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Forest soils contain a substantial portion of global terrestrial carbon stores. Forest management can influence the soil carbon pool and how soil organic matter functions. The long-term productivity of forests is an ongoing goal where land managers utilize biomass and timber. A site-specific understanding of intensively managed forests can ensure achievements of this goal. Within a managed forest in the western Oregon Cascades, treatments were installed to harvest three levels of biomass, with and without compaction, to monitor impacts to growing season characteristics of Douglas-fir roots. Soil temperature and moisture conditions were continuously monitored from 10 to 100cm depth, and three sources of soil respiration were measured monthly for two years immediately following treatments. Negligible differences in the length of growing season were detected, however the daily-10cm average, maximum, and diel flux of soil temperatures significantly increased by 1.5, 2.7, and 2.5°C, respectively, with increasing biomass harvesting. Organic matter removal strongly influenced growing season soil characteristics down to a 100cm depth. Diel temperature flux at 100cm for the least and most impacted treatments were 5.7 and 7.8°C, respectively, a magnitude equivalent to seasonal shifts in soil temperature at the same depth. In spite of favorable temperature and moisture conditions with less organic matter left on the surface, soil respiration was moderately higher on bole only harvests. A priming effect may explain why these sites with more surface biomass, although significantly cooler, had the highest rates of soil respiration. The combination of increased temperatures throughout the soil profile after forest harvesting, and higher additions of dissolved organic matter from forest residuals, could have an impact on deep soil carbon. These responses have implications for long-term nutrient cycling that have yet to be elucidated for deeper soils; but this should be considered when land managers are planning forest fertilization and rotation lengths.

Response of Soil Temperature, Moisture, and Respiration Two Years Following Intensive Organic Matter and Compaction Manipulations in Oregon Cascade Forests

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Adrian Carlos Gallo, Author

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1. INTRODUCTION

1.1. Carbon Cycling in the Environment

Understanding how greenhouse gasses move through the global system is imperative in order for scientists to inform policy makers of potential climate change scenarios. The month of July 2016 was the hottest July since record keeping began in the year 1880, and current projections show global temperatures and greenhouse gas emissions will continue their upward trend (IPCC, 2013a; b; NOAA, 2016). Global climate change models use a variety of data inputs, however the potential carbon (C) feedbacks of the biosphere-C release that contributes to atmospheric CO_2 is a serious concern of unknown magnitude (Schmidt et al., 2011; IPCC, 2013b). The size of the Soil Organic Carbon (SOC) pool is impressive (storing three times more C than vegetation and atmosphere combined), but rates of C exchange are needed for improved global climate change predictions because small changes to these rates can lead to large impacts on global C cycles (Jobbágy and Jackson, 2000; Davidson and Janssens, 2006; Tamocai et al., 2009; Stockmann et al., 2013; Lehmann and Kleber, 2015).

The primary mechanism of transfer from SOC to atmospheric C is soil respiration (Rs). In the context of this thesis Rs is meant to include the carbon dioxide (CO_2) contributions from soil microbes, roots, and small a quantity from abiotic chemical oxidation (Raich and Schlesinger, 1992). There is substantial research to confirm soil temperature, moisture, and organic matter content are driving factors in SOC cycling (Lloyd and Taylor, 1994; Davidson and Janssens, 2006; Curiel Yuste et al., 2007). However, Rs is one of the least understood processes of the global C cycle (Trumbore, 2006; Bond-Lamberty and Thomson, 2010).

The spatial and temporal patterns of soil moisture, soil temperature, and their associated plant communities have a considerable imprint on rates of soil respiration (Raich and Schlesinger, 1992; Schlesinger and Andrews, 2000). Within the temperature range of terrestrial ecosystem processes, the response in soil respiration to higher soil temperatures follows a non-linear convex relationship (Sierra et al., 2011). Diel flux, defined as the the maximum and minimum recorded temperature over a 24-hour period, and soil temperature variation, have been found to be as important a measure as average temperature when considering decomposition processes over the long term (Sierra et al., 2011). Soil moisture is commonly a limiting factor in potential productivity and heavily relied on especially in drier ecosystems (Davidson et al., 1998). Harvesting trees removes vegetation changing the inputs of organic matter on site, the removal of timber significantly alters the hydrology of the area, and removing trees influences the thermal regime of the hill slope or site in question (Binkley and Fisher, 2013). All three of these factors interact with each other and significantly influence which forms of carbon, and how quickly that carbon cycles through the process of Rs.

1.2. Forest Management Impacts on Soil Carbon

Forests cover approximately one-third of earth's landmass, forest *soils* also contain a majority of the terrestrial C, and are actively managed ecosystems making them critical to our understanding of how the SOC pool responds to long-term intensive forest management strategies (Nave et al., 2010; Binkley and Fisher, 2013). The combination of an increased demand for forest products (such as wood and biofuels), and diminished land area available for fiber production, have led to the expansion of intensively managed forests (Food and Agriculture Organization, 2006). These plantations have shorter time periods between forest harvests and lead to greater nutrient removals per unit time and more acute physical site impacts. This has caused many to question the long-term sustainability aspects of short rotations and the potential implications it could have for nutrient limitations to successive rotations (Worrell and Hampson, 1997; Johnson and Curtis, 2001; Burger, 2009; Perakis et al., 2013; Mainwaring et al., 2014).

Declines in long-term potential forest productivity due to active management can generally be attributed to negative impacts on two ecosystem properties: site organic matter content and soil porosity (Powers, 1990). Harvest activities can compact soils decreasing total soil porosity. This negatively affects major physical process such as water infiltration rates, root growth potential, and oxygen diffusion gradients. Harvesting timber removes biomass and often redistributes site organic matter; these disturbances can increase topsoil erosion potential, decrease microbial decomposition rates, and diminish long-term nutrient stores. Within the constraints of climate, soil porosity and site organic matter content determine major ecosystem properties such as water holding capacity, gas exchange, and the site's potential net primary productivity (Powers, 1990, 2006). There is no question that inappropriate forest management can have a measureable impact on soil carbon resources. Under appropriate management strategies and an understanding of site-specific soil resources, most losses in mineral soil carbon can be ameliorated (Nave et al., 2010). There are many organic matter manipulation studies across the globe, however in North America the Long-Term Soil Productivity (LTSP) network is the most prevalent in relation to a forest management focus, so the experimental design was applied in this study.

1.3. Concepts of the Long-Term Soil Productivity (LTSP) Network

The findings discussed below come after a comprehensive literature review that lead to the formation of a national-wide Long-term Soil Productivity (LTSP) network in the late 1980's. The objectives of this project were to (1) gain site-specific knowledge, (2) support soil-quality monitoring techniques, and (3) understand the connections between soil properties and long-term forest management practices (Powers, 1990). To obtain a history of “the most broadly reviewed study plan [LTSP network] ever produced by the USDA Forest Service.” (Powers, 2006), the author suggests visiting Powers, 1990, 2006; Powers and Ayers, 1995, as well as a comprehensive list of research findings contained within Page-Dumroese, 2010. The following is a very narrow characterization of this tremendous project, and is not meant to encapsulate the full scope or output from this ongoing international research endeavor.

1.3.1. LTSP Experimental Design

Site organic matter and soil porosity manipulations designed for the LTSP network were chosen to encapsulate the full range of potential management strategies, while simultaneously producing successive levels of nutrient removals disproportionate to biomass removals (Table 1) (Powers et al., 2005). For example, in a mature forest the tree bole contains the majority of the site's above ground organic matter content, but less than one-third of the nitrogen content (Powers et al., 2005). Three levels for each main effect (site organic matter and soil porosity) produced a 3x3 factorial with nine individual treatment combinations replicated across Holdridge Life Zones on forest types that were likely suitable for active forest management (Powers et al., 2005). The treatment descriptions for this study follow the larger study design (Table 1):

BO: Bole Only harvest, no compaction - Bole only harvest to a saw log top with all limbs and tops to remain unless variation in remaining biomass is high across the whole site, then a standardized mass of biomass per ha of material will be left on the plots. Trees hand-felled towards plot centerline, limbed in place, and cable yarded to transport away from plots.

BOC: Bole only harvest, with compaction - Bole only harvest to a saw log top with all limbs and tops to remain unless variation in remaining biomass is high across the whole site, then a standardized mass of biomass per ha of material will be left on the plots. Trees harvested using ground-based methods, limbed in place, and additional compaction used large machinery to maximize bulk density.

TT: Total tree harvest, no compaction - Total tree harvest where ~75% of limb and top material is removed along with the bole. Remaining material will be dispersed within plots. Trees hand-felled towards plot perimeters and cable yarded to transport away from plots. Limbed off-plot, 25% of broken branches and tops allowed to remain on plots.

TTC: Total tree harvest, with compaction - Total-tree type harvest where ~75% of limb and top material is removed along with the bole. Remaining material will be dispersed within plots. Trees harvested using ground-based methods, limbed off-plot, and additional compaction used large machinery to maximize bulk density.

TTP: Total tree harvest plus forest floor removal with compaction - Total tree harvest where >90% of limb and top material is removed along with the bole. Legacy wood, forest floor are removed but stumps remain. Trees harvested using ground-based methods with all surface biomass removed from soil surface. Additional compaction used large machinery to maximize bulk density.

1.3.2. Modern Developments from the LTSP Network

The LTSP network is the largest coordinated effort on testing sustainable forest productivity with more than 100 installations focused on pulse disturbances and their effects. However, as of 2006 only 26 of these sites have reached 10 growing seasons (Powers et al., 2005). It is important to note 10 years still reflects a relatively young study compared to the 80-year life expectancy of this program, and canopy closure has not been reached which is when site resources are at the highest demands. For a more detailed assessment of individual geographic behaviors, please see Powers et al. (2004, 2005, 2013), Page-dumroese et al., (2006), and Ponder et al., (2012). The following discussion are only general trends across the 26 sites that reached a decade of observations.

