; Maher et al., 2005). In winter months, vegetation may have little or no effect on soil temperature (Prévost and Pothier, 2003).

Forest floor materials such as harvest residues or litter may significantly affect diurnal and seasonal soil temperature patterns through their influences on heat transfer at the soil surface (Smethurst and Nambiar, 1990; Zabowski et al., 2000). An organic layer on the forest floor may exhibit extreme diurnal temperature fluctuations, but this layer will have low thermal diffusivity, and thus, the mineral soil beneath it will be insulated from aboveground temperature extremes (Spittlehouse and Stathers, 1990; Liechty et al., 1992). The presence of logging slash is negatively related to mean and maximum summer soil temperatures (Lopushinsky et al., 1992; Zabowski et al., 2000; Heithecker and Halpern, 2006). Whole-tree harvests may result in warmer summer and cooler winter soil temperatures compared to conventional harvests, as residues from conventional harvests shade soil in summer and insulate soil in winter (Proe et al., 2001).

Forest management practices and natural disturbances affect soil temperature at a variety of temporal and spatial scales, resulting in a heterogeneous soil temperature environment (Chen et al., 1999; Paul et al., 2004; Bond-Lamberty et al., 2005). This heterogeneity may affect stand regeneration, as soil temperature influences growth and survival of young trees (Childs and Flint, 1987). Most studies of the effects of silvicultural treatments on soil temperature have been at the stand or treatment level. While some studies have evaluated these effects at the microsite level (e.g., Hermann, 1963; Stathers et al., 2001), there has been very little research that included replicated sampling within various microsite types (exceptions include Minore (1986) and Hungerford and Babbitt (1987)). Analysis at this level is useful in understanding management effects at the scale of specific planting locations (e.g., so-called microsite planting; Koot, 2005) or individual seedlings. In this study, our primary objective was to evaluate the effects of harvest residue and understory vegetation control treatments on diurnal and seasonal soil temperatures by sampling within the various microsites associated with each treatment in a recently planted Douglas-fir stand in southwestern Washington, USA. A secondary objective was to evaluate microsite effects on near-ground air temperatures. Results are presented for 5 years after plantation establishment.

2. Methods

2.1. Study site

The study site is located in the Coast Range, in southwestern Washington (46°43′N, 123°24′W) at an elevation of 300 m above the mean sea level. The site slopes gently (<10%), with a westerly aspect. Mean annual air temperature (height of 2.0 m) during the study was 9.4 °C, with a mean daily minimum of 2.4 °C in January and a mean daily maximum of 22.8 °C in August (data from on-site weather station). Mean annual precipitation at the study site from 2001 to 2004 was 1612 mm, with an average of 195 mm between 1 June and 30 September. Soils are of the Boistfort series, a medial over clayey, ferrihydritic over parasesquic, mesic Typic Fulvudand, formed in basalt (Soil Survey Staff, 1999), with volcanic ash present in the surface horizons. This series is very deep and well drained. A layer of coniferous litter (Table 1) overlays the surface mineral A horizon (0–17 cm), which is silt loam in texture and has a bulk density of 0.59 g cm^{-3} (Ares et al., 2007). Beneath this horizon is a silt loam AB horizon (17–40 cm) and

Table 1
Characteristics of four microsite classes within two harvest treatments

Parameter	Harvest treatment	
	Bole-only	Total-tree
Coverage within treatment (%)		
Slash	50	3
Exposed mineral soil	9	31
Decaying wood over soil	12	24
Intact forest floor	29	42
Depth (cm)[a]		
Decaying wood	19.0 (3.1)	7.0 (0.7)
Intact forest floor	8.8 (3.2)	4.0 (1.0)
Dry weight (Mg ha^{-1})[a]		
Intact forest floor	29.8 (11.2)	29.9 (7.0)
Recent coarse woody debris[b]	49.8 (6.9)	1.9 (0.9)

[a] Data from Ares et al. (2007); standard errors in parentheses.
[b] Slash from stand harvested in 1999 (decay classes 1 and 2; Maser et al., 1979). Does not include stumps or old-growth materials.

silty clay loam 2Bw1 and 2Bw2 horizons (40–140+ cm). Douglas-fir site index at age 50 is 41–43 m (King, 1966).

The site is in the western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) vegetation zone, and prior to treatment implementation, the plant association was identified as *Tsuga heterophylla* (Raf.) Sarg./*Polystichum munitum* (Kaulfuss) K. Presl-*Oxalis oregana* Nutt. (Franklin and Dyrness, 1973). The study site was formerly occupied by a 47-year-old Douglas-fir/western hemlock stand that was harvested in May–July 1999 (Ares et al., 2007). During this harvest, trees were directionally hand-felled so that tops remained within the same study plot. Plots in this study were cable yarded.

2.2. *Study design*

This study is a component of the Fall River Long-Term Site Productivity Study which examines the effects of silvicultural treatments on soil processes, the microenvironment, and tree growth (Terry et al., 2001). Following harvest of the previous stand in 1999, a randomized complete-block design study was established to evaluate 12 combinations of organic matter removal (primarily as harvest residues), vegetation control, fertilization, soil compaction, and soil tillage on the subsequent stand of Douglas-fir, planted in March 2000 (1 + 1 seedlings) at a spacing of 2.5 m × 2.5 m. To isolate the effects of various processes, many of the treatments were more intensive than operational treatments (e.g., the total-tree harvest treatment included removal of legacy coarse woody debris from the forest floor). This microclimate study includes three treatment combinations, each applied to two replicate plots (30 m × 85 m) in each of the study's four blocks, for a total of eight plots in each of the following treatments:

(i) Bole-only harvest of the previous forest stand with no vegetation control (BO − VC). Merchantable stems (>10 cm diameter) were removed. Logging slash was scattered on site. No herbicides were applied. Coverage of competing vegetation was 32% in year 1 (2000) and >80% in subsequent years.

