Soil Temperature following Logging-Debris Manipulation and Aspen Regrowth in Minnesota: Implications for Sampling Depth and Alteration of Soil Processes

Robert Slesak*
Minnesota Forest Resources Council
150 Skok Hall
2003 Upper Buford Cir.
St. Paul, MN 55108

Soil temperature is a fundamental controller of processes influencing the transformation and flux of soil C and nutrients following forest harvest. Soil temperature response to harvesting is influenced by the amount of logging debris (biomass) removal that occurs, but the duration, magnitude, and depth of influence is unclear. Logging debris manipulations (none, moderate, and heavy amounts) were applied following clearcut harvesting at four aspen-dominated (*Populus tremuloides* Michx.) sites in northeastern Minnesota, and temperature was measured at 10-, 30-, and 50-cm depths for two growing seasons. Across sites, soil temperature was significantly greater at all sample depths relative to uncut forest in some periods of each year, but the increase was reduced with increasing logging-debris retention. When logging debris was removed compared to when it was retained in the first growing season, mean growing season soil temperatures were 0.9, 1.0, and 0.8°C greater at 10-, 30-, and 50-cm depths, respectively. These patterns were also observed early in the second growing season, but there was no discernible difference among treatments later in the growing season due to the modifying effect of rapid aspen regrowth. Where vegetation establishment and growth occurs quickly, effects of logging debris removal on soil temperature and the processes influenced by it will likely be short-lived. The significant increase in soil temperature that occurred in deep soil for at least 2 yr after harvest supports an argument for deeper soil sampling than commonly occurs in experimental studies.

Abbreviations: LTSP, Long Term Soil Productivity; SWC, soil water content.

In recent decades, greater amounts of aboveground biomass (variously referred to as logging debris, slash, organic matter, harvest residue, among others) are being removed during timber harvesting for operational efficiency, easier planting, reduced fire risk, and utilization as bioenergy. Increased biomass removal has potential to reduce site productivity via impacts to soil (Powers et al., 1990; Jurgensen et al., 1997) giving rise to a slew of case studies, experimental networks, and meta-analyses attempting to assess impacts on soil chemical and physical properties associated with greater removal of biomass (e.g., the Long Term Soil Productivity [LTSP] network; Powers et al., 2005). A central hypothesis of many of these studies is that greater removal of nutrients in biomass may translate into smaller site nutrient pools because of reduced inputs over time and eventual reductions in tree growth (Burger, 2009). Less attention is given to the indirect influence that biomass removal may have on nutrient pools via modification of the soil environment and its influence on nutrient transformation and efflux (e.g., Slesak et al., 2010).

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*Corresponding author (raslesak@umn.edu).

Evaluation of the soil environment response to biomass removal may provide early indication of effects on the growth trajectory of the succeeding stand given the effects of removal on survival and growth during stand establishment (Harrington et al., 2013; Thiffault et al., 2011). In particular, soil temperature is known to have large influence on biologic activity when soil moisture is not limiting, influencing nutrient transformation and supply (Pregitzer and King, 2005), root uptake (Bassirirad, 2000), carbon flux (Conant et al., 2011), vegetative community composition and growth (Farnsworth et al., 1995), and many other temperature-mediated processes. It follows that the magnitude and duration of altered soil environment following forest harvesting and related management practices (e.g., logging debris removal, vegetation control) may provide an index to assess the relative effects on soil functions over time (e.g., nutrient supply).

