Effects of fire rotation interval and overstory type on ambient soil temperatures in ponderosa pine forests in Arizona

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Abstract

Ambient soil temperatures were measured every four weeks from May 1986 to November 1986 at three depths under the organic forest floor in ponderosa pine forests in three stand types subjected to periodic prescribed burning. Temperatures at the organic layer/soil surface interface in sawtimber stands were higher and more variable than in pole and saplings stands. Temperature variability reached a maximum in the summer and decreased into the fall and early winter. Soil temperature variability decreased as depth below the surface increased. Three years after the low intensity prescribed burns, soil temperatures in the burnt stands were not significantly different from the unburnt controls suggesting that any effect, though none was detected, of the low intensity prescribed burns on soil temperature and below-ground processes affected by temperature is short-lived in these stands.

Keywords: Pinus ponderosa, prescribed burning, Mogollon Rim, thermocouple

Introduction

Soil temperature acts as a fundamental regulator of basic physical, chemical, and biological processes important in pedogenesis (Jenny 1994). Regeneration and microbiological processes are affected by soil temperature which is influenced by the soil's thermal properties and residue covering the soil (Barbour et al. 1980; Spurr and Barnes 1980). Wildland fires typically occur in the organic residue (fuel) that covers the soil. Another soil factor influenced by fire is albedo which affects the absorption and retransmission of solar energy by the soil surface; impacts are both local and regional in scope (Covington and Sackett 1990; Govaerts 2002). The effects of fire and temperature on belowground soil processes have been studied in different ecosystems (e.g. Neary et al. 1999, 2005; González-Pérez et al. 2004; Certini 2005; Davidson and Janssens 2006; Mataix-Solera et al. 2011; Bento-Gonçalves et al. 2012; Hu et al. 2017); however, many of these studies have focused on temperatures that occurred while the fire was actively burning or the temperatures were measured in an immediate post-wildfire setting. Ahlgren (1974) cited numerous studies reporting increased soil surface temperatures following fire when compared with similar unburned forests. None of the cited studies examined ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson)[1] forests or the effect of stand structure on soil temperatures in the burned area. In ponderosa pine forests, prescribed burning has typically lower energy release rates than wildfires resulting in lower fire severity than wildfires. It is currently unknown if soil temperatures after prescribed burning in southwestern ponderosa pine forests respond as soil temperatures do in more humid environments.

Prescribed burning in ponderosa pine forests can have drastic effects on the forest floor as well as the cover from understory and overstory vegetation (e.g. Covington and Sackett 1984;

[1] Plant nomenclature from USDA, NRCS. 2018. The PLANTS Database (http://plants.usda.gov, 18 July 2018). National Plant Data Team, Greensboro, NC 27401-4901 USA.

Swezy and Agee 1991; Peterson et al. 1994; Stendell et al. 1999; Scudieri et al. 2010). Burning forest stands often eliminates large amounts of forest floor exposing the mineral soil and changing the surface color by producing blackened organic material and grayish residual ash (Kozlowski and Ahlgren 1974; Spurr and Barnes 1980). Depending on the burn objectives, the overstory may be reduced by the heat of a fire, allowing solar radiation to penetrate to the forest floor surface. This direct radiation is the most important component of the soil temperature regime (Spurr and Barnes 1980).

In a study of microclimatic changes following a prescribed burn in jack pine (*P. banksiana* Lamb.) in Minnesota, United States, Ahlgren (1981) found maximum soil surface temperatures higher on burned sites compared to unburned sites for 7 years after the high intensity prescribed fire which consumed all slash fuels and the above-ground portions of shrubs. Minimum soil surface temperatures remained lower than unburned sites for 13 years after. Five centimeters into the mineral soil, maximum and minimum temperatures were higher than unburned sites for 6 years after the fire. Other ambient soil temperature studies around the world have reported similar results (Raison et al. 1986; Swift et al. 1993; Auld and Bradstock 1996; Amacher et al. 2001; Iverson and Hutchinson 2002; Vermeire et al. 2005; Hu et al. 2017). With the exception of Iverson and Hutchison (2002), none of the recent studies or the historical studies cited in Ahlgren (1974) measured soil temperatures in a variety of stand types subjected to the same prescribed fire or set of repeated prescribed fires. Similarly, none of the studies examined ambient soil temperatures following repeated prescribed burns in ponderosa pine, one of the most widely distributed pines in the western United States (Oliver and Ryker 1990).