Soil C, N, and Tree Productivity

Even after a decade following complete removal of boles, harvest residues, O-horizon, and coarse woody debris (total tree plus of TTP), there was “no discernable, unambiguous impact on productivity [tree growth] … despite sizeable reductions in [forest floor] soil C or N availability” (Powers et al., 2005). Total tree plus (TTP) caused decreases in surface (0-10 cm) potential N availability, soil C and nitrogen content; however there was a paradoxical increase in soil C for the bole only (BO; removal of boles) and total tree (TT; removal of boles and harvest residues) treatments compared to pre-harvest values.

Soil texture played a key role in the response of tree productivity to compaction. Coarse-textured soils had an increase is productivity in response to compaction; this is attributed to increased water holding capacity of compacted sands. Compaction can also increase thermal conductivity in soils allowing them to warm with less thermal energy (Hillel, 2004). There appears to be either no difference, or a small increase in soil C content from compacted (C1) to non-compacted (C0 treatments) down to the 30cm mineral soil depth. Differences in soil bulk density between C1 and C2 were small, therefore this study attempts to bracket the impacts of compaction implementing treatments more similar to C2 of the wider LTSP network. One of the main objectives of the LTSP network was to enhance site-specific knowledge, and for the purposes of this thesis, special attention will be paid to the Pacific Northwest (PNW).

Soil Temperature in the PNW

Soil temperature acts to mediate the level of potential activity of soil microbes that produce available nutrients for plants, and the quantity of surface residue controls the soil heating potential. As many other researchers have found in the PNW, soil temperatures increase as more surface biomass is removed, however these results have been limited to surface mineral soils (0-20 cm) (Roberts et al., 2005; Ares et al., 2007; Devine and Harrington, 2007; Slesak et al., 2011). Similar studies in Washington and Oregon found the average increase in soil temperature of TTP treatments were between 0.6-3.0°C (5-10 cm) higher than BO during the growing season (Roberts et al., 2005; Slesak et al., 2010). For a Washington LTSP site, seedling height, diameter, and volume growth were largest in TTP and researchers posit this was in part due to higher soil temperatures when soil moisture was not limiting (Roberts et al., 2005).

Soil Moisture in the PNW

Plants require water for biomass production, but water also provides a transport medium for nutrients to move to roots and microorganisms. Surface biomass is a physical barrier to light and helps limit soil evaporative losses;

however it can also act as a sponge limiting how much precipitation is transferred to mineral soil by infiltration (Jury and Horton, 2004). Interception by the O-horizon and slash is often described as the “mulch effect”, but patterns are highly dependent on the local climate. The LTSP sites in the PNW generally show growing season soil moisture to be negatively correlated with increasing biomass coverage; the growing season volumetric water content (VWC) was between 2-4% lower in BO compared to TTP (Roberts et al., 2005; Slesak et al., 2010). Due to the sensitivity of seedlings to soil moisture limitations, even a small change in below ground access to water and nutrients can impact above ground tree productivity (Roberts et al., 2005). There is also strong evidence that soil moisture content, and its interplay with soil oxygen concentrations, is another main driving factor in the behavior and rate of soil respiration (Skopp et al., 1990; Curiel Yuste et al., 2007; Moyano et al., 2013).

Soil Respiration in the PNW

The breakdown of plant and animal debris produces smaller fragments of organic matter, nutrients, and carbon in the gaseous form of CO_2. This relationship allows researchers to use soil respiration (Rs) as a proxy for mineralization rates and potential nutrient cycling in soil (Wardle, 2002; Coleman et al., 2004). Similar to patterns in soil temperature, Rs was negatively correlated with biomass left on site during the growing season (Slesak et al., 2010). This study also found the largest increase in soil C content in TTP treatment over two years; this was attributed to higher soil temperature accelerating the breakdown of roots that assimilate into mineral soil C. It is important to note that intermediate retention of logging debris (similar to TT) and vegetation control treatments did not show significant differences from either TTP or BO Rs responses. Soil moisture, temperature, and organic matter inputs govern the patterns of Rs and integrating these aspects will provide a better understanding of carbon dynamics in forest ecosystems.

1.4. Objectives

The goal of this research is to investigate the roles of harvest, forest harvest residues, and the forest floor on soil temperature, moisture, and respiration in an Oregon Douglas-fir stand where experimental treatments were applied.

The specific objectives were to determine (1) if soil temperature and moisture patterns were sufficiently different throughout the profile to change the growing season characteristics, and (2) if changes in soil temperature and moisture can explain patterns in soil respiration over the first two years immediately following treatment implementation.

We hypothesize (1) Increasing the level of organic matter removal will promote higher soil temperatures and longer growing seasons, (2) compaction will result in higher soil temperature and soil moisture lengthening the growing season, and (3) treatments with the highest soil temperature and moisture, will have the highest rates of soil respiration.

2. METHODS

2.1. Site Description

The study site is located approximately 30km east of Eugene, Oregon along the western side of the Cascades (Figure 1). The geology of the area is composed of a heterogeneous assemblage of tuffaceous sedimentary rocks with significant contributions of basaltic andesite and flow breccias between 32-17 million years old (Walter and Duncan, 1989). The soils of the area are composed of the Peavine, Kinney, and Cumley series; however they are best represented by the Kinney series described as Fine-loamy, isotic, mesic Andic Humudepts with clay and clay loam textural classes to 100cm depth (Soil Survey Staff, 2015). The area is between 600-660m elevation, has a simple convex-convex slope shape topography with approximately 15-25% slope traversing the upper to mid-backslope hill positions. The region is characterized as a Mediterranean climate with warm dry summers and cool wet winters. Mean annual temperature and precipitation was 11.4°C and 170cm respectively for the period between 1981-2010 (Table 2) (Wang et al., 2016).During the two years of observation, the mean annual temperature was 10°C with a mean April-October air temperature of 16°C (Figure 2). Approximately 130-140cm of precipitation fell over each water year with a majority of precipitation falling from November to May. During the winter of 2014-2015 there was approximately 15cm of precipitation in the form of snow, however there was no other period of snow-fall recorded for the remainder of the study period. The surrounding area was logged in the mid to late 1950's with an unconfirmed broadcast burn post-harvest; Douglas-fir was allowed to naturally regenerate, and a thinning was implemented at mid-rotation (S. Holub Personal Communication).

2.2. Scope of Inference

Other LTSP locations have been installed in the Pacific Northwest (PNW) (Ares et al., 2007; Harrington and Schoenholtz, 2010); however this geographic location was chosen to encompass the lower range of the precipitation gradient for intensively managed Douglas-fir. The treated site needed to satisfy some operational and practical constraints required for a study of this size, they include: (1) within the vicinity of Cottage Grove/Springfield, Oregon, (2) uniform soils with low coarse fragment percentage (rocks), (3) an area large enough to accompany 30 one-acre plots with appropriate operational buffers between plots for equipment access, (4) and were harvest units from Weyerhaeuser's 2013 harvest plan. The scope of inference for this thesis is limited to one PNW Douglas-fir stand on Weyerhaeuser land grown to a harvest age of ~55 years.

2.3. Experimental Design

Plots were delineated with soils sampled using 25-points per plot prior to treatment application and run for elemental analysis to ensure similar site characteristics (Table 4). Treatments were installed in a randomized complete block design that were assigned to one of four blocks based on soil N content of the upper 100cm. Plots were rotated 9 degrees to align with site topography, allow for equipment access, and overall operational efficiency. Each plot is one-acre square in area, with an internal area of ½ acre used as the measurement plot to limit any buffer effects. Each plot is considered the unit of observation for analysis, and each treatment consists of four replicates blocked on soil nitrogen content.

Harvesting concluded during the summer of 2013. The area was fenced to prevent herbivore activity on the treatment area and planted with Douglas-fir plug+1 0.7-0.9cm double graded early in 2014. The area was sprayed every year beginning in 2014 using Velpar, Transline, and Glyphosate to keep competing vegetation below 30% coverage (Personal Communication N. Meehan). The unharvested forest reference plots (also four replicates) were added opportunistically and located immediately adjacent to the treated area. Although these reference plots did not undergo the same level of pre-harvest scrutiny, the topography, soils, and vegetation were reasonably similar to those found on the treated areas.

2.4. Biomass Removal and Compaction Treatments

This is considered an ‘affiliate’ LTSP site because all nine-treatments are not present (Table 1, Table 3). The compaction treatment on this site most closely mimics the C2 treatment from previous studies and attempted to reach the maximum possible Bulk Density (D_b)(Table 4). The BO1-C0 treatment was considered unrealistic for normal forest management practices and was not included. Due to these exclusions, this is an incomplete-factorial matrix of treatment combinations. There were seven treatments installed on the sites along with the unharvested forest reference (Table 3). Two of the treatments (TTC and TTP) were replicated on the site and will be used as a future fertilization experiment. For the purposes of this thesis we will not consider the future fertilization plots as part of the analysis.

2.5. Instrumentation and Observation Frequency

Temperature and moisture data loggers

All plots including Reference (REF) have soil moisture and temperature probes installed at 10, 20, 30, and 100cm depth, as well as air temperature and relative humidity sensors 15cm above mineral soil surface at the approximate plot centers. Soil moisture is measured on a volumetric basis (Volumetric Water Content - VWC) and has an accuracy of ±3%, temperature has an accuracy of 0.1°C (Decagon Devices, 2015). Weather stations were installed at the highest point of the treated area, and along the midpoint of the REF plots transect. Weather stations record wind speed, direction, relative humidity, air temperature, solar radiation, and leaf area wetness. All data were logged hourly, and were remotely accessible to limit any equipment malfunctions or missing data.