Most studies that assess soil temperature following experimental harvesting or postharvest manipulation limit measurement to shallow soil depths (<10 cm) (Devine and Harrington, 2007; Holmes and Zak, 1999; Fleming et al., 2006; Zabowski et al., 2000; Belleau et al., 2006). However, substantial amounts of C and nutrients can be found in deeper soils (Jobbagy and Jackson, 2000; Harrison et al., 2011), which presumably influence resources available for tree exploitation given reported rooting depths (Stone and Kalisz, 1991). It is possible that these deeper pools may be even more responsive to changes in soil temperature following harvesting than those found at the surface because of greater microbial sensitivity to temperature (Davidson and Janssens, 2006; Schmidt et al., 2011; Fierer et al., 2003). Despite this, most soil sampling conducted in experimental biomass manipulations is commonly restricted to shallow depths (e.g., <30 cm in the LTSP network; Powers et al., 2005). It is unclear whether or not soil temperature changes are propagated to deeper portions of the soil, introducing uncertainty on the suitability of common sampling schemes used to assess the influence of biomass removal on soil properties.

Table 1. Site characteristics and select soil properties at each of the four study locations.

Variable	Site 1	Site 2	Site 3	Site 4
Latitude	47.254° N	47.005° N	48.028° N	48.157° N
Longitude	92.321° W	92.416° W	92.989° W	92.979° W
Annual precipitation (mm) †				
2010	750	830	770	780
2011	560	610	570	560
Mean growing season air temperature (°C) ‡				
2010	15.3	15.6	14.8	14.8
2011	15.0	15.2	14.9	14.9
NRCS Soil Series§	Dusler and Ellsburg	Brimson	Ashlake and Effie	Suomi and Ashlake
Soil texture	silt loam	fine sandy loam	loam–silty clay	loam–silty clay
Bulk density¶				
10 cm	1.33 (0.05)	1.03 (0.05)	1.23 (0.06)	1.15 (0.07)
30 cm	1.58 (0.07)	1.53 (0.07)	1.68 (0.04)	1.52 (0.06)
50 cm	1.51 (0.070	1.51 (0.07)	1.66 90.04)	1.44 (0.06)

† Predicted with the PRISM model (PRISM Climate Group, 2012).

‡ Predicted with the PRISM model for the months of May–September.

§ Official series descriptions available at http://soils.usda.gov/technical/classification/osd/.

¶ Estimated with the core method, $n = 16$, standard error in parenthesis.

I examined the influence of forest harvesting and varying levels of woody debris retention at four aspen-dominated sites in northeastern Minnesota on soil temperature profiles and soil moisture for 2 yr following harvest. My primary objectives were to determine (i) magnitude and duration of microclimate effects following harvesting and whether or not they are modified by varying levels of logging debris retention, and (ii) whether or not the aforementioned effects are limited to surface soil or propagated to deeper portions of the soil profile. Underlying questions related to these objectives include to what degree is the soil environment modified followed harvesting, and what is the appropriate depth for sampling of soil C and nutrient pools following harvest and experimental manipulation?

MATERIALS AND METHODS

Four sites located in northeastern Minnesota were used in this study (Table 1). The sites are part of an ongoing project assessing the effects of biomass harvesting and green-tree retention on biologic communities, nutrient availability, and productivity in trembling aspen forests. Sites were similar in stand composition, elevation (395–428 m), topography (0–8% slopes), and climate (Klockow et al., 2013) with some variation in soil texture and bulk density (Table 1). The climate of the study area is continental, with a predicted mean growing season (May–September) temperature of 15°C and annual precipitation of 700 mm from the period 1990 to 2011 (PRISM Climate Group, 2012). Each site was clearcut harvested in February of 2010 with mechanized equipment (feller-buncher in combination with grapple skidding) under frozen ground conditions.