Many of the ponderosa pine forests of the southwestern United States are open stands dominated by grass. Occasional low intensity fires are believed to encourage vigorous growth and increased variety of herbaceous vegetation (Biswell 1972), which was noted by early explorers (Beale 1858; Dutton 1887; Muir 1961). In 1986, we hypothesized that this growth and increased diversity in herbaceous vegetation might be due, in part, to increased soil temperatures following burning as Lemon (1967) suggested in longleaf (*P. palustris* Mill.) and slash (*P. elliottii* Engelm.) pines in the southeastern United States (Sackett 1986). With greater exposure to solar radiation and less insulation from deep forest floor material, burned and unburned areas may have different soil temperature regimes which in turn may cause differences in biological functions in the soil that are dependent on temperature. To address this hypothesis, a study measuring soil temperature in a group of ponderosa pine stands subjected to repeated prescribed burning was established in 1986. Due to organizational changes, only one year of ambient soil temperature data were collected and no other measurements were made in conjunction with these data. This note presents the results of these limited measurements because rarely, if ever, have ambient soil temperatures following fire been measured, particularly in a range of stand conditions subjected to the same low intensity prescribed fires.

Materials and Methods

In 1976, a study was established at Chimney Spring (111° 41’ 7.1” W, 35° 16’ 0.4” N, elevation 2256 m) on the Fort Valley Experimental Forest near Flagstaff, AZ (Sackett and Haase 1998) to understand the effects of repeated prescribed burning on hazardous fuel accumulation in ponderosa pine. The study design was based on a previous study in loblolly (*P. taeda* L.) and longleaf (*P. palustris* Mill.) pines (Sackett 1975). Fort Valley Experimental Forest is located in an uneven-aged ponderosa pine forest composed of small, even-aged groups (Covington and Sackett 1986). The soils are basaltic and classified as Brolliar stony clay loam (fine montmorillonitic, frigid Typic Argiborolls). Mean annual temperature between 1909 and 1968 was 7 °C and mean annual precipitation was 57.4 cm, half of which fell as snow (Covington and Sackett 1986). Seven prescribed burn frequencies (none, 1, 2, 4, 6, 8 and 10 years) were replicated three times in 1 ha plots to determine the most effective fuel treatment interval to reduce hazardous fuels. A map of the study area can be found in Scudieri et al. (2008). The small, even-aged groups occurred within each 1 ha plot. Tree size varied considerably between the even-aged groups so three overstory conditions were delineated within the plots: sapling (1.5-9.9 cm at d.b.h., 2751 stems per ha), pole (10-27.8 cm, 771 per ha) and sawtimber (> 27.9 cm, 133 per ha) (Sackett 1980). Different aspects of this long-term research study are reported elsewhere (Sackett 1980; Covington and Sackett 1984, 1986, 1992; Sackett and Haase 1998, 2008; Neary et al. 2008; Scudieri et al. 2008, 2010). The 3, 6, 10-year and unburned sites were selected to provide a range of fire frequencies for ambient temperature measurement. The canopy cover of the overstory was measured using convex fisheye mirrors.

Soil temperature was measured at paired locations (burned and unburned sites in close proximity were paired by overstory condition). Four replicates were placed within each burn frequency (3) and overstory condition (3) combination resulting in 72 burned measurement sites paired with 72 unburned controls. At each site, two arrays of three thermocouples were located about 1.8 m apart (Figure 1). Type K thermocouples inserted into a 0.32 cm brass tube were placed at 3 depths. Using the O2/A1 interface as 0, the depths were 0, 2.54 and 7 cm. The original study plan is included with the archived data (Sackett et al. 2018). Covington and Sackett (1986, 1992) found nutrient changes and nutrient mineralization changes to be most drastic and ponderosa pine regeneration (Sackett 1984; Haase 1986) occurred at the selected depths. The TCs were left in place for the duration of the study and connected to recording devices monthly from May to November 1986 for a three-day period to record temperature hourly. We collected temperature measurements for the time periods May 14-June 1, June 3-June 22, June 24-July 13, July 15-August 3, August 5-August 24, August 26-September 14, September 16-October 5, October 7-October 27, and October 30-November 16, 1986. Ambient air temperature, relative humidity, and precipitation also were measured hourly in an open area within the study area. The 10-yr plots were burned by prescription on Oct. 24, 1986; the subsequent November temperature measurements were dropped from the analysis because they did not represent 10 years of fuel accumulation. Depth of forest floor material was measured at each soil temperature site.

The experiment was setup as a split-split plot design with repeated measures because of restrictions in our ability to randomize two factors – burn treatment and overstory condition (Cochran and Cox 1957; Montgomery 1976). Burn treatments were randomly assigned to a 1 ha plot, with each of the three overstory conditions occurring within each plot. Each overstory condition within a plot contained a measurement location with six thermocouple probes, each probe measuring temperature hourly. Thus, site is the whole-plot, overstory condition within site is the split-plot factor, and probe is the split-split-plot factor. Random intercepts were included for each of these quantities to properly model the error structure associated with the split-split plot experiment with repeated measures. The data are available in the Forest Service Research Data Archive (Sackett et al. 2018).