Soil moisture and temperature data were averaged to the day-scale, and daily maximum temperature was taken as the maximum for a given day. The diel temperature flux was calculated as the difference between the maximum and minimum temperature values within a single day. These variable will be assessed over the growing season, which required the daily average soil temperature and moisture to exceed 11°C and 19%VWC respectively (see section 2.5.1).

Soil Respiration

The root exclusion method, using PVC tubes to exclude roots, was used to partition soil respiration into bulk soil respiration and microbial respiration (Hanson et al., 2000). All observations were done with a Li-COR 8100A, using suggested base timing settings optimized for the 10cm survey chamber (LI-COR Biogeosciences, 2012a; b). The O-horizon respiration was measured by placing the chamber directly on the O-horizon that included woody debris <2mm in diameter and <10cm in length. PVC collars were installed in December of 2013 to allow enough time after disturbance before the first observation. Bulk soil respiration PVC collars were installed 2cm in the mineral surface, and microbial PVC collars were installed 30cm into the mineral soil. The underlying assumption for the microbial collar is that the rooting zone is only 30cm deep; this is acceptable for the treated areas, however the well-established trees and understory vegetation on REF plots likely have active rooting systems well below 30cm. Each plot was split into three random nests (i.e. pseudo-replicates) and each nest included a bulk, microbial, and O-horizon observation location that were repeatedly measured on monthly intervals for two years. However subsequent analyses are only focused on the growing season (April-October) to focus on the months when differences were expected to be greatest. Each observation period required two days in order to measure all plots, these were done between the hours of 05:00 and 17:00 on successive days during each month.

Due to the high degree of variability in soil respiration (space and time), the *average* (from three pseudo-replicates) respiration from each plot-source combination was used as the response variable. This was done primarily to minimize the influence of missing or erroneous soil respiration observations. For example, summer O-horizon observations reported negative values if winds were too high, and winter microbial observations we often accompanied by flooded

PVC tubes producing very little if any measureable CO_2. If any observation appeared to be inaccurate in the field, the source was immediately re-measured two additional times (triplicate observations) and the median value was used for further data aggregation. The impact on soil carbon pools are directly affected by the rates of soil respiration, and microbial activity has been correlated to mineralization rates necessary to understand nutrient dynamics (Coleman et al., 2004). By using the average soil respiration we believe an adequate trend can be developed for soil carbon stores, and site-specific impact to nutrient cycling.

2.5.1. Growing Season Characteristics - A Biologic Approach

The term 'growing season' is highly dependent on the hemisphere, plant species, and climatic variation within and between years. Rather than use an arbitrary 6-month period when air temperatures gradually differ from winter seasons, we use biologically important moisture and temperature thresholds for our climate and species of interest. Douglas-fir (DF) roots in the PNW do not become active until the subsoil reaches at least 10°C (Lopushinsky, 1990; Lavender and Hermann, 2014). The estimated permanent wilting point (PWP) for clay loam textures is approximately 18% VWC based on VWC-matric potential relationship curves (Saxton and Rawls, 2006). In order for any day to be considered part of the 'growing season', the average daily values for individual plots needed to exceed 11°C and 19% VWC to ensure it was warm and moist enough to perform necessary biologic functions. Growing season length was calculated individually for the 10, 20, 30, and 100cm depths.

2.6. Statistical Design

Linear mixed-effect models were used to fit all data; comparisons of means were done using paired two-sided t-tests in R statistical software (v.3.3) (Bates, 2005; Zurr et al., 2008; Pinheiro J et al., 2014; R Core Team, 2014). All models included plots nested within blocks as random effects; both year and treatment were fixed effects. Average soil respiration analysis required the source (O-horizon, bulk, and microbial) to be represented as a factor.

Furthermore an autoregressive function was fit to account for the repeated measures covariance matrix and minimize the influence of seasonality on soil respiration. All comparisons use the years of observation as a fixed effect; no attempt was made to differentiate effects between years. Treatments exhibited heteroscedastic behavior with all response variables; groups were allowed have non-constant variances in order to meet basic model assumptions of normality. A family-wise Bonferroni adjustment, corrected to $\alpha=0.10$, was used to assess statistical significance for all tests.

Biologic significance required the difference in means to (1) satisfy statistical significance, and (2) their respective confidence intervals to be at least ±1day or ±1°C for each response variable in question. Soil respiration comparisons where the difference in means was greater than 0 were interpreted as biologically significant. The biologic temperature threshold used for this analysis is derived from soil enzyme activities, specifically the maximum potential rate of hydrolytic enzyme activity, because they have been shown to have significant differences with as little as a 1°C in soil temperature (Stone et al., 2012). The one-day biologic difference for growing season was chosen based on the methodology used by Lopushinsky (1990) which also used a single day as evidence of true difference in response. Biologic significance for the overall F-tests of main effects and interaction effects require (1) statistical significance, and (2) the $F_{critical}$ values to exceed 3.36 and 3.07 for 1,9 and 1,14 degrees of freedom respectively. Practical significance of tests on volumetric water content (VWC) requires (1) statistical significance, and (2) their respective confidence intervals to exceed the precision of the instrument (±3%) (Decagon Devices, 2015).

For the purposes of this thesis, any *significance* is equivalent to the more stringent *biologic* or *practical significance* and all statistical analysis are constrained within the biologically defined growing season unless otherwise noted. Due to the partial factorial design of the installed treatments, there are two approaches used to compare effects:

Main Effects

These are used to test the levels of organic matter removal and compaction using only a full-factorial 2x2 matrix (BO, BOC, TT, TTC). The interaction between organic matter removal and compaction were assessed with an overall F-tests and the main effect of organic matter removal is the difference between Bole Only (BO, BOC) and Total Tree (TT, TTC) removal treatments. The main effect of compaction is the difference between treatments without compaction (BO, TT) to those with compaction (BOC, TOC).

Treatment Effects

These pertain to all instrumented plots (BO, BOC, TT, TTC, TTP, REF) in an incomplete-factorial matrix to test the additive effects of (1) forest harvesting BO-REF), (2) harvest residue and forest floor removal after harvesting keeping compaction constant (BOC-TTP), and (3) forest floor removal after harvesting keeping compaction constant (TTC-TTP). Note the direction of comparisons are always the difference between the less intensive to more intensive treatment(s) and the sign (±) of coefficients reflect this directionality.

3. RESULTS

I examined soil temperature, moisture, and respiration over two years. To isolate the pertinent portion of the year for these measurements we determined the beginning and end of the growing season using thresholds in soil moisture and temperature. Most variables were analyzed over the biologically defined growing period to examine the effects of these treatments on the growing conditions for trees. Average monthly soil respiration was also examined over the entire two years to determine the effect of the treatments on soil carbon. I performed two kinds of statistical tests on the response variables due to the incomplete nature of the experimental design. The ‘Main Effects’ include the 2x2 factorial of (1) bole only (BO, BOC) vs total tree (TT, TTC) harvesting, (2) no compaction (BO, TT) vs compaction (BOC, TTC) treatments, and (3) their interaction. Finally, the ‘Treatment Effects’ compare specific treatment combinations using the difference in means between (1) BO-REF, (2) BOC-TTC, and (3) TTC-TTP.

3.1. Growing Season Length

There were obvious differences in soil temperature and moisture patterns over the two years of data collection (Figure 3, Figure 4). Nearly all treatments (“treatments” does not include the unharvested forest reference - REF), at all depths, accumulated 80-120 growing season days per year which is far less than the 180 days estimated by the May-October definition used by many in the PNW (e.g. Ares et al., 2007) (Figure 5).

There was strong evidence from overall F-tests the length of growing season from 10-30cm was significantly influenced by the level of organic matter removal (OM) (Table 5). Generally speaking, there was a trend of a slightly longer growing season with Total Tree Harvesting, however most comparisons were not robust enough to detect a biologically significant difference. The main effect of Total Tree Harvesting was only statistically significant at 30cm depth increasing the number of growing season by approximately 4.1 days (Table 6).

There were very few significant differences in growing season length between biomass harvesting treatments (Table 6). The additive effect of total tree harvesting and forest floor removal (BOC-TTP) increased the number of growing season days by approximately 8 days at 20cm depth (Table 6). The BO treatment had a significantly longer growing season compared to the forest reference (BO-REF) at all soil depths, averaging 27 more days, but up to 71 additional days at the 10cm depth (Table 6). The REF plots are sufficiently warm over a similar time period as the BO treatments, however the decrease in soil moisture due to understory vegetation and trees occurred relatively early in the summer months (Figure 4).

3.2. Average Soil Temperature

Increasing organic matter removal and compacting the soil generally showed a small positive increase in average soil temperature throughout the profile (Figure 6). There was very strong evidence that the main effect of organic matter removal (OM) significantly influenced the average temperature at all soil depths (Table 7). There was no evidence that the either the main effect of Compaction, or its interaction with organic matter removal (OM:Compaction), influenced the average soil temperature at any depth (Table 7). The main effect of Total Tree Harvest increased the daily average soil temperature approximately 1.3°C throughout the soil profile, however these differences were not biologically significant (Table 8).

Total tree and forest floor removal (BOC-TTP) had a significantly higher (+2.6°C) average daily growing season temperature at the 10-20cm depths compared to BOC treatments (Table 8). The additive effect of removing the forest floor (TTC-TTP) increased the average growing season temperature approximately +1.6°C from 10-20cm, however this was only statistically significant (Table 8). Deeper than 30cm, no significantly different temperatures were observed for any treatments (Table 8). The unharvested forest reference (REF) was on average 2.2°C cooler compared to bole only harvests (BO-REF) throughout the entire soil profile, suggesting the sunlight intercepted by the tree canopy and understory vegetation caused the soil to be between 1.2-3.5°C cooler down to 100cm (Table 8). It should be noted the magnitude of cooling from canopy and vegetation (BO-REF) overlaps with the amount of cooling observed from the main effect of Total Tree Harvest (0.6-2.8°C) (Table 8). This suggests maintaining an intact forest canopy cools the soil to the same extent as bole only harvesting where a high amount of residual forest slash is left on site.