Slash Manipulation and Sensor Installation

In May of 2010, four locations were randomly identified at each site away from features that might confound the microclimate response to logging debris (e.g., plot edge, presence of green trees). At each of these locations, logging debris manipulation treatments of none (0% surface coverage), moderate (~40% surface coverage), and heavy levels (~80% surface coverage) were applied to 4-m^2 areas. Experimental manipulations were applied by utilizing the existing matrix of logging debris (primarily aspen branches and tops <10 cm in size without foliage) remaining after harvest and then modifying the preexisting amount by placing a 2- by 2-m PVC frame on the ground and adding or removing debris as needed to achieve the target level of surface coverage for each treatment. For the no logging-debris treatment, all woody material was removed from the 4-m^2 area while taking care to minimize disturbance of the forest floor. Logging debris volume was estimated at the moderate and heavy retention treatments with the line transect method as outlined in Brown (1974). For the estimate, a 2 by 2-m frame was centered on the experimental unit, and woody debris counts by size class were conducted along three transects (2-m length) with random start points and extending in one of the cardinal directions. Volume estimates were converted to mass estimates using the specific gravity values in Harmon et al. (2008). Across sites, estimated mass of logging debris was 45 Mg ha^{-1} (SE = 4.4) in the moderate treatment and 71 Mg ha^{-1} (SE = 5.2) in the heavy treatment.

Soil temperature and moisture was measured at each of the logging debris manipulation areas at each of the four sites (Table 1) in 2010 and 2011. Soil temperature (I-button model DS1921G, Maxim Integrated Products, Inc., Sunnyvale, CA) was measured at 10-, 30-, and 50-cm depths, and soil moisture (model EC-5, Decagon Devices, Inc., Pullman, WA) was measured at a 30-cm depth only. The 30-cm SWC sensor depth was chosen because it is the midpoint of the soil temperature depths. Sensors were installed in the approximate center of each experimental unit by digging a narrow soil pit, placing the sensors at the prescribed depth, and then backfilling the pit with soil. Soil between measurement depths was packed to the approximate density of undisturbed soil to minimize artifacts associated with changes in bulk density (i.e., total porosity). Sensors were installed in the same manner at three random locations in nearby uncut forest. In each year of the study, sensors were installed during May and retrieved in October at each of the sites.

Data Analysis

Soil temperature and moisture was measured every 1.5 h. Factory equations were used to convert soil water sensor readings to estimates of volumetric soil water content (SWC). Before analysis, all values were first averaged by day and then by week. At each site, mean weekly values were calculated among the four measurement areas by logging debris treatment and measurement depth. Mean weekly values per site × treatment × depth were then expressed as the difference from mean values calculated for corresponding depths in the uncut forest, with positive values indicating absolute increases in soil temperature or SWC in logging debris treatments relative to uncut forest.

The effect of logging debris treatment on soil temperature and SWC was assessed across sites using a mixed effects model with repeated measures analysis and an autoregressive level 1 covariance matrix that assumes homogenous variance and exponential reduction in correlation with distance between measures. Site and logging debris treatment within site were treated as random effects, and logging debris treatment, week, and their interaction were treated as fixed effects. When F-tests indicated significant treatment effects, a priori orthogonal contrasts were performed to test for a significance of difference between (i) the absence and presence of logging-debris (none vs. the mean of the moderate and heavy treatments), and (ii) the moderate and heavy logging debris treatments. One-tailed *t* tests were used to determine if weekly mean differences by treatment and depth (relative to uncut forest) were significantly different from zero. Examination of the residuals indicated assumptions of normality and homogeneity were valid for untransformed data. An α level of 0.05 was used to assess statistical significance in all evaluations. All analyses were performed in SAS Version 9.3 (SAS Institute, Cary, NC).

RESULTS

Soil Temperature in Uncut Forest

Weekly soil temperatures in uncut forest among the four study sites were very similar in most weeks of the growing season of each year (as evidenced by weekly SE shown in Fig. 1). Soil temperature in uncut forest at all measurement depths followed a seasonal pattern similar to that of air temperature (Fig. 1). Weekly soil temperature decreased by 1 to 2°C with each successive measurement depth in most of the growing season, but soil temperature at 50-cm depth was warmer than shallower depths in the fall of each year. Maximum mean weekly soil temperature at a 10-cm depth was 17.2 and 17.8°C in 2010 and 2011, at a 30-cm