(ii) Bole-only harvest of the previous forest stand with vegetation control (BO + VC). Same treatment as BO − VC except competing vegetation was treated with a combination of broadcast and spot-applied herbicides from prior to planting through the fifth year of the study (Ares et al., 2007). As a result, coverage of competing vegetation averaged 4% during the 5-year period.

(iii) Total-tree harvest plus removal of legacy coarse woody debris, with vegetation control (TTP + VC). All woody residues from the 1999 harvest were removed, including limbs and foliage. From the forest floor, limbs >0.6 cm diameter, old-growth logs, and all intact woody debris other than stumps also were removed. Competing vegetation was treated as in the BO + VC treatment, and coverage was 15% or less throughout the study.

Following treatment application, the most common microsite types within each treatment were classified and surveyed. Microsite classes were as follows:

(i) Slash: where woody residues from the 1999 harvest cover the forest floor. Residues consist primarily of scattered tops (diameter < 10 cm), broken logs, and sections of logs with sweep or rot. This microsite class included locations where microsite classes *ii–iv* occurred beneath slash.

(ii) Exposed mineral soil: bare mineral soil present following harvest of the previous stand or mineral soil exposed and mixed with forest floor materials, not covered by slash.

(iii) Decaying wood over mineral soil: decomposing old-growth woody debris in decay class 5 (Maser et al., 1979) overlaying the mineral soil. This wood is unconsolidated, blocky cubical or granular rot. The greater coverage and shallower depth of decaying wood in the TTP treatment compared to the BO treatment (Table 1) was due in part to the scattering of decaying wood during whole-tree harvesting and subsequent removal of coarse woody debris. This class does not include areas covered by slash from the 1999 harvest.

(iv) Intact forest floor: an undisturbed mat of brown and gray needles not covered by slash.

To quantify the extent of the microsite classes within each treatment, a 1.25- × 1.25-m frame was used to delineate four quadrats around each of 30 randomly selected seedlings in four plots per treatment, and the percent coverage of each microsite class in each quadrat was visually estimated (Table 1). A fifth microsite class, shade of old-growth stumps (i.e., intact forest floor adjacent to the northeastern face of a stump), was included for comparison with other microsite classes, but coverage was not assessed for this microsite. Because characteristics of microsite classes differed by harvest treatment (e.g., forest floor depth was 8.8 cm in BO and 4.0 cm in TTP), a nested treatment arrangement was used (microsite within treatment), and microsite comparisons were made within each treatment.

2.3. Data acquisition

Beginning 6 April 2000 (study year 1), soil temperature was recorded in each microsite class in each treatment using two- and four-channel HOBO® dataloggers (Onset Computer Corp., Bourne, MA). Soil temperature was recorded at 30-min intervals at 10 cm beneath the surface of the mineral soil, although depth of materials overlaying the mineral soil varied by microsite (Table 1). The 10-cm mineral soil depth was selected to represent the major rooting zone of young Douglas-fir seedlings, although roots certainly occupied other depths as well. Due to technical problems, the HOBO® dataloggers were replaced on 1 May 2001 with iButton® Temperature Loggers recording at 60-min intervals (Maxim Integrated Products Inc., Sunnyvale, CA). Treatment/microsite class combinations with $\geq$10% coverage were sampled with 8–10 sensor locations, while those with <10% coverage were sampled with a minimum of 4 sensor locations, distributed evenly among blocks (120 total sensor locations). Sensor placement within plot depended upon the distribution of microsites, but sensors were typically placed between seedlings rather than in close proximity to them. Data collection continued until 9 February 2005 (study year 6).

Near-ground air temperature (25-cm height) was measured in 2004 (study year 5) in the BO − VC treatment (slash and intact forest floor microsites) and in the TTP + VC treatment (exposed mineral soil and intact forest floor microsites) in each of the four blocks (16 sensor locations). Other treatment/microsite combinations are not presented here as equipment failure resulted in insufficient replication. Data were recorded at 60-min intervals with HOBO Pro® dataloggers which were shielded from direct sunlight by 18-cm diameter white plastic canopies.

A weather station located centrally among the study blocks recorded air temperature and photosynthetically active radiation (LI-190 Quantum sensor, LI-COR, Lincoln, Nebraska) at 2.0 m above ground level, as well as soil temperature at depths of 10 and 20 cm, at 60-min intervals throughout the study. Weather station temperatures were measured using type T thermocouples; data were recorded with a CR10X datalogger with a reference thermistor at the panel (Campbell Scientific Inc., Logan, Utah).

2.4. Data analysis

Temperature data were analyzed at the treatment level and at the microsite level by analysis of variance (ANOVA; Snedecor and Cochran, 1967) using PROC MIXED (SAS Institute Inc., 2005). Treatment and microsite were fixed effects, and block was a random effect. All treatment-level analyses used temperature values calculated by weighting data from the microsite classes within each treatment by the percent coverage per class in that treatment (excluding the shaded class which was not used in treatment-level comparisons) and included protected comparisons of least-square means. For microsite-level analyses, pre-planned, single-degree-of-freedom contrasts were used to compare the microsite classes nested within each treatment (classes with $\geq$10% coverage plus the shaded class). To test the significance of individual contrasts, comparison-wise alpha levels were calculated using the Bonferroni adjustment.

Mean soil temperature and mean diurnal range in soil temperature were analyzed by month at both the treatment level and at the microsite level using repeated measures ANOVA, with year as the repeated unit of time ($n = 4$ or 5, depending on month). To assess biological implications of treatment-level effects on temperatures, analyses of cumulative degree-days were performed using hourly temperature data (one degree-day = 24 h at 1.0 °C above a specified base temperature). Soil degree-days were calculated for years 2–5 using a base temperature of 10.0 °C. This base temperature was chosen because the rate of root growth of Douglas-fir increases significantly above 10 °C, while growth is much slower below this threshold (Lopushinsky and Max, 1990). In a similar analysis, air degree-days were calculated for year 5 using a base temperature of 5.0 °C. Dependent variables in analyses of cumulative degree-days were either the day of year at which a specified number of degree-days was reached or the total number of degree-days per year. Gaps in the data, owing to equipment failure, prevented calculation of cumulative soil degree-days in year 1 and the latter half of year 2.