3.3. Maximum Soil Temperature

Increasing organic matter removal and compacting the soil generally showed a positive increase in maximum soil temperature throughout the profile, although the effects were more evident near the surface (Figure 7). There was very strong evidence that the main effect of organic matter removal (OM) made a significant difference in maximum soil temperature at all depths during the growing season (Table 7). There was no evidence that the main effect of Compaction, nor the interaction (OM:Compaction), influenced the growing season maximum soil temperature (Table 7). The strength of evidence (F-statistics > $F_{critical}$) for the organic matter removal (OM) effect on maximum soil temperature remained strong from 0-30cm, but decreased at the 100cm depth while remaining biologically significant (Table 7). The main effect of Total Tree Harvesting, increased the maximum soil temperature by +2.5 and +2.3°C at 10 and 30cm depths respectively (Table 8).

There were consistent significant increases in maximum soil temperature at all depths as a result of forest floor removal (TTC-TTP) or total tree and forest floor removal (BOC-TTP) treatments (Table 8). The effect of total tree and forest floor removal (TTP) significantly increased the maximum soil temperature by +5.5°C at 10cm, and +2.9°C at 100cm with proportional increases at intermediate soil depths relative to BOC (Table 8). The additive effect of removing the forest floor (TTC-TTP) significantly increased the maximum soil temperature by +3.3°C and +2.9°C at 10 and 30cm depths respectively (Table 8).

Interestingly, the magnitude of temperature shift as a result of total tree harvesting and forest floor removal (BOC-TTP) was similar (albeit in the opposite direction) to the magnitude of changes observed the BO-REF comparison at 30 and 100cm depths (Table 8). This suggests the removal of harvest slash and forest floor (BOC-TTP), increased the daily maximum soil temperature to a greater extent than the act of harvesting itself (BO-REF) at these deeper soil depths.

3.4. Diurnal Soil Temperature Flux

There is very strong evidence that the effect of organic matter removal made a significant difference in diurnal soil temperature (the range of temperatures within a single day) at all depths during the growing season (Table 6). The main effect of total tree harvesting (TT) caused statistically significant increases (1.5-2.5°C) in diurnal temperatures across all depths, however only the 10cm depth provided enough evidence to be biologically significant (Table 7). There was no evidence that the main effect of compaction influenced the growing season diurnal soil temperature (Table 8).

There were consistent significant differences, between 2.5-4.5°C, in the growing season diurnal soil temperature for all treatment comparisons and across all depths (Table 8). The additive effect of removing forest residuals and forest floor (BOC-TTP) increased the diurnal soil temperature between 3.8-5.5°C for the 10-30cm soil depth. Furthermore, removing the forest floor (BOC-TTP) had a larger effect on diurnal soil temperature compared to removing the forest canopy and understory vegetation (BO-REF). Soil at 100cm depth had an average deviation in diurnal temperature of +2.5 and -2.9°C for the BO-REF and BOC-TTP treatment comparisons respectively (Table 8).

In summation, the main effect of total tree removal, significantly increased the diurnal flux by approximately 2.6°C at 10cm depth. Although this effect was only statistically significant from 20-30cm, it did not represent a biologically important difference. The increase in diurnal flux between treatments was greatest near the soil surface (10cm), representing an average increase of 5.5 and 3.4°C difference for the BOC-TTP and TTC-TTP comparisons respectively. The actual estimated diurnal temperature flux at 100cm depth are 1.7, 4.2, 5.7, 6.1, and 7.8°C for REF, BO, BOC, TTC, and TTP treatments respectively (Table 8; p-value<0.005 for all estimates on 14 degrees of freedom). Diel flux at deep soil depths (100cm) are generally thought to be close to zero, the TTC and TTP diel flux values approach shifts in temperature associated with seasonal-level changes.

3.5. Average Soil Moisture

There were no reliable significant differences in average soil moisture between any treatments or depths over the two years of data collection (Table 9; Figure 9). There is strong evidence that the years of observation were different from each other. There was very weak evidence that the main effects of compaction and organic matter removals differed from each other at the 30cm depth, however these data are called into question. Two soil moisture probes, both on TT treatments, experienced highly questionable readings over the two years of observation. They could not reasonably be dismissed as outliers as the range of soil moisture were within reason, however the behavior of the moisture readings suggest they may have been inconsistently influenced by air pockets. A pattern in malfunction could not be found and thus data were left unedited to maintain consistent time series records, and to maintain all appropriate levels of degrees of freedom for data analysis. The range of volumetric soil moisture experience at the study site remained within 30-50% for a majority of the year at all depths. The natural variation within treatments, and within blocks, was so wide we believe it is unlikely for any statistically robust method to be able to detect any differences for the immediate future .

There is a trend of decreasing VWC as more organic matter is removed, however, these are only consistent at the 10 and 20cm depths (Table 10). BOC and TTC had approximately 3.7% higher VWC at 10 and 20cm depth compared to TTP treatments, however this was not significant. We were able to detect an average increase of 7.7% VWC for BO treatments compared to REF at 20 and 30cm, however this was not biologically significant. There were no discernable differences found in VWC at 100cm depth (Table 10). In summation, the only significant result was the main effect of total tree harvesting at 30cm depth (Table 10), however the author cautions placing too much emphasis on this result.

3.6. Average Respiration of All Sources Over Two-Years

When considering bulk and microbial respiration sources, there is little evidence to support the inclusion of factors such as organic matter removal (OM), Compaction, and their interaction into this statistical analysis (Table 11; Figure 10, 11, 12). There is very strong evidence that for every source tested, at least one treatment is different over the entire observation period (intercept), and the years of observation were different from each other (Table 11). When considering the O-horizon respiration, there is significant evidence to suggest OM influences the average. Interestingly, the microbial source shows moderate evidence that the interaction of organic matter removal and compaction (OM:compaction) significantly influenced the average rates of respiration over the two year observation period (Table 11).

Total Tree Harvesting for the O-horizon and bulk soil show decreases in respiration with higher levels of organic matter removal (Table 12; Figure 10). The additive effect of Total Tree Harvesting significantly decreased average soil respiration by 0.43 and 0.44μmolCO_2 m^{-2} sec^{-1} when analyzing the microbial and O-horizon sources respectively (Table 12). The only discernable effect from the microbial sources of respiration show the retention of the forest canopy and understory, compared to a bole only without compaction (BO-REF), increases soil respiration by 2.8μmolCO_2 m^{-2} sec^{-1}

3.7. Growing Season Respiration of Bulk Soil

Based on the overall F-tests, there is strong evidence the main effect of treatment are different from each other, and that 10cm soil temperature had a significant influence on average soil respiration (Table 11). This relationship remained consistent even when using 20, 30, and 100cm soil temperature data (Figure 13), although the size of the temperature effect (F-statistic) decreased at the 100cm depth.

There were no clear effects on bulk soil respiration due to any of the treatment manipulations on the LTSP site (Table 12) (Figure 12). However, the growing season soil respiration of the unharvested forest reference plot (REF) respired between 2.2-4.5μmolCO_2 m^{-2} sec^{-1} more CO_2 compared to the BO treatment during the growing season ((confidence intervals for growing season bulk Rs; Table 12). Soil moisture probes on the REF plots recorded values well below the permanent wilting point threshold at the 10 and 20cm soil depth during the growing season (Figure 4); this could be able to explain the strong reduction in O-horizon respiration at higher temperatures (Figure 13). In spite of the potential moisture limitation, peak soil respiration was observed prior to the first rains that resulted in a rapid decrease in soil respiration rates from all sources over both years of observation (Figure 11).

The author questions the efficacy of the method used to obtain the microbial and O-horizon sources for multiple reasons. The tubes were inserted 30cm into the mineral soil; this inhibited lateral water movement causing artificially high soil moistures inside the tubes throughout the year. Even during the early summer months, there was a visual moisture difference inside and outside of the tubes. During the dry summer months, any measurable wind would decrease the accuracy of O-horizon observations. The air inside the chamber was not able to reach equilibrium due to winds moving through the O-horizon producing erroneous values. The average monthly analysis compares all source with all treatments, however in practice some treatments do not have an “O-horizon”. The O-horizon observations for TTP were done by placing the chamber directly on the *mineral* soil surface. Due to the fact that these were also considered O-horizon observations, it could have skewed the overall statistical analysis of organic matter removal.

4. DISCUSSION

The specific objectives of this thesis were to determine (1) if soil temperature and moisture patterns were sufficiently different throughout the profile to change the growing season characteristics, and (2) if changes in soil temperature and moisture can explain patterns in soil respiration over the first two years immediately following treatment implementation.

There appear to be few differences in the length of growing season as influenced by these drastically different organic matter removal and compaction scenarios. Soil moisture content was adequate to maintain plant available water through the summer months and thus probably keep seedlings out of any moisture limitations. The characteristics within the growing season, mainly the maximum soil temperature and diel flux, do indeed show a significant influence from the quantity of organic matter left on site. We expected the observed temperature differences to also produce proportional changes in soil respiration rates, but observed patterns in Rs are contradictory to a purely temperature-dependence concept. There have been documented cases that suggest organic matter additions can initiate the decomposition of ‘native’ soil C, and potentially leading to increased rates of soil respiration.