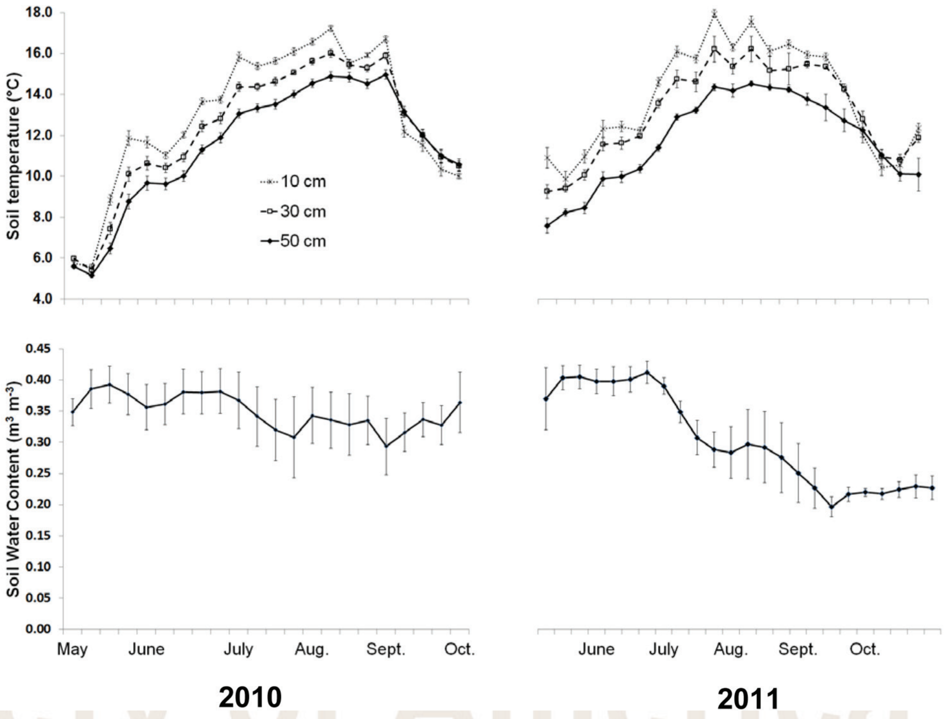

Fig. 1. Mean weekly soil temperature by measurement depth (top panels) and volumetric soil water content at 30 cm (bottom panels) in uncut control areas across four sites in northeastern Minnesota. Error bars are the standard error among weekly means for each site (*n* = 4 for each week and depth).