Using a mixed model framework (Pinheiro and Bates 2000) with the *lme* function in the *nlme* package (Pinheiro et al. 2018) in R version 3.5.0 (R Core Team 2018), we modeled the daily averages and the log daily sample variances of the hourly measurements. For fixed effects, each model contained a full factorial design of burn treatment, overstory condition, and soil depth. Additionally, the model for daily average soil temperature contained sine and cosine functions of the date to model the annual seasonality in average temperature. The model for log daily sample variance of soil temperature contained a linear trend for date (decreasing from summer to fall) as a part of the full factorial already included as this was found to be sufficient based on graphical inspection. ANOVA tests were performed using the *anova* function in the *lme* package to determine which fixed effects were significant at the 0.05-level using marginal sums of squares (Pinheiro and Bates 2000). Non-significant effects were removed and the reduced models refit. Tukey-adjusted *post hoc* pairwise comparisons of significant fixed effects were then performed using the *emmeans* and *emtrends* functions in the *emmeans* package (Lenth 2018) on the reduced models.

The experimental design paired a site in an unburned control with a site in an adjacent burn treatment. Using the same mixed model framework without repeat measures as above ANOVA tests were performed to determine if the fixed effects were significant for the paired differences for canopy cover and mean forest floor depth. Mean forest floor depth was calculated from the six depth measurements performed at each soil temperature site. This initial test indicated no differences between the paired sites, so all unburned controls were combined into a single treatment category. Significance of fixed effects on undifferenced canopy cover and forest floor depth were tested with ANOVA. Tukey-adjusted *post hoc* pairwise comparisons of significant fixed effects were then performed using the *emmeans* and *emtrends* functions in the *emmeans* package (Lenth 2018).

Results

The ANOVA tests indicated that the pairwise differences for canopy cover and forest floor depth between the burnt and unburnt stands were not significantly different from zero. Similarly, overstory type and burning interval treatment effects were not significant. Canopy cover did not differ between burning treatments but did differ between overstory types (Table 1). The sawtimber stands had significantly less canopy cover (79 percent) than the sapling and pole stands, which did not differ in canopy cover (~94 percent). The mean depth of the forest floor material located above each sample site differed between burning intervals and between the interaction terms for burning interval and overstory type (Table 2). The presence of significant interaction affected the estimates of depth for each burn interval. Mean forest floor depths of the burned treatments were significantly less than the unburnt treatment at the 0.05 level but did not differ between burn treatments. Eight of the twelve interactions were significantly different from zero. With the twelve estimated interactions, 66 pairwise comparisons were possible and 17 were significantly different from zero at the 0.05 level. All eleven possible comparisons with the unburnt sawtimber treatment were significantly different from zero indicating that the greatest observed forest floor depths were in these stands. The remaining six significant comparisons included the unburnt pole stands.

Air temperature measured in an open area in the study site exhibited typical diurnal and seasonal change and ranged from below freezing to over 30 °C. Patterns in soil temperature over date and time were dominated by three seasonal effects: 1) a seasonal component over the year with high temperatures in the spring and summer and lower temperatures in the fall (Figure 2a), 2) a daily variation component with higher temperatures during the day hours and lower temperatures during the night, and 3) a seasonal component over the year for the daily variation component wherein there was more daily variation in the summer than in the fall (Figure 3a). As originally designed, the study paired a treated plot to the unburned control closest to it. In this analysis, all control plots were combined into one class resulting in more frequent measurement than the treated plots.

The fitted linear mixed model for daily average soil temperature was dominated by a seasonal trend (i.e. COS date and SIN date), soil depth and a burn-interval by overstory type interaction effect (Table 3, Figure 2b). The Akaike Information Criterion for the full and reduced models was 28204 and 28170, respectively. The full model had 42 degrees of freedom in contrast to the 20 degrees of freedom for the reduced model for soil temperature. Based on the AIC and the principle of parsimony, the reduced model was used to estimate the marginal means. Note that burn interval was not a significant main effect. The estimated daily average temperature was significantly greater in the sawtimber stands (13 °C versus 11.5 °C) at all three depths (Figure 4a). Similarly, daily soil temperatures in sawtimber (13 to 14 °C) were greater than temperatures in pole and sapling stands (11.5 to 12 °C) in all three burn treatments (Figure 4b). Most of the pairwise comparisons of soil temperature for the overstory condition by burn interval interaction that involved the burning of the sawtimber stands differed significantly from the other overstory types (see supplemental table S1). The supplemental material contains details of the statistics associated with the pairwise comparisons of the various sets of estimated marginal means. The means and associated confidence intervals are presented graphically in the manuscript.

The daily variability in soil temperature appeared to decrease over the measurement period and was highest for the sawtimber stands. Variability of soil temperature appeared to decrease with increasing depth (Figure 3a). The daily sample variance for soil temperature changed appreciably (Figure 5). The soil/litter horizon temperatures in the burned sawtimber stands had the greatest variability and the temperatures had greater variability than the temperatures at 2.54 and 7 cm depth. The full and reduced models for log sample variances had AIC values of 20985 and 20747 with 76 and 54 degrees of freedom, respectively. The *emtrends* function was used to determine if date interacted with depth, burn interval, and overstory; in other words, did the time trend in daily variability differ between depth, burn interval, and overstory? Date and many of its interactions were significant in the reduced model (Table 3). In the reduced model, the dominant effects of a linear trend over date by burn interval by overstory condition interaction, a linear trend of date by soil depth interaction, and a depth by burn interval by overstory condition interaction. Note that the trend in daily variance in unburned sawtimber stands was significantly different than the 10-yr burn interval sapling stands (Figure 6a). Similarly, the trends in variability varied significantly by depth also (Figure 6b).