To assess diurnal patterns in soil temperature, a sine-wave model (Campbell and Norman, 1998) was applied (PROC NLIN; SAS Institute Inc., 2005). The model was:

$$T(t) = T_{ave} + A \sin\left[\left(\frac{\pi}{12}\right)(t + s)\right]$$

where $T(t)$ is soil temperature at hour t, T_{ave} is mean soil temperature for the 24-h period, A is amplitude of the sine wave, and s is the phase shift. Of primary interest in this analysis was phase shift, as this parameter indicates the predicted time of day when soil temperature reaches its maximum, a function of soil thermal properties and the depth of forest floor materials. The sine-wave model facilitated estimation of this parameter, particularly when a sensor's maximum daily temperature spanned multiple consecutive readings. The sine-wave model was applied to each replicate per microsite class per treatment for five randomly selected days (with <1.0 mm precipitation) per month in May, June, and July of year 2 (five clear days and five cloudy days were analyzed separately for July). Resulting parameter values were then compared by treatment within each month using repeated measures ANOVA. Results at the microsite level are presented only for the phase shift parameter (s), as variables equivalent to T_{ave} and A are already presented at the microsite level by month (as mean soil temperature and diurnal range, respectively). Distribution of residuals was examined graphically for all sine-wave models to verify fit. For all tests, significance was judged using an experiment-wise alpha level of 0.05.

3. Results

3.1. Microsite-level effects

In the presence of harvest residues (i.e., BO − VC and BO + VC treatments), mean monthly soil temperatures did not differ between intact forest floor and slash microsites or between intact forest floor and decaying wood microsites (Fig. 1; Table 2). In the absence of harvest residues (TTP + VC), summer soil temperatures were significantly greater beneath exposed mineral soil than beneath intact forest floor or decaying wood (in July, 18.2 °C vs. 17.6 and 17.0 °C, respectively). In all three treatments, soil temperature in the shade of old-growth stumps was significantly lower compared to the other microsites (e.g., in July it was 1.2 °C lower in TTP + VC and 0.6 °C lower in BO + VC). There were no significant year × microsite interactions affecting mean soil temperature for any month.

The diurnal soil temperature range in the BO − VC treatment was less in February, April, and May beneath decaying wood than beneath intact forest floor (in February, 0.7 °C vs. 1.1 °C) (Fig. 2; Table 2). In the TTP + VC treatment, the diurnal soil temperature range was generally greater beneath exposed mineral soil than beneath intact forest floor or decaying wood (in July, 3.6 °C vs. 2.8 and 2.2 °C, respectively). Diurnal soil temperature range was smallest in the shade of old-growth stumps in the TTP + VC treatment. There were no significant year × microsite interactions affecting the diurnal range in soil temperature.

Near-ground air temperature, quantified as accumulated degree-days, did not differ significantly in year 5 between slash and intact forest floor microsites within the BO − VC treatment or between exposed mineral soil and intact forest floor microsites within the TTP + VC treatment (Table 3). Within the BO − VC and TTP + VC treatments, monthly averages of mean, maximum, and minimum daily air temperature each differed by less than 1.0 °C between microsite classes (data not shown). On a daily basis, the difference in maximum and minimum air temperature between microsites in the BO − VC and TTP + VC treatments was variable and small in magnitude (BO − VC microsites are shown in Fig. 3). There was a non-significant trend in the BO − VC treatment in which maximum air temperature was slightly lower for the slash microsite, particularly during

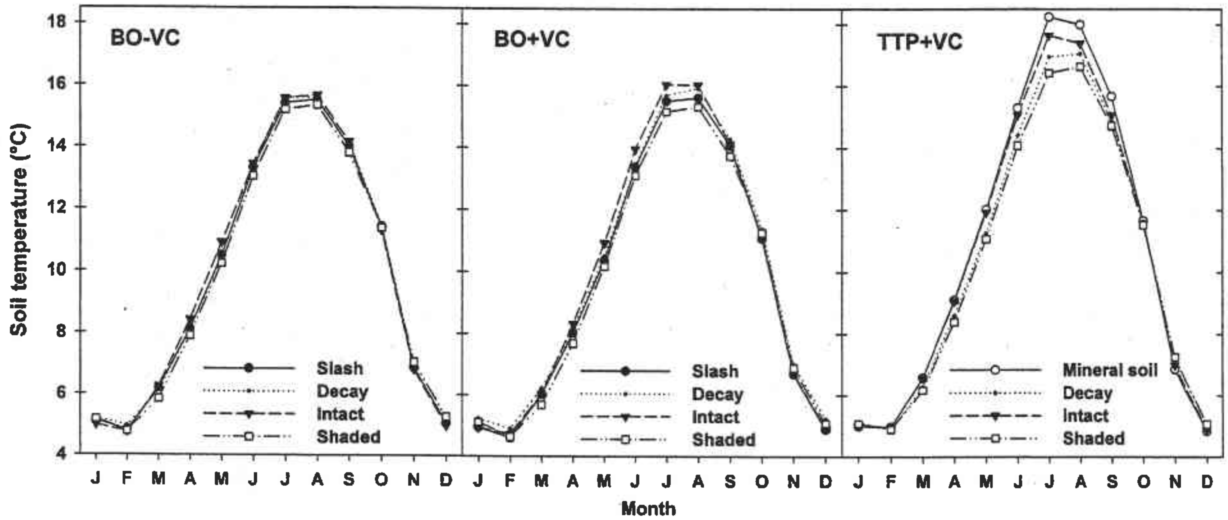

Fig. 1. Monthly soil temperature (10-cm depth) for four microsite classes within bole-only harvest treatments without and with vegetation control (BO − VC; BO + VC) and a total-tree harvest plus legacy wood removal treatment with vegetation control (TTP + VC). Data are for the first 5 years post-planting.