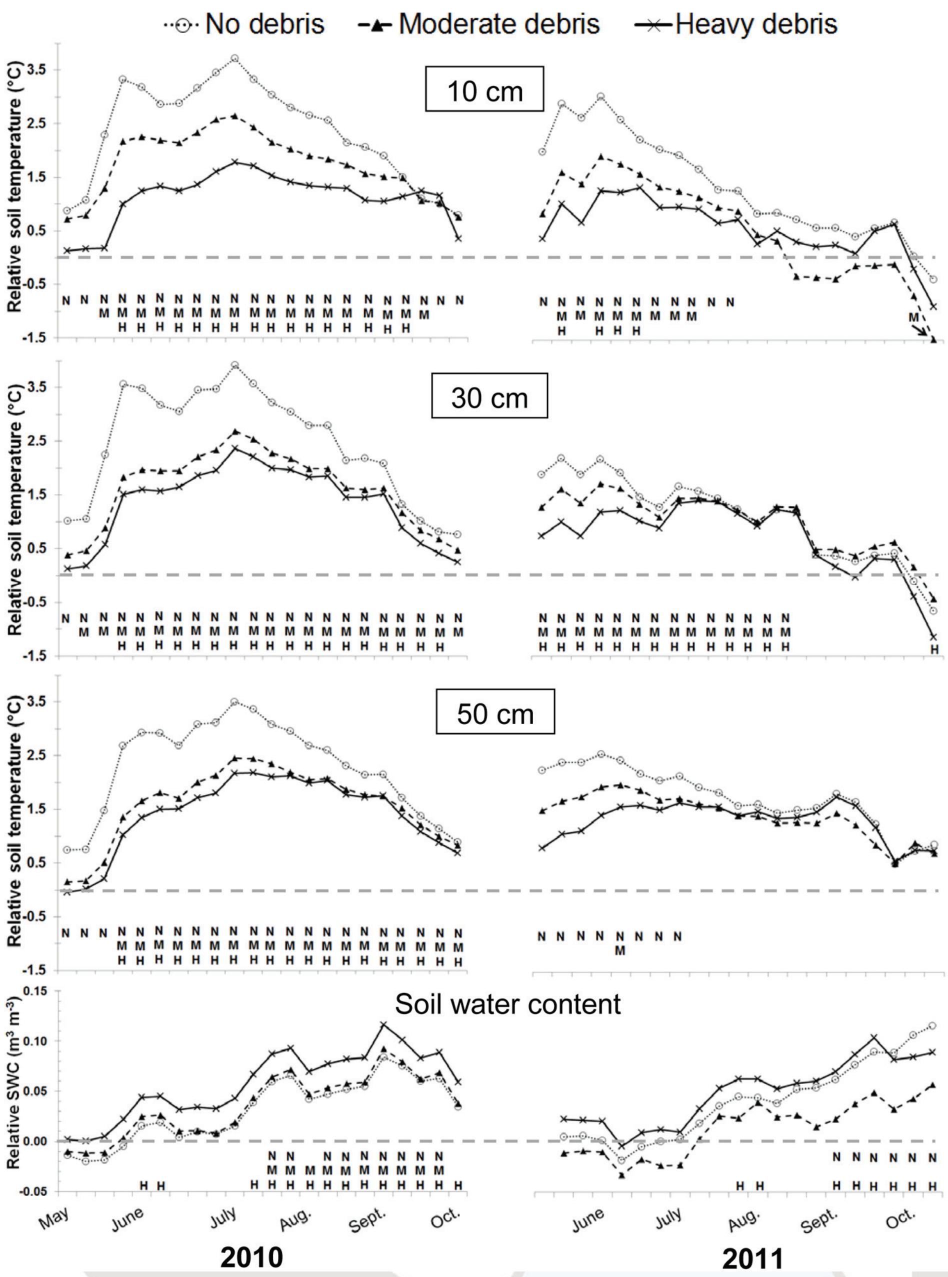

Fig. 2. Mean weekly soil temperature relative to uncut controls by soil depth and logging debris cover at four sites in northeastern Minnesota. Soil water content measured at a 30-cm depth is shown in bottom panels. All values are expressed relative to those recorded in uncut forest. Letters under a given week indicate when a treatment value is significantly different from zero (N = none, M = moderate, H = heavy).

depth was 16.0 and 16.1°C in 2010 and 2011, and at a 50-cm depth was 15.0 and 14.4°C in 2010 and 2011.

Effects of Harvesting on Soil Temperature and Water Content

In each year of study, soil temperatures at each measurement depth were significantly greater than those in uncut forest in some part of the growing season (Fig. 2). Increases in soil temperature following harvesting were more often significant and greater in magnitude in 2010 than in 2011 at all depths and generally peaked later in the growing season in 2010 compared to 2011. Temperatures in uncut forest followed similar seasonal patterns to those in harvest areas, but SWC patterns between harvested and uncut areas diverged (data not shown). Higher SWC occurred after harvesting relative to uncut forest, with the amount increasing throughout the growing season due to greater SWC depletion in uncut forest (data not shown).

Effects of Logging Debris Abundance on Soil Temperature and Water Content

There were significant main effects of debris abundance on soil temperature at each measurement depth in 2010, where the absence of debris caused significantly higher soil temperature compared to those treatments where it was present. In that year, growing season soil temperature was on average 0.9 (SE = 0.2), 1.0 (SE = 0.2), and 0.8°C (SE = 0.2) greater when debris was absent for the 10-, 30-, and 50-cm depths, respectively. Moderate amounts of debris also had consistently greater increases in soil temperature compared to heavy amounts at every measurement depth in 2010, but differences were only significant at a 10-cm depth (mean 0.63°C, SE = 0.26). Similar patterns were observed on the first half of the growing season in 2011, but differences among treatments were not significant at any depth (Table 2). However, increases in the no debris treatment at a 50-cm depth were significantly different from zero during 2011 but not when debris was present. There was no effect of woody debris treatment on SWC in either year (Table 2).