Discussion

Daily average soil temperatures were greatest in the sawtimber stands compared to the pole and sapling stands for the different burning intervals and at the three soil depths. This is not a surprising result given the number of stems present in these stand types. The sawtimber stands were much more open permitting more solar insolation. This would result in the higher temperatures observed at the litter/soil interface. The smaller, more numerous trees in the pole and sapling stands effectively provided more shade. In 2007-08, overstory canopy cover was measured and found to be relatively high (Scudieri et al. 2010) with relatively low understory plant cover and little difference between the burn frequency which was attributed in part to the relatively low intensity prescribed burns applied at Chimney Spring. Unfortunately, the data as reported did not distinguish between stand types.

Burn interval did not affect the daily average temperatures measured in the study. At the time of measurement, litter fall had accumulated since the previous burn for 3, 6, 10 or more (unburnt controls) years. Depths of forest floor material were greatest in the unburnt sawtimber and pole stands and the relative stability of soil temperature reflected this. Crude estimates (based on interpolation from Figure 2 in (Sackett and Haase 1998) of the amount of new material deposited on the soil surface since the prior burn range from 1.3 to 2.7 Mg/ha for the 3- and 10-year treatments. This material would be sufficient to cover the previous residual fuel (an equivalent amount) thus ameliorating any increase in absorbance by the blackened organic residue and increase the insulating properties of the organic layer as well. At this site, it appears that three years was sufficient for ambient temperatures to return to those observed in the unburnt stands. It is interesting to note that this period of recovery closely corresponds to the fire return interval of 3.7 to 6.5 years for presettlement fires in southwestern ponderosa pine (Fulé et al. 1997). From an ambient soil temperature perspective only, the low intensity prescribed fires used on this study site up to the time of measurement in 1986 may have replicated presettlement fire effects. Both the initial prescribed burn and subsequent repeated burns have substantially reduced the number of stems per unit area on this site (Harrington and Sackett 1990; Haase and Sackett 2008) since the late 1970s. The ambient temperature regime today in these more open stands may be more similar to the sawtimber stands since there are fewer trees. Recall that the differences in soil temperature that we noted occurred principally at the organic layer/soil surface interface.

While these results also might suggest that prescribed burning (as implemented in this study and in these stands) in ponderosa pine might not have any negative effects as a result of post-fire soil warming, these data are limited in scope and the results should not be generalized. As Harrington and Sackett (1990) concluded, prescribed burning is important for the maintenance of southwestern ponderosa pine forest health and stability. However, prescribed burning is also site-specific, and results can vary between fires on the same site due to varying weather and fuel conditions. Careful application of fire and monitoring of post-fire effects to ensure that desired results were achieved are always good practices to consider when using prescribed burning.

The trend of reduced variability in daily soil temperature as the year progressed from May until November is attributed to day length. In Flagstaff, the number of hours of daylight ranges from 14.5 hours at the summer solstice to 9.75 hours at the winter solstice. Shorter heating time resulted in lower increases in surface temperatures. The dampening effect of soil depth on temperature variation in soils is a well-established fact (Spurr and Barnes 1980) which is supported by the data collected in this study.

As a final consideration, soil temperatures in ponderosa pine stands (and other forested stands and vegetation types) contain several periodic fluctuations which must be accounted for in order to detect differences due to experimental and ecological factors. We modeled separately the daily variation and annual seasonal patterns in hourly soil temperature data with two components-- daily average behavior and daily variation. Other approaches such as joint estimation using a nonlinear mixed model (Pinheiro and Bates 2000) did not converge or took very long wait times for model convergence which is why they were not included. A nonparametric smoothing approach could have been taken, such as with generalized additive mixed models (Wood 2017); however, we found the smooth curves fit to be too smooth, missing the within day variation. This can be seen in Figure 2 and Figure 3 where we used a generalized additive model smoothing technique to show general trends. If the smoothing did capture the within day variation, the method was not designed to make inferences about the amount of within day variation. Additionally, the main function for implementing generalized additive mixed models, *gamm* in the *mgcv* package (Wood 2018), is not compatible with the *emmeans* package, limiting our ability to make post hoc comparisons. This limitation is why we opted for the sine and cosine representation of the annual seasonal pattern in daily average temperatures instead of a generalized additive mixed model: to allow post hoc comparisons using the *emmeans* package.