Table 2
Significance of contrasts comparing mean soil temperature and daily soil temperature range (10-cm depth) by month among microsite classes during a five-year period after planting

Treatment[a]	Microsite contrast[b]	Microsite difference[c]	Month											
			January	February	March	April	May	June	July	August	September	October	November	December
Mean temperature														
BO + VC	Intact vs. slash	–	–	–	–	–	–	–	–	–	–	–	–	–
	Intact vs. decay	–	–	–	–	–	–	–	–	–	–	–	–	–
	Shaded vs. others	<	–	–	–	*	*	–	*	*	*	–	–	–
TTP + VC	Intact vs. mineral soil	<	–	–	–	–	–	–	*	*	*	–	–	–
	Intact vs. decay	>	–	–	–	*	*	*	*	–	–	–	–	–
	Shaded vs. others	<	–	–	–	*	*	*	*	*	*	–	–	–
Daily temperature range														
BO – VC	Intact vs. slash	–	–	–	–	–	–	–	–	–	–	–	–	–
	Intact vs. decay	>	–	*	–	*	*	–	–	–	–	–	–	–
	Shaded vs. others	–	–	–	–	–	–	–	–	–	–	–	–	–
TTP + VC	Intact vs. mineral soil	<	*	*	*	*	*	–	*	*	*	*	*	–
	Intact vs. decay	>	–	–	–	*	*	*	*	*	*	–	–	–
	Shaded vs. others	<	–	*	*	*	*	*	*	*	*	*	*	–

Treatments were bole-only harvest of the previous stand without and with vegetation control (BO – VC; BO + VC) and total-tree harvest plus legacy wood removal with vegetation control (TTP + VC).

[a] Treatments containing no significant microsite contrasts are not shown (BO – VC for mean temperature and BO + VC for daily temperature range).

[b] Intact = intact forest floor; decay = decaying wood over mineral soil; shaded = shade of old-growth stump.

[c] Within each contrast, the direction of the inequality was consistent for significant differences across all months.

[*] Significant at an experiment-wise alpha level of 0.05 (Bonferroni adjustment); dash denotes non-significance.

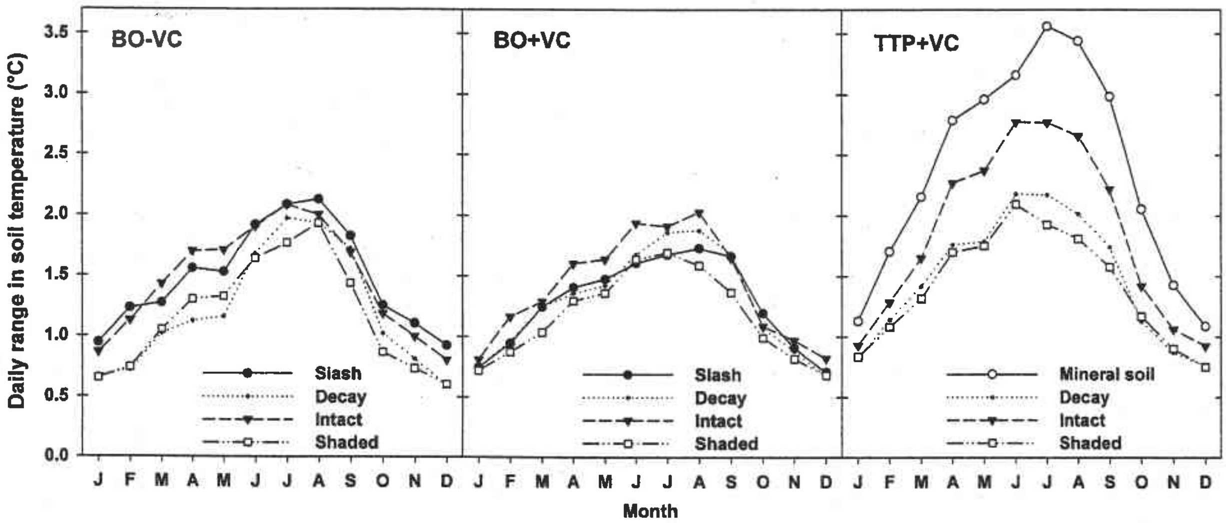

Fig. 2. Diurnal range in soil temperature (10-cm depth) for four microsite classes within bole-only harvest treatments without and with vegetation control (BO − VC; BO + VC) and a total-tree harvest plus legacy wood removal treatment with vegetation control (TTP + VC). Data are for the first 5 years post-planting.

fall and winter months. Minimum air temperatures in this treatment were slightly, but not significantly, higher for the slash microsite during spring and summer.

3.2. Treatment-level effects

Soil degree-days accumulated more rapidly in the TTP + VC treatment than in the BO − VC or the BO + VC treatments in all years analyzed (Table 4). In the presence of vegetation control, accumulation of 100 degree-days occurred 9–25 days earlier in the TTP + VC treatment than in the BO treatments. Similarly, accumulation of 200 degree-days occurred 10–19 days earlier in the TTP + VC treatment. Total soil degree-day accumulation was 37% greater in year 3 and 25% greater in years 4 and 5 in the TTP + VC treatment than in BO + VC treatment. The effect of vegetation control (i.e., BO − VC vs. BO + VC) on degree-day accumulation was not significant in any year.

Mean soil temperature was greater ($P < 0.05$) in the TTP + VC treatment than in the BO + VC treatment for all months from March (0.2 °C greater) through October (0.4 °C greater), with the largest difference occurring in July (1.5 °C greater) (data not shown). In December, soil temperature in the TTP + VC treatment was significantly cooler than in the BO + VC treatment (0.2 °C difference). There was no significant difference in soil temperature between the vegetation control treatments (BO + VC vs. BO − VC) in any month. However, monthly soil temperature was affected by a significant year × treatment interaction in the months of April ($P = 0.005$), July ($P = 0.022$), and August ($P = 0.045$) (Fig. 4). For July and August, soil temperatures in the BO − VC treatment decreased over time relative to the BO + VC treatment. In year 5, the difference between the TTP + VC treatment and the other treatments increased for the month of April but decreased slightly for July and August.