DISCUSSION

In temperate regions, soil temperature generally increases during the growing season following forest harvesting. Increased soil temperature is a result of increased soil radiation reaching the soil surface due to loss of the forest canopy, which varies depending on latitude, climate, and post-harvest conditions. The increases observed here at a 10-cm depth in both 2010 and 2011 are comparable to those observed in other studies following harvesting with similar climate. Temperature increases usually occur for at least 2 yr following harvesting and range from 1 to 6°C at shallow soil depths (<10 cm) (Edwards and Ross-Todd, 1983; Fleming et al., 2006; Holmes and Zak, 1999; Laporte et al., 2003).

The effect of logging debris on soil temperature measured in this study is almost assuredly due to its physical presence, which shades the soil surface and reduces solar radiation input. Other studies involving logging debris manipulation have also observed increased soil temperature with greater logging debris removal (Edwards and Ross-Todd, 1983; Zabowski et al., 2000; Devine and Harrington, 2007; Fleming et al., 2006), although the effect has not been observed in some boreal regions (Belleau et al., 2006). These studies and others have almost uniformly limited measurement of soil temperature following forest harvesting to surface soil (<10 cm). The results presented here indicate that the influence of logging debris abundance on surficial soil temperature can extend at least to a 50-cm soil depth. Indeed, the similarity of differences between the absence and presence of logging debris at all depths suggests that effects could occur at greater depths than measured here. Propagation of these temperature effects to such depths may be a result of the combination of relatively fine textured soils at these sites and the humid climate (i.e., high soil moisture), which would increase soil thermal conductivity (Brady and Weil, 2008).

The magnitude and significance of debris effects on soil temperature were greatest early in the growing season of the first year and not apparent in the latter portion of the second year after harvesting. This reduction in harvesting and treatment effects is likely predominantly due to vigorous aspen growth, which shaded the soil surface (pers. obs.). At these sites, vegetation regeneration occurred in the first year after harvest, but did not obtain full occupancy and cover the soil surface until part way into the second growing season when differences among debris treatments were no longer apparent (Fig. 2). Others have also noted the modifying effect of vegetation on the temperature response to logging debris abundance (Harrington et al., 2013) and the role that early revegetation plays in reducing harvest-induced increases in soil temperature (Vitousek and Melillo, 1979; Carlson and Groot, 1997). Differences in soil moisture between years may have also contributed to the lack of treatment effect in 2011. In that year, SWC was on average 15% lower than 2010 (Fig. 1), which could have reduced heat conduction and diminished any effect of debris at the soil surface.

Logging debris has been shown to conserve SWC via a mulch effect (Devine and Harrington, 2007; Law and Kolb, 2007; O'Connell et al., 2004) or have no detectable effect on SWC (McInnis and Roberts, 1995). The lack of any significant treatment effect at these sites may be due to low statistical power because SWC was consistently higher in the heavy debris treatment relative to other treatments in both years of the study (Fig. 2). However, when mulch effects have been observed, they usually were found at shallow soil depths (~10 cm) and in Mediterranean climates (Devine and Harrington, 2007; Law and Kolb, 2007). In cool humid regions such as the upper Midwest, precipitation throughout the growing season probably shrouds any mulch effect of logging debris on SWC.

Table 2. F-statistic probabilities from ANOVA of effects of logging debris manipulation on soil temperature by soil depth and soil water content at a 30-cm depth by year across the four study sites.