Summary

Ambient soil temperatures were measured every four weeks from May to November 1986 at three depths under the organic forest floor in ponderosa pine forests in three stand types subjected to periodic prescribed burning. The burn treatment did not affect the ambient soil temperatures. Temperatures at the organic layer/soil surface interface in sawtimber stands were higher and more variable than in pole and saplings stands, presumably due to more open canopy structure. Temperature variability reached a maximum in the summer and decreased into the fall and early winter. Soil temperature variability decreased as depth below the surface increased. Three years after the low intensity prescribed burns, soil temperatures in the burnt stands were not significantly different from the unburnt controls.

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Table 1. Effects of overstory and burning interval on canopy cover in a ponderosa pine forest near Flagstaff, AZ.

Effect	Numerator DF	Denominator DF	F-value	p-value
Intercept	1	51	1183.81	0.00
Burn	3	51	0.97	0.41
Overstory	2	6	14.34	0.01
Burn*Overstory	6	51	0.90	0.50

	Sapling	Pole	Sawtimber	CL
Mean	95.4	94.2	79.0	±3.7

Contrast	Estimate	Student's t	Prob(> t)
Sapling-Pole	1.2	0.74	0.75
Sapling-Sawtimber	16.4	10.07	0.0001
Pole-Sawtimber	15.2	9.32	0.0002

Table 2.Effects of overstory and burning interval on forest floor depth (cm) in a ponderosa pine forest near Flagstaff, AZ.

Effect	Numerator DF	Denominator DF	F-value	p-value
Intercept	1	51	9.80	0.003
Burn	3	51	3.71	0.017
Overstory	2	6	0.07	0.930
Burn*Overstory	6	51	6.80	0.000

Burn Interval	Overstory	Mean	CL
3		2.03	±0.41
6		2.96	±0.41
10		2.38	±0.41
Unburnt		6.45	±0.24
3	Sapling	2.25	±2.29
3	Pole	1.98	±2.29
3	Sawtimber	1.88	±2.29
6	Sapling	3.50	±2.29
6	Pole	2.93	±2.29
6	Sawtimber	2.45	±2.29
10	Sapling	2.33	±2.29
10	Pole	3.13	±2.29
10	Sawtimber	1.70	±2.29
Unburnt	Sapling	4.48	±1.33
Unburnt	Pole	6.01	±1.33
Unburnt	Sawtimber	8.87	±1.33

		Significant Differences	
		Unburnt Pole	Unburnt Sawtimber
3	Sapling		-6.62
3	Pole	-4.03	-6.90
3	Sawtimber	-4.13	-7.00
6	Sapling		-5.37
6	Pole	-3.08	-5.95
6	Sawtimber		-6.42
10	Sapling		-6.55
10	Pole	-2.88	-5.75
10	Sawtimber	-4.31	-7.17
Unburnt	Sapling		-4.40
Unburnt	Pole		-2.86

Table 3 Marginal ANOVA tables for full and reduced model of daily average soil temperature and daily sample variance of soil temperature.

	Full model daily average				Reduced model daily average		
	Num DF	Den DF	F-value	p-value	Den DF	F-value	p-value
Intercept	1	7900	1664.49	<0.0001	7900	1793.03	<0.0001
Depth	2	336	3.04	0.0489	358	24.78	<0.0001
Burn	3	20	2.98	0.0558	20	1.76	0.1881
Overstory	2	40	8.41	0.0009	40	13.58	<0.0001
SIN year	1	7900	29457.25	<0.0001	7900	29163.62	<0.0001
COS year	1	7900	18092.74	<0.0001	7900	17910.89	<0.0001
Depth*Burn	6	336	1.68	0.1253			
Depth*Overstory	4	336	1.27	0.2815			
Burn*Overstory	6	40	6.10	0.0001	40	4.01	0.0031
Depth*Burn*Overstory	12	336	1.43	0.1520			

	Full model daily sample variance				Reduced model daily sample variance		
	Num DF	Den DF	F-value	p-value	Den DF	F-value	p-value
Intercept	1	7866	233.59	0.0000	7888	257.29	<0.0001
Depth	2	336	174.63	0.0000	336	290.21	<0.0001
Burn	3	20	4.21	0.0183	20	8.88	0.0006
Overstory	2	40	36.92	0.0000	40	42.28	<0.0001
Date	1	7866	520.21	0.0000	7888	1120.46	<0.0001
Depth*Burn	6	336	1.51	0.1740	336	3.75	0.0012
Depth*Overstory	4	336	4.88	0.0008	336	5.27	0.0004
Burn*Overstory	6	40	18.36	0.0000	40	20.87	<0.0001
Depth*Date	2	7866	59.02	0.0000	7888	281.71	<0.0001
Burn*Date	3	7866	8.24	0.0000	7888	30.86	<0.0001
Overstory*Date	2	7866	52.30	0.0000	7888	146.40	<0.0001
Depth*Burn*Overstory	12	336	1.97	0.0261	336	2.70	0.0017
Depth*Burn*Date	6	7866	2.55	0.0182			

Depth*Overstory*Date	4	7866	1.71	0.1451			
Burn*Overstory*Date	6	7866	13.56	0.0000	7888	37.39	<0.0001
Depth*Burn*Overstory*Date	12	7866	0.28	0.9922			