Table 3
Day of year (DOY) for near-ground (25 cm) air degree-day accumulation (base 5.0 °C; standard error in days) and total number of air degree-days accumulated (standard error in degree-days) among four treatment/microsite class combinations in year 5

Treatment	Microsite	Degree-day accumulation (DOY)			Total degree-days
		500 degree-days	1000 degree-days	1500 degree-days	
BO − VC	Slash	146 (2)	197 (1)	234 (2)	2113 (30)
BO − VC	Intact forest floor	145 (2)	196 (1)	233 (2)	2103 (35)
TTP + VC	Mineral soil	142 (2)	192 (2)	226 (3)	2204 (35)
TTP + VC	Intact forest floor	142 (2)	193 (2)	228 (3)	2204 (43)

Treatments were bole-only harvest of the previous stand without vegetation control (BO − VC) and total-tree harvest plus legacy wood removal with vegetation control (TTP + VC). There were no significant differences ($P \geq 0.05$) between microsite classes within treatments.

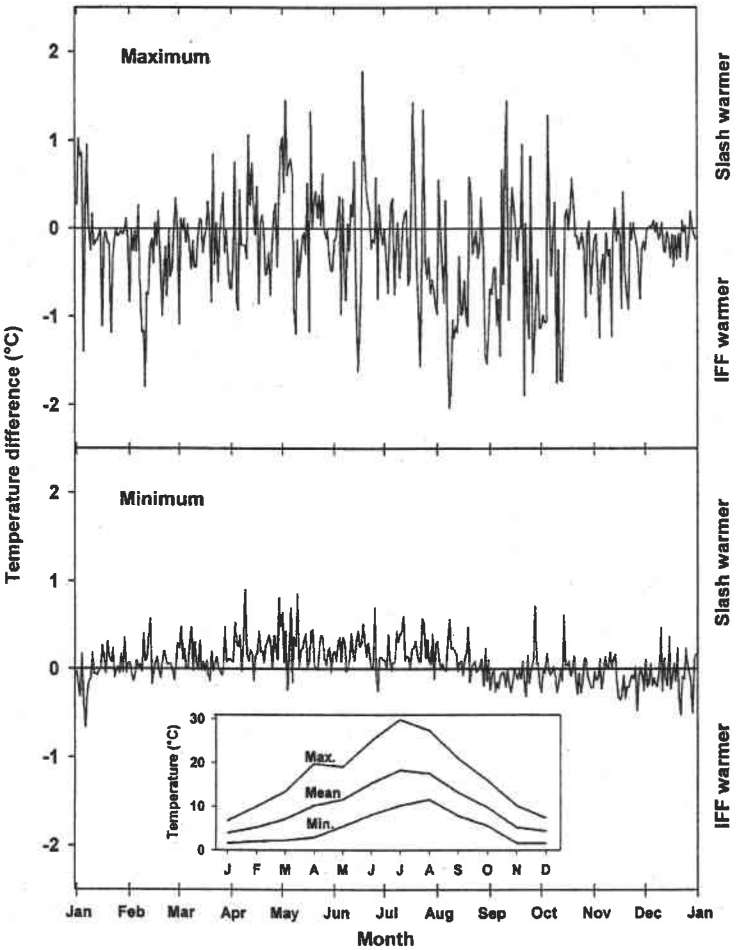

Fig. 3. Differences between the slash and intact forest floor microsites for daily maximum and daily minimum near-ground (25-cm height) air temperatures in the bole-only harvest treatment with no vegetation control in year 5 ($n = 4$ per microsite type). Positive values indicate warmer temperatures in the slash microsite; negative values indicate warmer temperatures in the intact forest floor (IFF) microsite. Inset graph shows monthly averages of maximum, mean and minimum near-ground air temperatures across treatments.

3.3. Diurnal patterns in soil temperature

The sine-wave model was consistently significant ($P < 0.001$) in predicting diurnal soil temperature in all treatments and microsites. Treatment-level parameter values are shown in Table 5. Parameters for the TTP + VC models generally differed from those of both the BO + VC and BO − VC models. The mean residual was largest for clear July days (mean = 0.8 °C) compared to other months, and on clear July days, the mean residual was smaller in the BO − VC treatment than in the TTP + VC treatment. Modeled phase shift values indicated that, in the BO − VC treatment, soil beneath both the intact forest floor and the slash microsites warmed significantly earlier in the day than soil beneath the decaying wood (Table 6). On average, intact forest floor and slash microsites reached their daily maximum temperature 181 min earlier than the decaying wood microsite. This pattern was less consistent in the BO + VC treatment, where the difference averaged only 46 min. In the TTP + VC treatment, the exposed mineral soil microsite reached its daily maximum earliest, an average of 91 min before the soil beneath decaying wood.

4. Discussion

Soil microsites showed greater variation in mean soil temperature and in diurnal range of soil temperature in the absence of harvest residues (i.e., the TTP + VC treatment). This may be due in part to the fact that harvest residues dispersed across the BO treatments occupied a significant portion of the surface area (50%), and these residues probably influenced soil temperatures to some extent across all microsites in these treatments through a shading or mulching effect (Lopushinsky et al., 1992). In the absence of this

Table 4
Day of year (DOY) for soil degree-day accumulation (base 10.0 °C; standard error in days) and total number of soil degree-days accumulated (standard error in degree-days) at 10-cm depth in each of 4 years for three treatments: bole-only harvest without and with vegetation control (BO − VC; BO + VC) and total-tree harvest plus legacy wood removal with vegetation control (TTP + VC)