Effect	Soil temperature			Soil water content
	10 cm	30 cm	50 cm	
2010				
Debris treatment	0.009	0.006	0.035	0.169
Week	<0.001	<0.001	<0.001	<0.001
Debris × week	0.291	0.411	0.056	1.000
2011				
Debris treatment	0.190	0.117	0.873	0.436
Week	<0.001	<0.001	<0.001	<0.001
Debris × week	0.495	0.980	1.000	1.000

Implications to Management and Research

The relatively short-lived effect of logging debris on soil temperature at these sites suggests that soil processes influenced by temperature will not be modified to any great extent by the amount of logging-debris remaining after harvesting. Given that the short duration of effect was largely due to vigorous aspen suckering and growth, vegetative response to harvesting and management practices (e.g., weed control strategy) will control the extent to which logging debris modifies the soil microenvironment. In situations where vegetation cover is low following harvest, logging debris abundance will likely play a larger role in mediation of soil processes controlled by the soil microenvironment (e.g., Slesak et al., 2010). Alternatively, logging debris abundance could modify the initial vegetation response and indirectly influence the soil microenvironment because logging debris and soil temperature are known factors that influence vegetation establishment (Frey et al., 2003; Harrington and Schoenholtz, 2010; Thiffault et al., 2011).

The significant increases observed in soil temperature to at least a 50-cm depth strengthens the argument for deeper (>30 cm) soil sampling following experimental manipulation (Harrison et al., 2011) and also casts doubt on the suitability of many previous assessments related to soil elemental pool changes following intensive forest management (e.g., greater biomass removal, complete weed control, etc.) when only shallow soil was sampled. For example, early findings from the LTSP network (Powers et al., 2005) have demonstrated the role that root decomposition plays in changes in soil C and nutrient pools following harvesting, which is heavily dependent on soil temperature (Chen et al., 2000). Further, Diochon et al. (2009) concluded that changes in total C pools in a harvesting chronosequence were driven by changes at depths greater than 20 cm, attributing the change to greater C mineralization in deeper soil. Changes in soil pools of C and nutrients may be more common in deep soils than previously thought due to greater temperature sensitivity of microbial activity compared to surface soils (Davidson and Janssens, 2006; Fierer et al., 2003).

The logging debris mass of the moderate (45 Mg ha^{-1}) and heavy (71 Mg ha^{-1}) treatments used in this study are similar to that remaining after operational whole tree and bole only harvests, respectively (Klockow et al., 2013). This similarity, in combination with a range of site conditions representative of northeast Minnesota, provides a level of inference applicable to management in that region. However, in operational settings the logging debris levels used in this study will likely occur in a mosaic of conditions across the harvest area (Slesak et al., 2011; Eisenbies et al., 2005). Given this, the net effect of logging debris abundance on soil temperature at the scale of the harvest site is unclear. Scaling of temperature response to harvesting and experimental manipulation, and the response of biologic processes influenced by it, will continue to be an area of challenge for application of these and other research findings.

CONCLUSIONS

Increased logging debris removal can increase soil temperature following harvesting in northeastern Minnesota, but the magnitude and duration of the effect is largely dependent on the amount of vegetation present in the early years of stand establishment. In situations where vegetation is able to rapidly recolonize a site (e.g., regeneration from coppice or suckering, no weed control, etc.), the effect of logging debris removal on soil temperature and the processes influenced by it will likely be short-lived. At these sites, if any longer-term effects of logging debris removal on soil processes occur, they will likely be associated with a reduction in nutrient inputs rather than microenvironment modification because of the transient effects of debris on microclimate.

A strong case can be made for deeper soil sampling to assess nutrient and C pools than commonly occurs in experimental studies and monitoring efforts based on (i) the increase in soil temperature that occurs in deeper soil following harvesting, (ii) the fundamental role that temperature plays in biologically-mediated processes, and (iii) the potential for greater temperature sensitivity in deep soils. In situations where soil properties, climate, and vegetative conditions are favorable to increased radiation inputs and heat conduction, soil sampling schemes should be designed to account for potential change in soil C and nutrient pools following harvesting at greater depths than commonly assessed.

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