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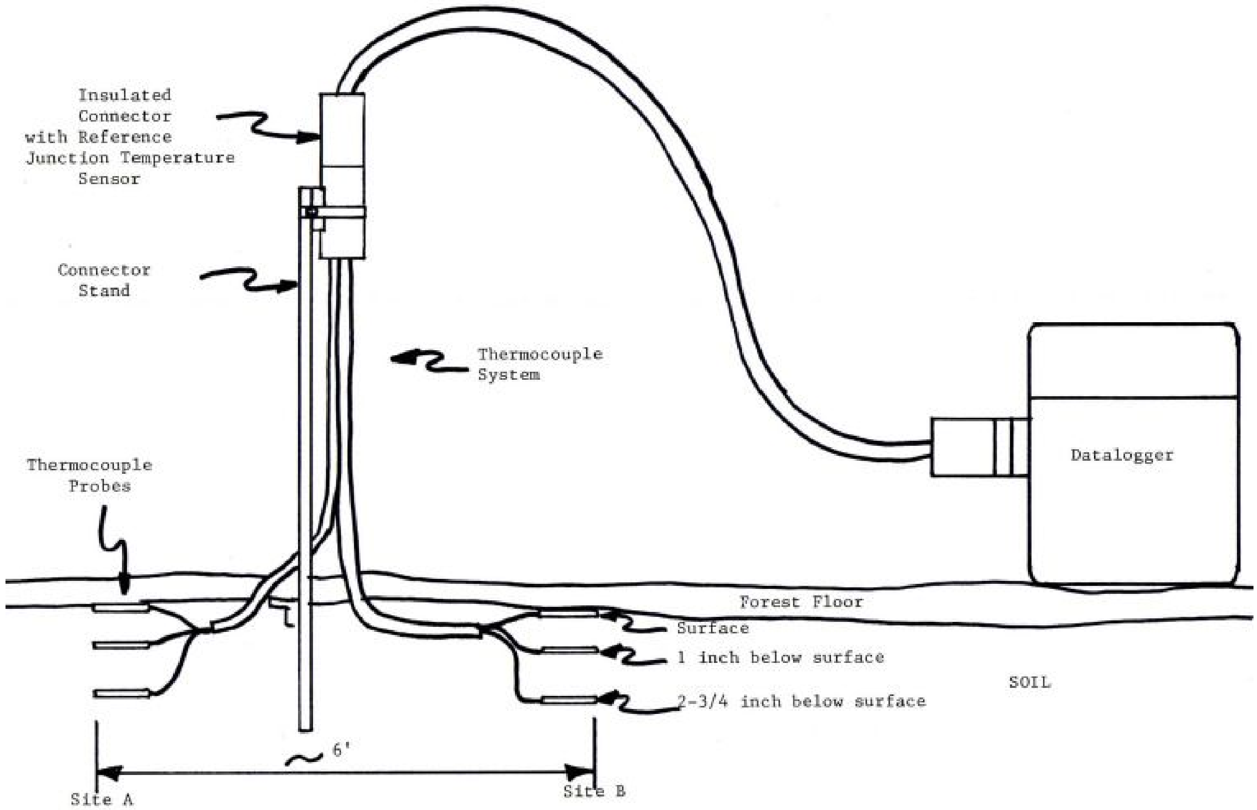


Figure 1. Thermocouple system used to measure ambient soil temperatures. Distance between site A and site B is 6 ft. (1.8 m).