Year	Treatment	Degree-day accumulation (DOY)				Total degree-days
		100 degree-days	200 degree-days	300 degree-days	400 degree-days	
2	BO − VC	173 (2) b	195 (3) b	ND	ND	ND
	BO + VC	174 (3) b	197 (4) b	ND	ND	ND
	TTP + VC	163 (2) a	186 (3) a	ND	ND	ND
3	BO − VC	182 (3) b	203 (3) b	222 (4) b	242 (4) b	561 (35) b
	BO + VC	180 (3) b	200 (3) b	217 (4) b	236 (4) b	597 (35) b
	TTP + VC	170 (3) a	190 (3) a	204 (4) a	218 (5) a	819 (35) a
4	BO − VC	171 (2) b	193 (2) b	209 (3) b	226 (3) b	697 (34) b
	BO + VC	167 (2) b	190 (2) b	206 (3) b	220 (3) b	742 (34) b
	TTP + VC	158 (2) a	177 (2) a	191 (3) a	203 (3) a	985 (34) a
5	BO − VC	164 (3) b	187 (3) b	203 (3) b	218 (3) b	778 (37) b
	BO + VC	162 (3) b	183 (3) b	199 (3) b	213 (3) b	809 (37) b
	TTP + VC	137 (3) a	164 (3) a	179 (3) a	192 (3) a	1071 (37) a

Same letter within year and column denotes no difference ($P \geq 0.05$). Data are not presented for year 1 or late summer of year 2 due to equipment failures. ND = no data.

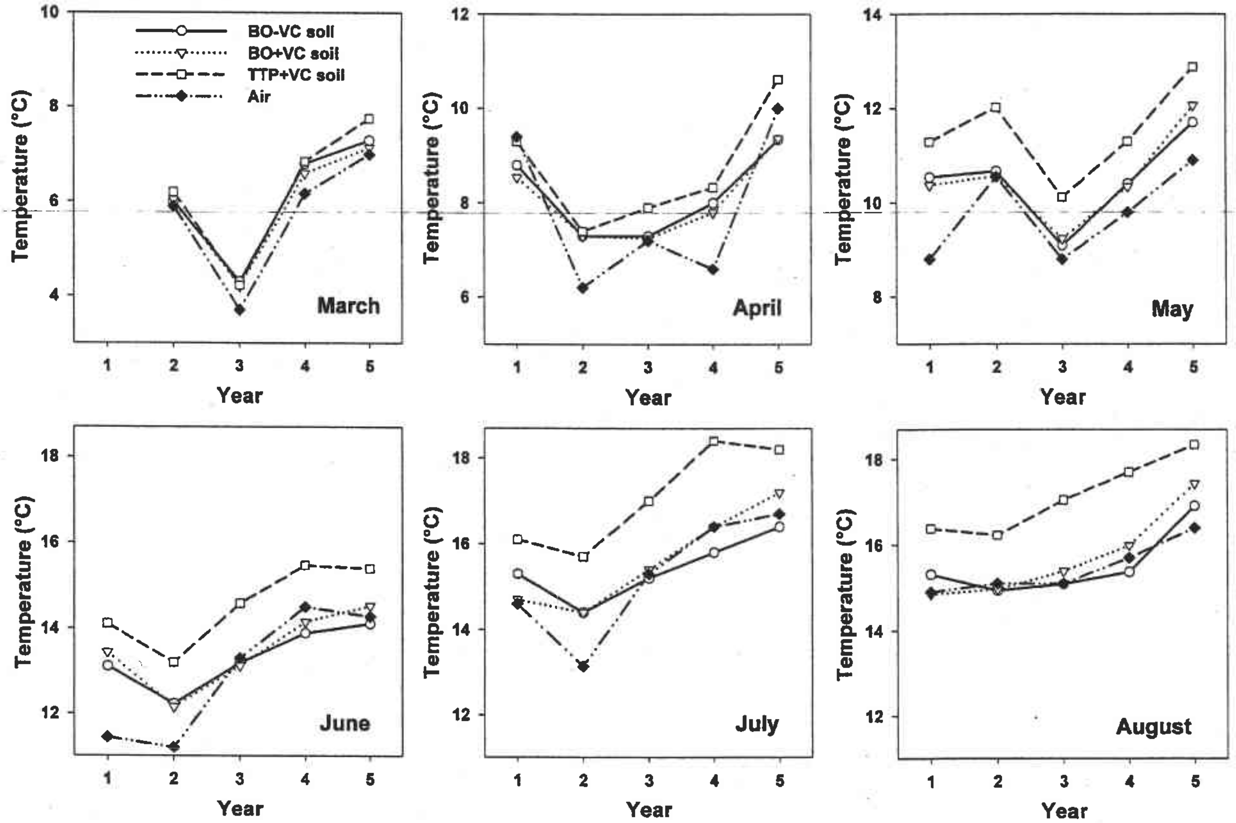

Fig. 4. Monthly air temperature (2.0-m height) for the study site and soil temperatures (10-cm depth) in bole-only harvest treatments without and with vegetation control (BO − VC; BO + VC) and a total-tree harvest plus legacy wood removal treatment with vegetation control (TTP + VC). Significant treatment × year interactions occurred for the months of April, July, and August.

Table 5
Values for mean temperature (T_{ave}) and amplitude (A) parameters (°C; standard error in parentheses) for a sine-wave model of daily soil temperature at 10-cm depth (phase shift values (s) appear in Table 6), with mean absolute values of residuals (°C) and weather conditions for the dates analyzed

Variable	Treatment	Month			
		May	June	July (clear)	July (cloudy)
Mean temperature	BO − VC	11.2 (0.1) b	12.4 (0.1) a	14.9 (0.1) a	14.1 (0.1) a
	BO + VC	11.0 (0.1) a	12.3 (0.1) a	14.8 (0.1) a	14.0 (0.1) a
	TTP + VC	12.4 (0.1) c	13.4 (0.1) b	16.6 (0.1) b	15.2 (0.1) b
Amplitude	BO − VC	0.68 (0.07) b	0.71 (0.05) b	0.94 (0.06) b	0.46 (0.03) a
	BO + VC	0.49 (0.07) a	0.54 (0.05) a	0.77 (0.06) a	0.41 (0.03) a
	TTP + VC	1.11 (0.06) c	1.10 (0.04) c	1.44 (0.05) c	0.74 (0.02) b
Absolute value of residual	BO − VC	0.60 (0.06) a	0.62 (0.07) a	0.73 (0.11) a	0.51 (0.07) a
	BO + VC	0.68 (0.06) a	0.68 (0.07) a	0.85 (0.11) ab	0.59 (0.07) a
	TTP + VC	0.70 (0.05) a	0.66 (0.07) a	0.86 (0.10) b	0.54 (0.07) a
Mean air temperature (°C)	–[a]	11.1	12.4	14.2	12.9
Minimum air temperature (°C)	–	5.7	7.6	8.6	9.3
Maximum air temperature (°C)	–	18.2	18.8	23.5	19.1
PAR (MJ m^{-2} day^{-1})	–	20.9	22.6	27.9	13.1

Each column represents data from five randomly chosen days in study year 2. Treatments are bole-only harvest without and with vegetation control (BO − VC; BO + VC) and total-tree harvest plus legacy wood removal with vegetation control (TTP + VC). Same letter within variable and column denotes no difference ($P \geq 0.05$).