4.1. Growing Season

There was very limited evidence of biologically significant differences in growing season length (as defined by Douglas-fir root growing temperature) for any treatments (recall ‘treatments’ do not include the unharvested reference plots). Furthermore, there were no organic matter removal or compaction treatments that caused a *minimum* difference (see lower confidence intervals) of more than nine growing season days (Table 6). We believe this is likely caused by the strong bi-modal distribution in temperature (either <10°C or >15°C) observed for all depths and all plots during both years of observation (Figure 3).

There are two distinctly different distributions of soil temperature that can be attributed to the sharply contrasting nature of PNW winters and summers. The soil temperature transition time from summer-to-fall and winter-to-spring is so rapid (days to a week) that treatment manipulations are eclipsed by strong and rapid seasonal shifts. This sudden transition is in part due to changing air temperature, but with a strong contribution from the cooling effect precipitation has on soils that ‘bookend’ growing seasons.

Rain events typically correspond to days with increased cloud cover and higher rates of evaporative cooling. The combination of these factors can decrease soil temperature 10°C in less than 24-hours due to a rain event given the same relative air temperature (Dai et al., 1999). In lower latitude areas (southern Oregon and northern California) that have longer transition times between growing seasons, it is possible that different levels of harvest residue removals will have a measureable effect on the length of growing seasons. In a California LTSP site, organic matter removal increased the growing season soil temperature by 2-4°C (Paz, 2001). Although this study did not directly address the growing season length, it is possible organic matter removals would have increased the number of growing season days if moisture was not a limiting factor.

4.2. Soil Temperature

General characteristics

The levels of organic matter removal had little influence on the number of growing season days, however there was very strong evidence that the amount of forest harvest residuals left on site have explanatory power on soil temperature characteristics *during* the growing season, especially the rate of temperature changes. The average, maximum, and diel flux of growing season soil temperature on total tree harvests show statistically significant increases throughout the entire soil profile (10-100cm) when compared to bole only harvesting (Table 8). Soil temperatures of forest floor removal treatments reached the optimal range for nitrification rates (Brady and Weil, 2010). Fertilization applications should consider nutrient cycling pathways at these higher temperatures, thus it’s possible a lower nitrogen concentration in the applied fertilizer can be used to obtain the same objectives.

Many LTSP studies have also found compaction to increase average soil temperatures, although these are typically restricted to the upper 30cm and with few statistically significant findings (Li et al., 2003; Fleming et al., 2006; Page-dumroese et al., 2006). Average soil temperatures of compaction treatments on this LTSP site were not statistically different than their non-compacted treatment pairs (Table 7), however there is a general trend of a slightly higher average, maximum, and diel flux of soil temperature when compaction is present (Figure 6; Figure 7; Figure 8). To the author’s knowledge, this is the first documentation of increased soil temperature down to 100cm soil as a result of the LTSP study design or of forest harvesting in general.

Organic matter removal effects on soil temperature

Some Pacific Northwest (PNW) LTSP sites have recorded summer month *average* temperature increases, as a result of total tree and forest floor harvesting, between 0.6-1.5°C at 10cm soil depth, but there are no records for deeper in the soil profile (Roberts et al., 2005; Devine and Harrington, 2007). I found that total tree harvesting significantly increased the average and maximum soil temperature ~1.3°C and ~2.1°C respectively throughout the entire soil profile (Table 8). Forest floor removal (TTC-TTP) significantly increased the average and maximum soil temperature by another ~1.6°C and ~3.1°C respectively but only in the upper 20cm. Deeper in the soil profile (30-100cm) forest floor removal did not show the same magnitude of soil temperature increases seen in total tree removals suggesting total tree removals have a larger impact on soil profile temperature characteristics compared to the additive impacts of forest floor removal. However the lack of statistical evidence for deep soil temperature impacts from forest floor removal may have an explanation from heat transfer dynamics.

Heat transfer dynamics of compacted soils without a forest floor

The soil-atmosphere interface greatly influence the characteristics of the temperature-wave propagation that dampens with increasing soil depth (Hillel, 2004). It's plausible that the dark-red, and albedo lowering, colored bare compacted soil (reducing the proportion of macropores and some insulating properties) altered the temperature wave function so much it created *destructive* interference at greater depths because the upper 100cm of soil are rapidly cooling and warming throughout the day (Figure 12.5 Hillel, 2004). Forest floor removal significantly increases the diel temperature flux throughout the soil profile by decreasing the soil's albedo (Table 8) (Brady and Weil, 2010). Compaction increases D_b, by decreasing the proportion of macropores, this also changes the thermodynamic properties such as greater thermal conductivity and diffusivity rates (pg 182 Hillel, 2004; Jury and Horton, 2004). The combination of these factors could result in the destructive interference of the temperature wave deeper (+30cm) in compacted soil without a forest floor masking any statistically detectable changes that could be occurring.

Impacts to Douglas-fir seedlings

Douglas-fir seedlings are susceptible to mortality if the site reach extreme conditions early in their transplant life (Lavender and Hermann, 2014). It has been well documented for Douglas-fir seedlings in the PNW that root and terminal bud growth rates are greatest when soil temperature reach 20°C, decreased at 25°C, and finally growth terminates with often lethal consequences at 30°C (Lavender and Hermann, 2014). A well-designed temperature controlled conifer seedling transplant study was used to define lethal temperatures for Douglas-fir roots (Lopushinsky, 1990), however that study used a soil depth of 4.5cm in a relatively small-volume container with constant soil water content to reach these conclusions.

If these temperature considerations are accurate, there should have been a decrease in root growth and subsequent decrease in tree growth, or even mortality, on sites exceeding 25°C (Figure 7). Based on monthly field visual observations over two-years, there did not appear to be excessive seedling mortality on forest floor removal treatments; recall they regularly exceed 25°C (Figure 3, Figure 7). Interestingly, the 25-35°C soil temperature range corresponds to optimized nitrification rates in forest soils (Brady and Weil, 2010). This expectation of seedling mortality as a result of temperatures exceeding 25°C assumes the rooting zone is 0-10cm. The planting of seedlings likely exceeded this depth, and root growth was likely to remain unhindered at deeper in the soil where it was cooler. Unless there is a year or longer lag effect of seedling mortality from excessive soil temperatures, there does not appear to be any negative consequences of the soil approaching the 30°C lethal threshold.

The effects of compaction on tree growth is highly site specific, but increases in tree growth due to compaction are not uncommon (Ares et al., 2007 and references therein). However, if a site experiences very long period of droughts (e.g. California Sierra Nevada LTSP sites) the increase in soil strength as it dries can produce negative effect on seedling growth (Gomez et al., 2002). This increase in soil strength from drying is exaggerated on the forest floor removal plots where drying cracks were observed, however this unusually dry portion of the soil extended to less than 5cm deep and there is limited evidence of strong drying at 10cm depth (Figure 4, Figure 15). The relatively low bulk density of these soils (0.60-0.85g cm^{-3} 0-15cm depth), as well as the limited impact of increased soil strength due to drying, suggest there is unlikely to be an impact on seedling growth due to compaction.

Diel effects on soil C

There is a consistent increasing diel temperature flux as more organic matter is removed (Figure 8). The unharvested reference has a 100cm diel flux of only 1.7°C during the growing season. However diel temperature flux at 100cm depth for bole only no compaction and total tree plus forest floor removal with compaction treatments are 5.7, and 7.8°C respectively (p-value<0.005 for both estimates on 14 degrees of freedom). These 100cm diel soil temperature flux data deviate substantially from the expected values in many soil physics textbooks (Hillel, 2004; Jury and Horton, 2004). To put this in perspective, the 100cm estimated *diel* flux values on forest floor removal treatments are of equivalent magnitude to a winter-spring or autumn-summer *seasonal* transition (Figure 12.5 Hillel, 2004).

A recent analysis of a Washington LTSP study 12-years after treatment show a substantial quantity of deep roots (2.0g roots kg^{-1} soil) that are contributing to the total soil organic carbon pool (Knight et al., 2014). That study also showed treatments with vegetation control, similar to this study, had higher soil C content between 45-100cm. Furthermore, the paradoxical increase in soil carbon following organic matter removals has been largely attributed to root decomposition (Powers et al., 2004). Changes in temperature variability, in this case diel flux, has been shown to potentially increase the expected rate of respiration and thus decomposition rates. If the average, diel, and maximum soil temperatures at greater depths seen on these sites are consistent across other PNW LTSP locations, this could be a mechanism for the observed increase in soil C at depth being sourced from rapidly decomposing roots due to increased deep soil temperature regimes. This mechanism suggests even whole tree harvesting forest management techniques can have an appreciable effect on long-term carbon cycling at deeper soil depths that are often incorrectly dismissed as remaining static (James et al., 2016).

4.3. Soil Moisture

There were no consistent, unambiguous patterns in soil moisture responses to organic matter or compaction manipulations. The level of practical significance for this analysis needed to exceed the level of precision of soil moisture probes (±3% VWC). This may have been one of the reasons there were few significant results. Furthermore the variance in VWC within blocks, and plots (as measured by hand-held probe during soil respiration observations) greatly exceeded the variance between treatment groups. This is likely due to the sensitivity of probe placement and maintaining a reliable soil-probe contact surface as animals burrow and soils shift over multiple years.

The range of VWC throughout the two years of observation were almost entirely restrained to 30-50% VWC for all treated plots and all depths (Figure 9). This range in VWC values are consistent with the Fall River PNW LTSP site (Roberts et al., 2005), however other PNW LTSP sites (Matlock and Mollala) with more established trees have found VWC drop to 15%VWC in the growing season (Slesak et al., 2010). These studies found *statistically* significant differences in VWC during the growing season; however those results do not surpass the level practical importance employed in this thesis. Taken all factors into account, it is unlikely differences in soil moisture will become biologically significant until seedlings develop larger rooting systems that will substantially alter soil-water dynamics through the growing season (Figure 15). This is with the caveat that these sites had complete vegetation control to minimize seedling competition for water, light and nutrients.