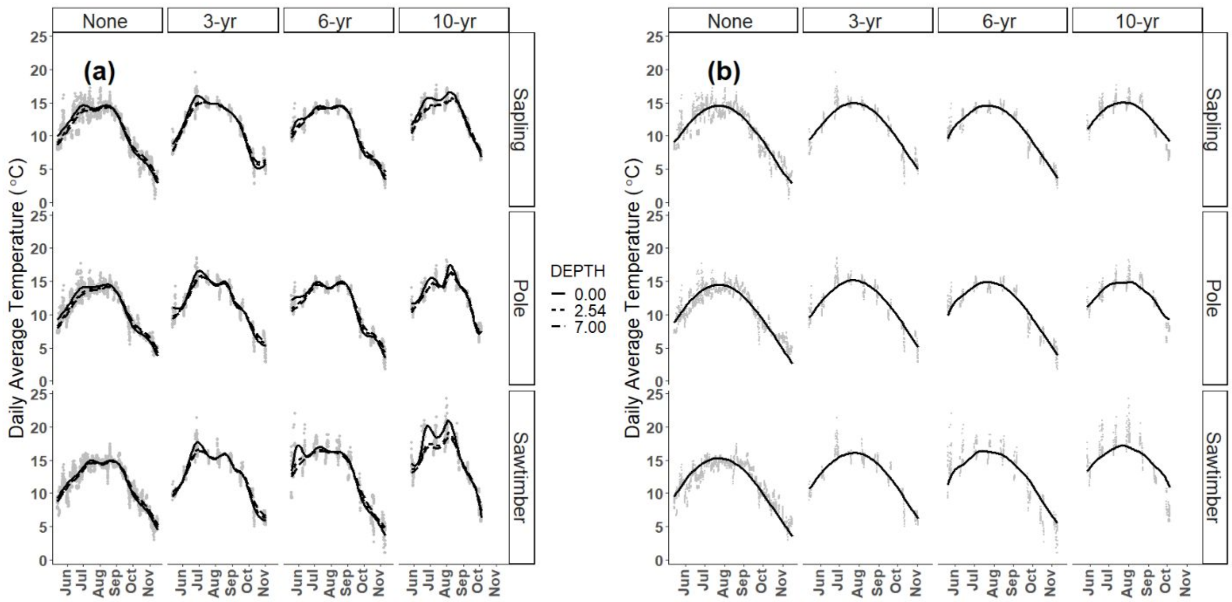
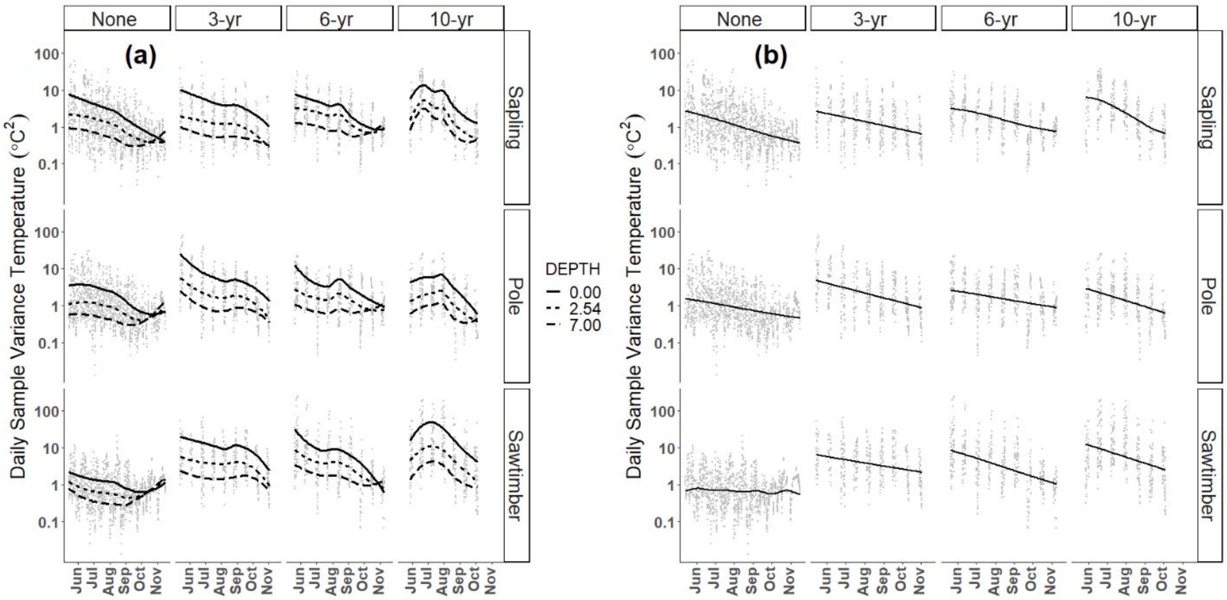


Figure 2. Daily average soil temperature (a) by burn interval, overstory type, and soil depth (b) compared with reduced fitted model.



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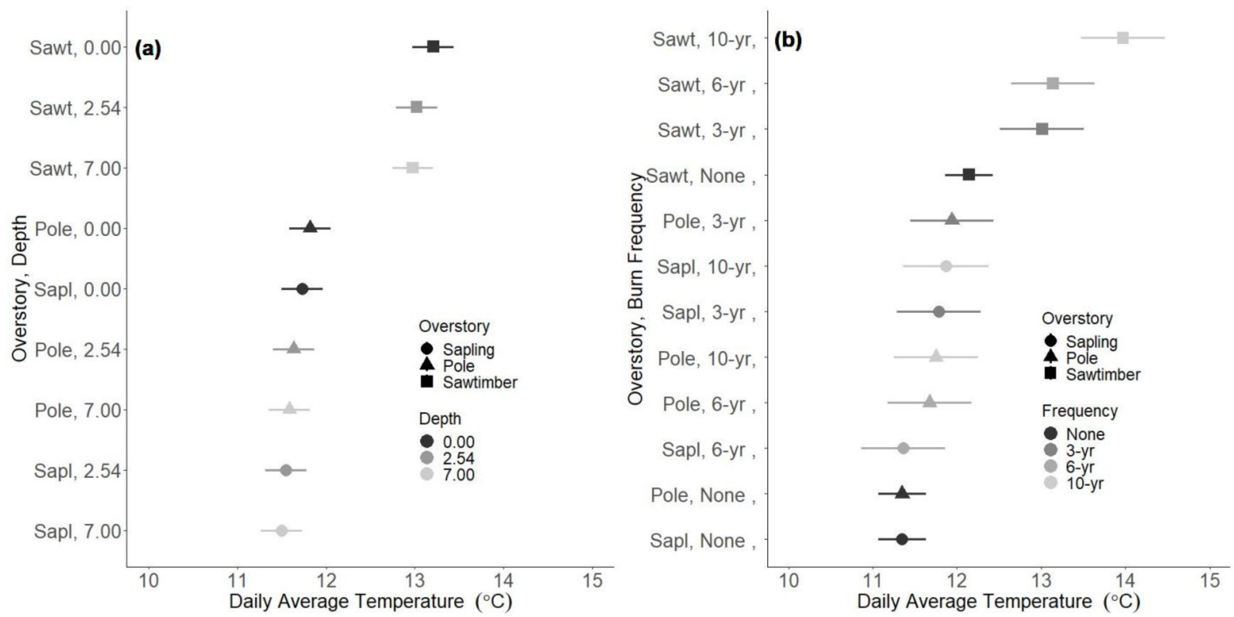