[a] Temperature and photosynthetically active radiation (PAR) data were collected at a height of 2.0 m at a centrally located weather station.

Table 6
Phase shift values (s), expressed as time of maximum daily soil temperature at 10-cm depth (standard error in parentheses), for a sine-wave model of daily soil temperature

Treatment	Microsite or contrast	Month			
		May	June	July (clear)	July (cloudy)
BO − VC	Slash	21:05 (0:28)	21:16 (0:19)	20:46 (0:18)	21:40 (0:21)
	Decay	00:27 (0:28)[a]	00:22 (0:21)[a]	23:58 (0:21)	00:56 (0:25)[a]
	Intact	21:25 (0:28)	21:36 (0:19)	21:15 (0:18)	22:21 (0:21)
	Shade	21:01 (0:28)	21:15 (0:19)	21:22 (0:18)	22:10 (0:21)
	Intact vs. slash	–	–	–	–
	Intact vs. decay	*	*	*	*
	Slash vs. decay	*	*	*	*
BO + VC	Slash	22:05 (0:28)	22:03 (0:19)	21:58 (0:19)	22:21 (0:23)
	Decay	23:32 (0:28)	22:31 (0:19)	22:37 (0:18)	23:36 (0:21)
	Intact	22:19 (0:28)	22:16 (0:19)	22:23 (0:18)	22:57 (0:22)
	Shade	22:23 (0:28)	21:47 (0:19)	21:37 (0:18)	22:14 (0:21)
	Intact vs. slash	–	–	–	–
	Intact vs. decay	*	–	–	–
	Slash vs. decay	*	–	–	*
TTP + VC	Mineral soil	20:22 (0:25)	20:52 (0:15)	20:48 (0:14)	21:37 (0:17)
	Decay	22:29 (0:25)	22:15 (0:15)	21:59 (0:15)	23:11 (0:18)
	Intact	21:10 (0:25)	21:18 (0:15)	21:21 (0:15)	22:08 (0:18)
	Shade	21:24 (0:25)	21:15 (0:16)	20:48 (0:17)	21:46 (0:19)
	Intact vs. mineral soil	–	–	–	–
	Intact vs. decay	*	*	–	*
	Mineral soil vs. decay	*	*	*	*

Each column represents data from five randomly chosen days in study year 2. Treatments are bole-only harvest without and with vegetation control (BO − VC; BO + VC) and total-tree harvest plus legacy wood removal with vegetation control (TTP + VC). Contrasts compare microsite classes within treatments.

[a] Maximum soil temperature occurred after midnight.

* Significant at an experiment-wise alpha level of 0.05 (Bonferroni adjustment); dash denotes non-significance.

substantial residue presence, thermal properties of individual microsites, such as intact forest floor and decaying wood, had a greater effect on temperatures of underlying soils. There also were differences in the type and quality of microsites between the TTP and BO harvest treatments that may have affected within-treatment microsite temperature variability. For example, the depth of the intact forest floor and decaying wood microsite classes differed by treatment (Table 1); additionally, the microsite with the warmest and most variable soil temperature (exposed mineral soil) had only minor coverage in the BO treatments.

Exposed mineral soil had the greatest diurnal temperature range throughout the year, even in winter months when the level of solar radiation was relatively low. Exposed mineral soil also was significantly warmer than the intact forest floor from July through September. These patterns are due in part to the greater thermal diffusivity of mineral soil compared to decaying wood and other organic forest floor materials (Hermann, 1963; Cochran, 1969; Hungerford and Babbitt, 1987). The low thermal admittance and diffusivity of the organic materials substantially reduce the transfer of heat to and from the underlying mineral soil, where our temperature sensors were located. The other primary reason for the reductions in soil temperature and diurnal temperature range that we observed beneath organic forest floor materials was that the distance between the sensor and the heat exchange surface (i.e., the upper surface of the organic materials) was much greater where these materials were present than where mineral soil was exposed. Amplitude of both diurnal and seasonal temperature fluctuation is negatively related to distance beneath the surface (Campbell and Norman, 1998; Hillel, 1998).

Shading was the greatest negative effect on microsite soil temperature. The fact that soils in the shaded microsite were significantly cooler than the other microsites during much of the spring and summer suggests that, on sites where low soil temperature is a growth-limiting factor, development of seedlings planted in these locations may initially be negatively impacted (Flint and Childs, 1987). Conversely, shaded microsites have improved early seedling survival on harsh sites and during unusually hot summers where high temperatures caused seedling mortality (Minore, 1986; Childs and Flint, 1987). Although summer soil temperatures did not reach lethal levels at our site, we did not measure surface temperatures, which were certainly higher than those at the 10-cm mineral soil depth.