4.4. Soil Respiration

I observed a wide range in soil temperatures but did not observe a proportional change in respiration rates to these increases in soil temperatures (Figure 13). Basic biologic principles predict the highest rates of activity occur as temperature increase (Lloyd and Taylor, 1994). I found significant increases in the growing season average, maximum, and diel flux of soil temperature without any evidence to suggest a moisture limitation (Figure 6, Figure 7, Figure 8). In spite of these potentially favorable conditions for microbial activity the average monthly, and growing season, soil respiration rates were slightly higher on the sites that were cooler caused by retaining more surface biomass (Figure 10).

Although this was surprising, each year produced very different patterns in soil respiration, also supported by the overall F-statistics (Table 11), which may have inhibited our ability to detect more robust differences in soil respiration. All treatments behaved very similarly during year 1, suggesting the disturbance of treatment implementation supersede the characteristics of the individual treatments (Levy-Varon et al., 2012; Rastetter et al., 2013). Furthermore the sites were heavily sprayed with herbicides (Velpar, Transline, Glyhosate) in year 1 to minimize the development of unwanted understory vegetation. It has been shown repeated glyphosate applications on soils of pH<7.5 and with a high organic carbon content can depress microbial respiration rates after 60 days (Nguyen et al., 2016). The combination of disturbance effects and herbicide applications may be able to explain the lack of differences between treatments during year 1. The effect of disturbance caused by implementing treatments may be able to explain the lack of differences between treatments during year 1. The additive effect of herbicide application immediately following treatments could have some contribution, however herbicide was applied every year and this individual impact cannot be quantified.

Another possible explanation for increased soil respiration following organic matter additions is commonly referred to as the ‘positive priming effect’ (Kuzyakov et al., 2000; Lajtha et al., 2014). This describes how the addition of a carbon source (dissolved organic matter in field experiments or glucose in lab), can promote the decomposition of carbon that is larger than the quantity of carbon added. Thus the turnover of ‘native’ soil organic matter is possible if the system is ‘primed’ by the addition of metabolically favorable compounds. There is a considerable quantity of dissolved organic matter that leaches from forest residues into mineral soils; another LTSP site in the PNW found the 3-year cumulative nitrogen flux past 100cm depth was approximately ~30% of the total nitrogen stores left as O-horizons and forest slash (Strahm et al., 2005). If microbial access to organic matter is limited at increasing soil depths, it may be possible that deeper soil carbon is disproportionately affected by increases in dissolved organic matter (Strahm et al., 2009). The average daily temperature at 100cm are 2°C warmer as a result of harvesting (Table 8), this could accentuate the potential for microbial induced priming to occur on these treatments with higher quantities of organic matter left on site. It should be noted that priming is thought to occur ‘very shortly after the treatment of the soil’ and may not be long-lasting; but senesced roots at depth may provide a continuous accessible source of carbon and should be further explored to identify the primary source(s) of soil carbon (Kuzyakov, 2010; Thevenot et al., 2010; Kaiser and Kalbitz, 2012). Long-term monitoring of soil respiration should continue on these sites to identify if these patterns in soil respiration continue to be dependent on organic matter additions, or if thermodynamic properties become more favorable.

At two LTSP sites in the PNW the peak growing season soil respiration rates correlated to peak soil temperatures, and the minimum soil respiration rates correlated to the observations when soil moisture content was lowest (Slesak et al., 2010). This suggests a relatively simple relationship between temperature, moisture, and soil respiration, however that contradicts the findings at this LTSP site. The very small differences in soil respiration seen here should be strongly considered in the context of the general patterns seen on other LTSP and organic matter manipulation treatments.

5. CONCLUSIONS

Pulse changes in organic matter content and soil porosity due to forest management can have impacts on long-term forest productivity. Organic matter removals had larger measureable impacts on soil temperature characteristics and soil respiration compared with compaction treatments. These results show there are few differences in the length of growing season as influenced by these organic matter and compaction manipulations. However the patterns observed in temperature and moisture *within* the growing season are significantly different. Daily average temperatures during the growing season increased as more biomass removals increased. The diel soil temperature flux at 100cm depth during the growing season showed fluxes comparable to seasonal changes within a single day. Maximum 0-30cm soil temperatures during the growing season increased between 3.7-5.5°C on forest floor removal treatments compared to bole only harvests. Soil temperatures of forest floor removal treatments reached the optimal window for nitrification rates, fertilization applications commonly used in intensively managed forests should consider this potential nutrient cycling pathway.

In spite of favorable temperature and moisture conditions on sites with less organic matter residues, soil respiration was moderately higher on bole only harvests. The observed characteristics in soil temperature and soil moisture could not accurately explain the magnitudes of soil respiration over two years. It is possible a priming effect was in action during the immediate two years following treatments. This could have resulted from the combination of increased soil temperatures at 100cm, and higher quantity of dissolved organic carbon from forest residuals on the bole only removal treatments. It is suggested long-term monitoring of soil respiration continue to determine the length of this effect, and whether this will have an impact on deeper soil carbon pools.

6. FIGURES

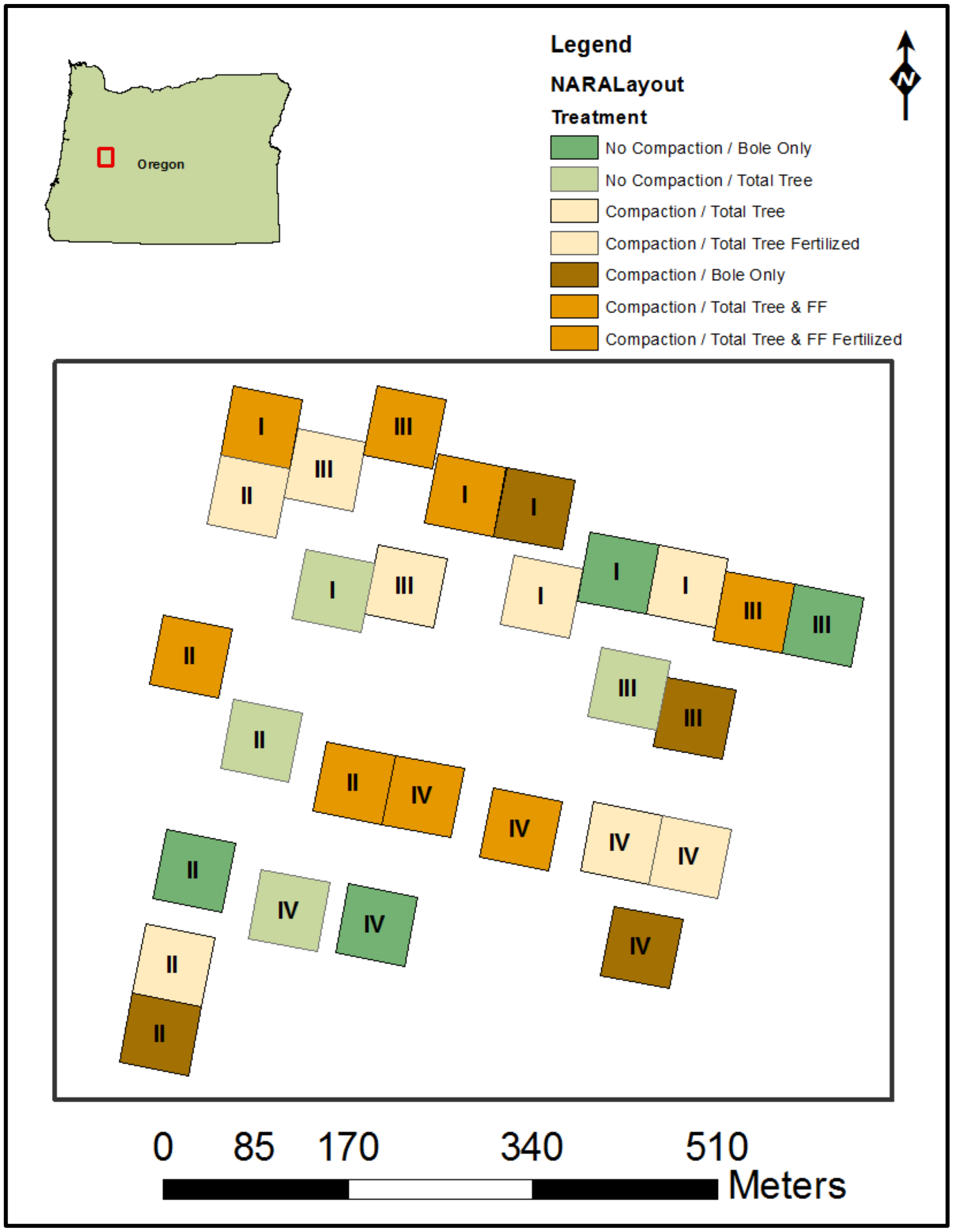

Figure 1. Treatment layout of blocks and plots for at an LTSP affiliate study site in the western Oregon cascades located east of Springfield, OR.