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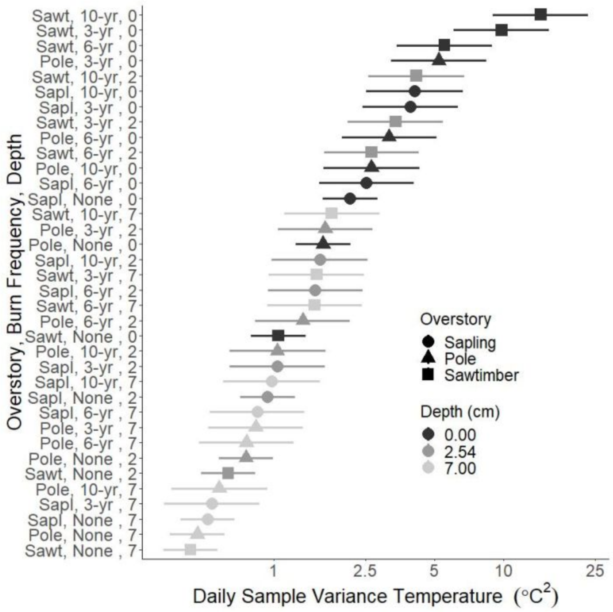

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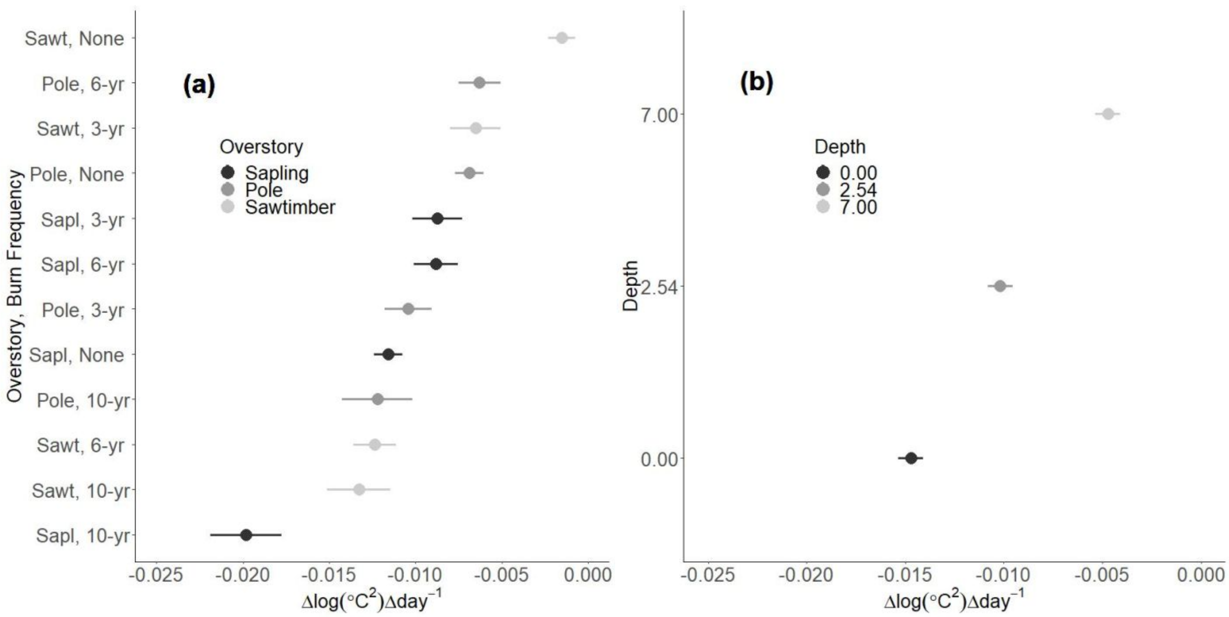

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