The difference in accumulated soil degree-days between treatments was most dramatic early in the growing season, where the TTP + VC treatment reached 100 degree-days 9–25 calendar days before the BO + VC treatment. Assuming that seedling chilling requirements have been met (Bailey and Harrington, 2006), springtime soil warming is positively related to development of seedlings (Sorensen and Campbell, 1978; Lopushinsky and Max, 1990). Soil water temperature is also closely related to seedling hydraulic conductivity (Carlson and Miller, 1990). Thus, treatments and microsites with warmer springtime soil temperatures may result in earlier growth which would be particularly advantageous for sites with short growing seasons or sites where soil water availability diminishes over the course of the growing season. While the TTP harvest treatment positively influenced degree-day accumulation in all years of analysis, the effect was greatest in year 5 when the 100 degree-day accumulation was reached 25 days earlier than in the BO harvest treatment. Weather station data showed that year 5 (2004) had the warmest March, April and May air temperatures of the study (Fig. 4); therefore, warmer spring temperatures increased the advantage of the TTP + VC treatment over the BO + VC treatment in early-season degree-day accumulation. As warmer spring temperatures are a part of predicted climate change scenarios for many regions including northwestern North America (Mote, 2004; Stewart et al., 2004), the effects of residue management on soil temperature may become increasingly important in the future.

Diurnal warming of soils for all treatments occurred later in the day than in other studies reporting temperatures at similar soil depths (Zheng et al., 2000; Heithecker and Halpern, 2006). The diurnal soil temperature patterns in our study were more similar to those reported for a 20-cm depth (Carlson and Groot, 1997) and a 32-cm depth (Childs and Flint, 1987), although diurnal soil warming at 20 cm at our site clearly lagged behind that at 10 cm (unreplicated weather station data; not shown). The considerable lag time for soil temperature relative to air temperature (air temperature peaked at 15:00–16:00 h during May–July) may be attributed, at least in part, to low thermal diffusivity of the mineral soil at the study site. When soil depth is incorporated into the sine-wave soil temperature model, the phase shift variable is influenced by the soil damping factor which is a function of thermal diffusivity (Campbell and Norman, 1998). Low thermal diffusivity results in a phase shift to the right, equivalent to greater lag time for diurnal soil temperature relative to air temperature. The apparent low thermal diffusivity of this soil may be due to a low mineral fraction (0.25; calculated from Ares et al. (2007)) and a high gas fraction (0.41; calculated from Devine and Harrington (2006) and Ares et al. (2007)), a combination closely linked to low thermal conductivity and diffusivity (Ochsner et al., 2001). These physical properties are typical of the highly porous soils formed in volcanic ash (Shoji et al., 1993).

Mineral soil beneath decaying wood generally exhibited slower diurnal warming relative to other microsite types. This slower warming (i.e., phase shift) may be attributed to the same two factors that probably caused the reduction in amplitude of the diurnal soil temperature pattern: (*i*) low thermal diffusivity of decaying wood relative to mineral soil, and (*ii*) the decaying wood increased the distance between the soil temperature sensor and the heat exchange surface. While soil conditions beneath decaying wood were cooler and less variable than for exposed mineral soil, the surface of organic forest floor materials, including decaying wood, typically reach much higher temperatures than the underlying mineral soil (Hungerford and Babbitt, 1987; Spittlehouse and Stathers, 1990; Marra and Edmonds, 1996). Because organic materials do not conduct heat away from the surface as rapidly as mineral soil, surface temperatures tend to reach greater daytime maxima, which may adversely affect tree seedlings planted among these materials (Hungerford and Babbitt, 1987).

Control of vegetation had little effect on soil temperature in the BO treatments. This was unexpected, given the intensive vegetation control in this study. The lack of a clear vegetation effect on soil temperature may have been due to the fact that harvest residues already provided substantial shading of the forest floor, and the shade from vegetation did not result in a significant amount of additional cooling. There was a treatment × year interaction for July and August soil temperatures indicating a cooling trend over time for the BO − VC treatment relative to the BO + VC treatment (Fig. 4). This trend apparently resulted from vegetation development in the BO − VC treatment, where coverage of vegetation increased from 28% in year 1 to 95% in year 5. Other regional studies have reported negative relationships between vegetation and soil temperature (Coates et al., 1991; Heithecker and Halpern, 2006).

The effect of shade from the planted seedlings was minimized by design in this study, as sensors were generally located between planting locations rather than beneath crowns. Although canopy cover of the planted trees averaged 10, 26 and 65% of surface area at the end of years 3, 4, and 5, respectively, only 22% of soil temperature sensors were beneath tree crowns in year 5. As canopy closure occurs in subsequent years, soil temperature patterns will likely be strongly influenced by the trees' shading and effect on air movement.

Near-ground air temperatures did not differ significantly between slash and intact forest floor microsites within the BO − VC treatment. This is contrary to other studies that reported greater air temperatures in the presence of logging residues compared to where residues were removed or burned (Lopushinsky et al., 1992; Zabowski et al., 2000), a pattern attributed to reduced movement of surface air amid slash and subsequent convective heating (Zabowski et al., 2000; Proe et al., 2001). In our study, air movement in the intact forest floor microsites (i.e., non-slash) was probably reduced by the proximity to slash in the plot. Thus, the dispersed slash may have contributed to uniformity of near-ground air temperature across the BO harvest treatment plots.

In summation, harvest residue treatments influenced the type and quality of microsite conditions present at the time of stand establishment, which in turn significantly influenced soil temperature regimes at both the microsite and treatment levels. Although more woody material was removed in the TTP treatment than would have been removed in an operational treatment, the types of microsites created by this treatment were similar to those that would be expected operationally, and within similar microsites, we would expect similar environmental conditions. Soil temperature heterogeneity at the microsite level was greater in the TTP harvest treatment than in the BO treatment, where generally cooler temperatures were attributed to the prevalence of dispersed slash. Because warmer soil temperatures in spring may increase the rate of seedling development, an understanding of the microsite soil temperature regime becomes relevant at planting, where microsite selection or preparation may be appropriate. The effect of harvest residue management on seasonal or diurnal soil temperature patterns may be of particular importance on sites with short growing seasons or extreme summer soil conditions that are potentially damaging or lethal to planted seedlings (e.g., Childs and Flint, 1987; Maher et al., 2005).

Under the conditions of the BO harvest treatment, vegetation had little effect on soil temperature, indicating that harvest residues had a greater influence on heat transfer at the soil surface than vegetation. However, further investigation is needed, as surface heat flux also may be affected by soil properties such as water content, which is strongly influenced by vegetation.

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