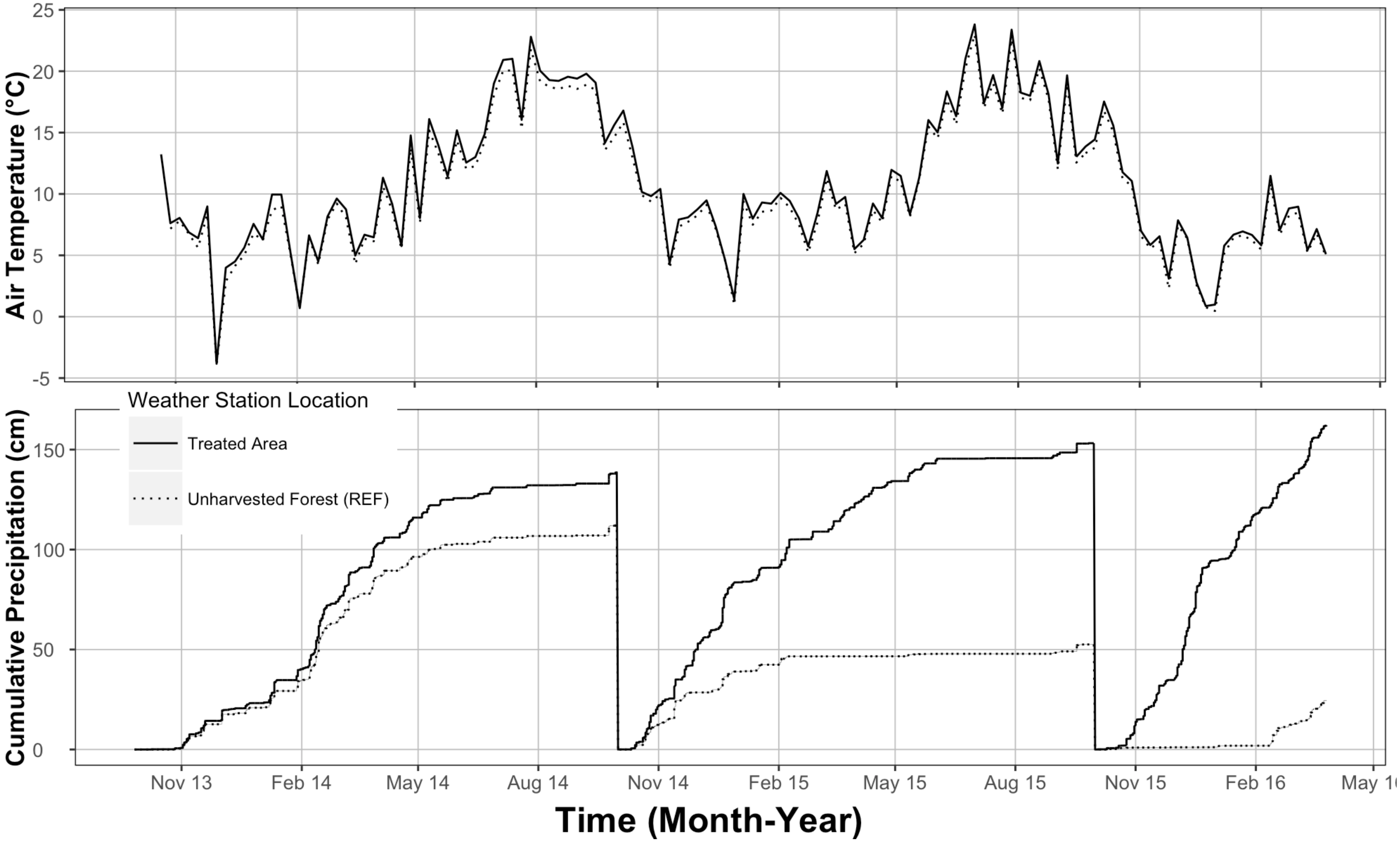

Figure 2. Air temperature and cumulative throughfall precipitation to forest floor of the treated area and the adjacent unharvested reference on an LTSP site near Springfield, OR. **Note: the 2015 and 2016 water year REF rain gauge malfunctioned due to clogging issues, water year 2014 represents true canopy interception differences.

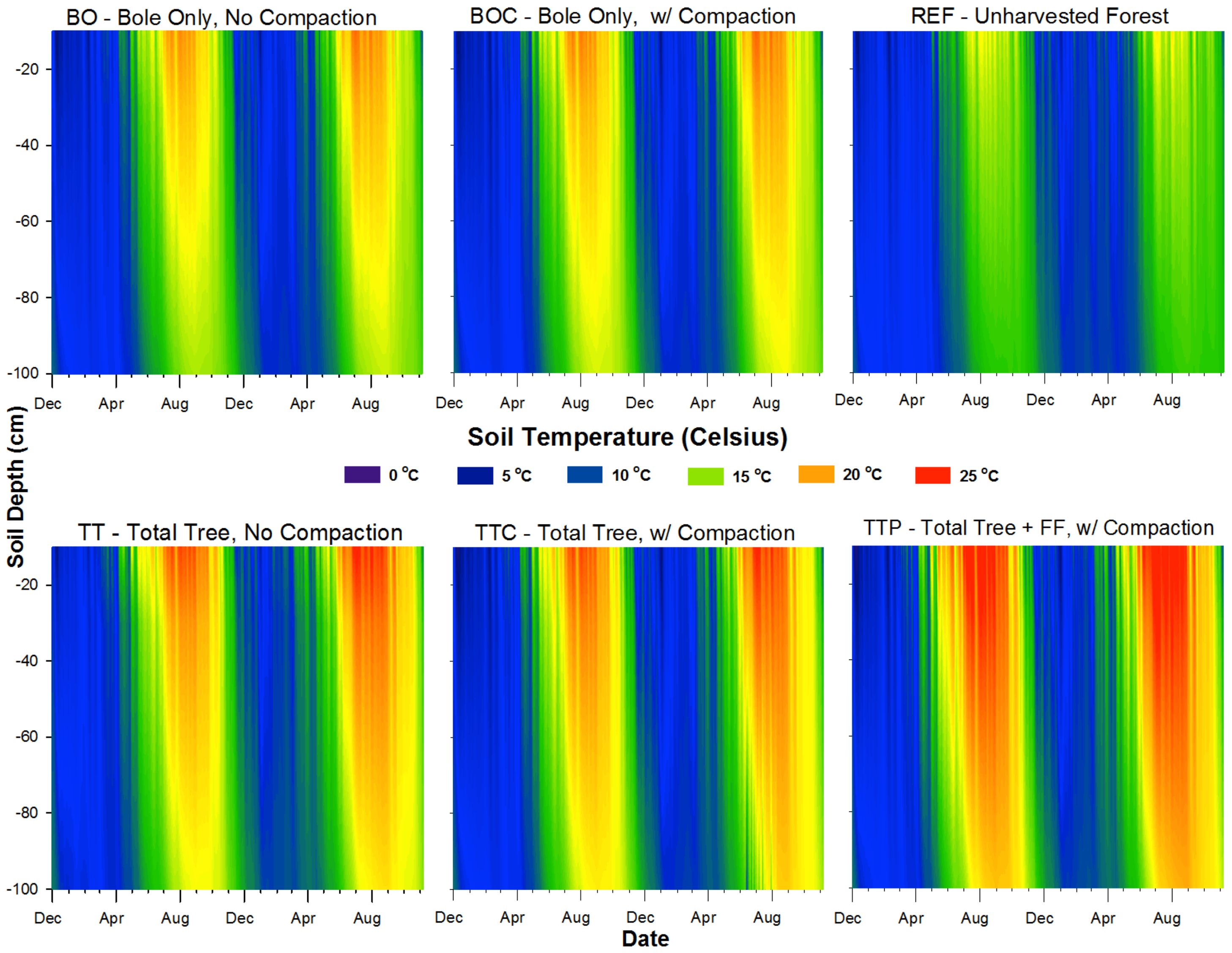

Figure 3. Observed two-year soil temperature patterns following intensive organic matter and compaction manipulations at the Springfield, OR LTSP site. Soil probes were installed at 10, 20, 30, and 100cm mineral depth recorded hourly but represented on daily time steps. A linear average is used to interpolate between all probes.

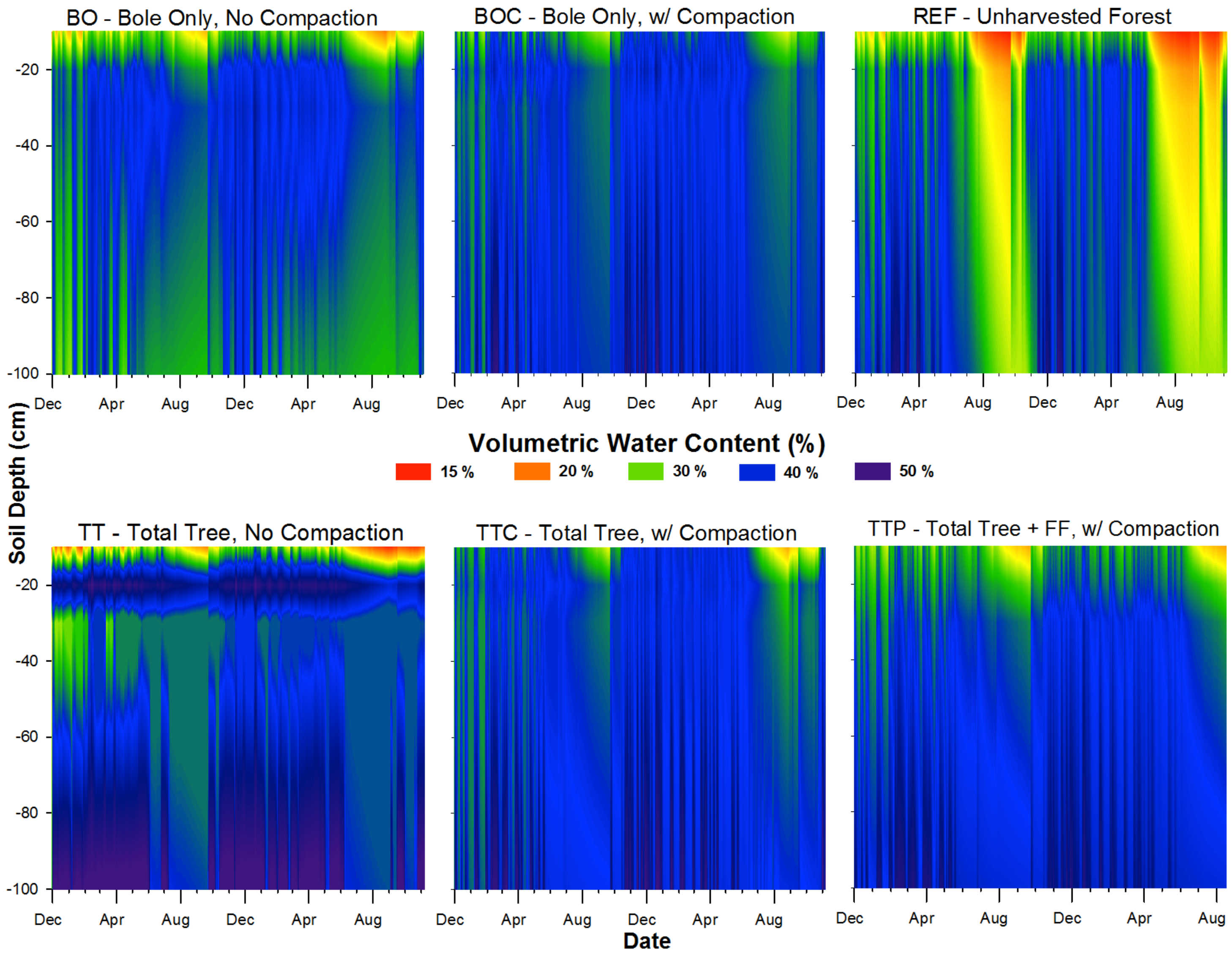

Figure 4. Observed two-year soil volumetric water content (VWC) patterns following intensive organic matter and compaction manipulations at the Springfield, OR LTSP site. Soil probes were installed at 10, 20, 30, and 100cm mineral depth recorded hourly but represented on daily time steps.

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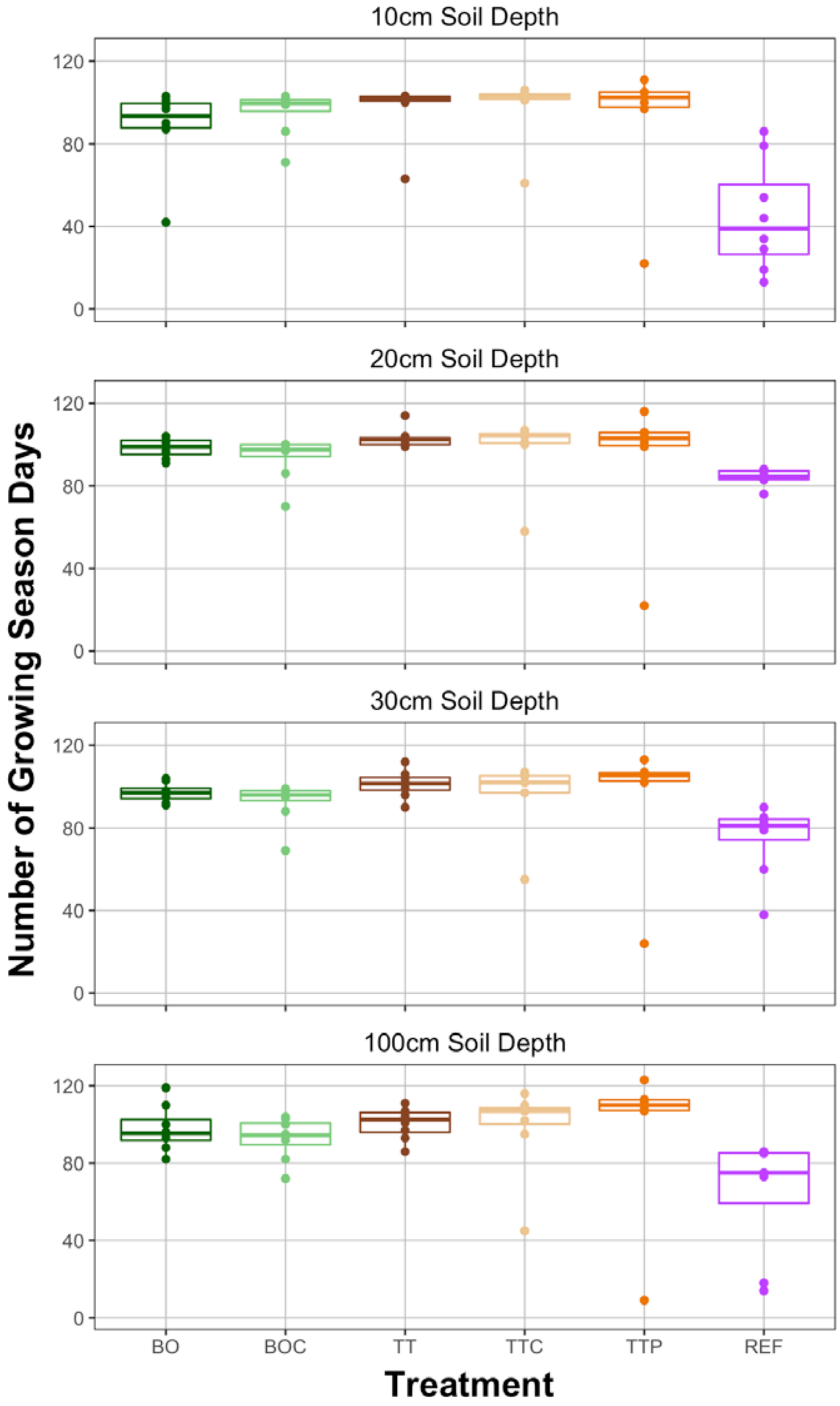


Figure 5. Number of biologically defined growing season days for an LTSP site in Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction

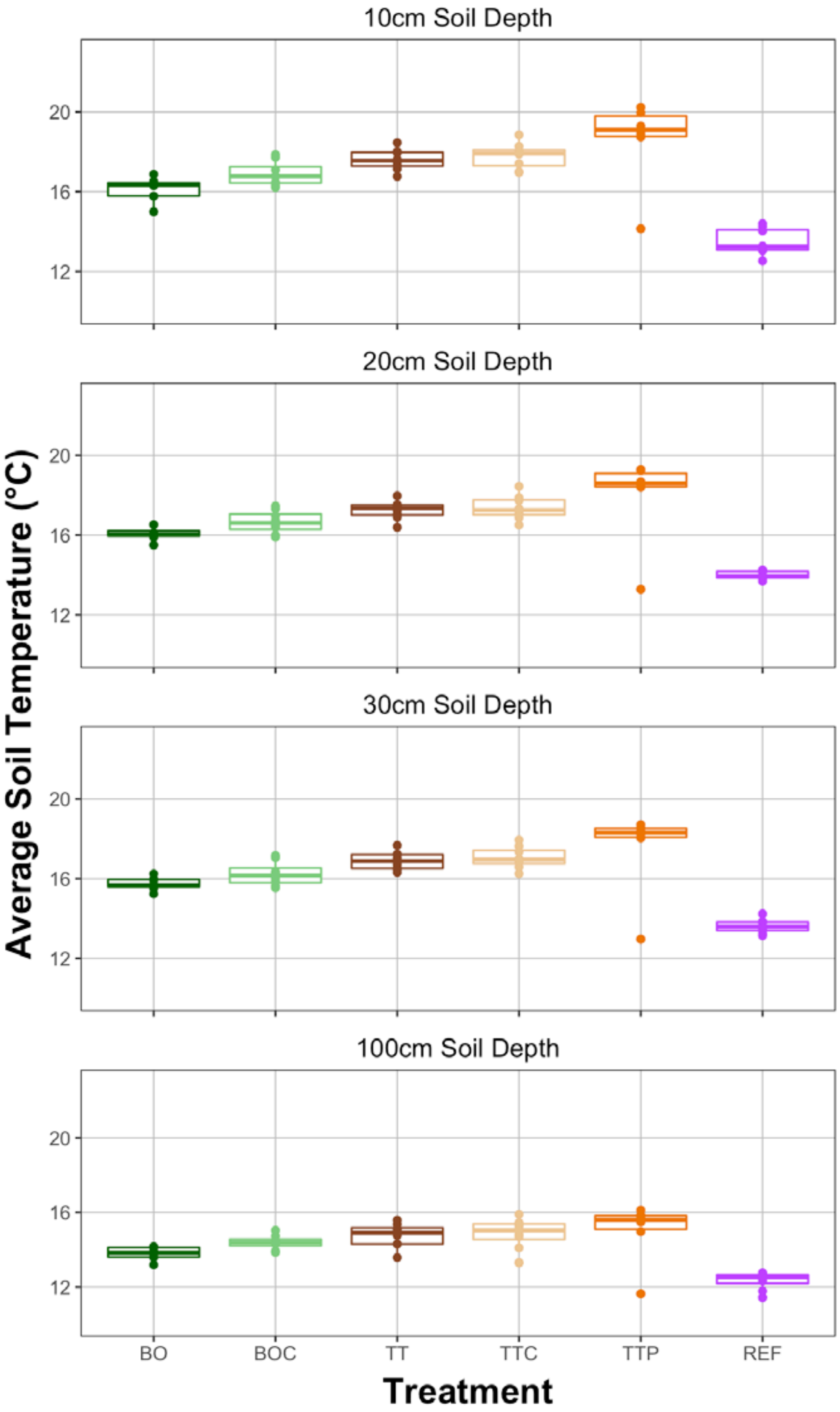


Figure 6. Average soil temperature for an LTSP site in Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction

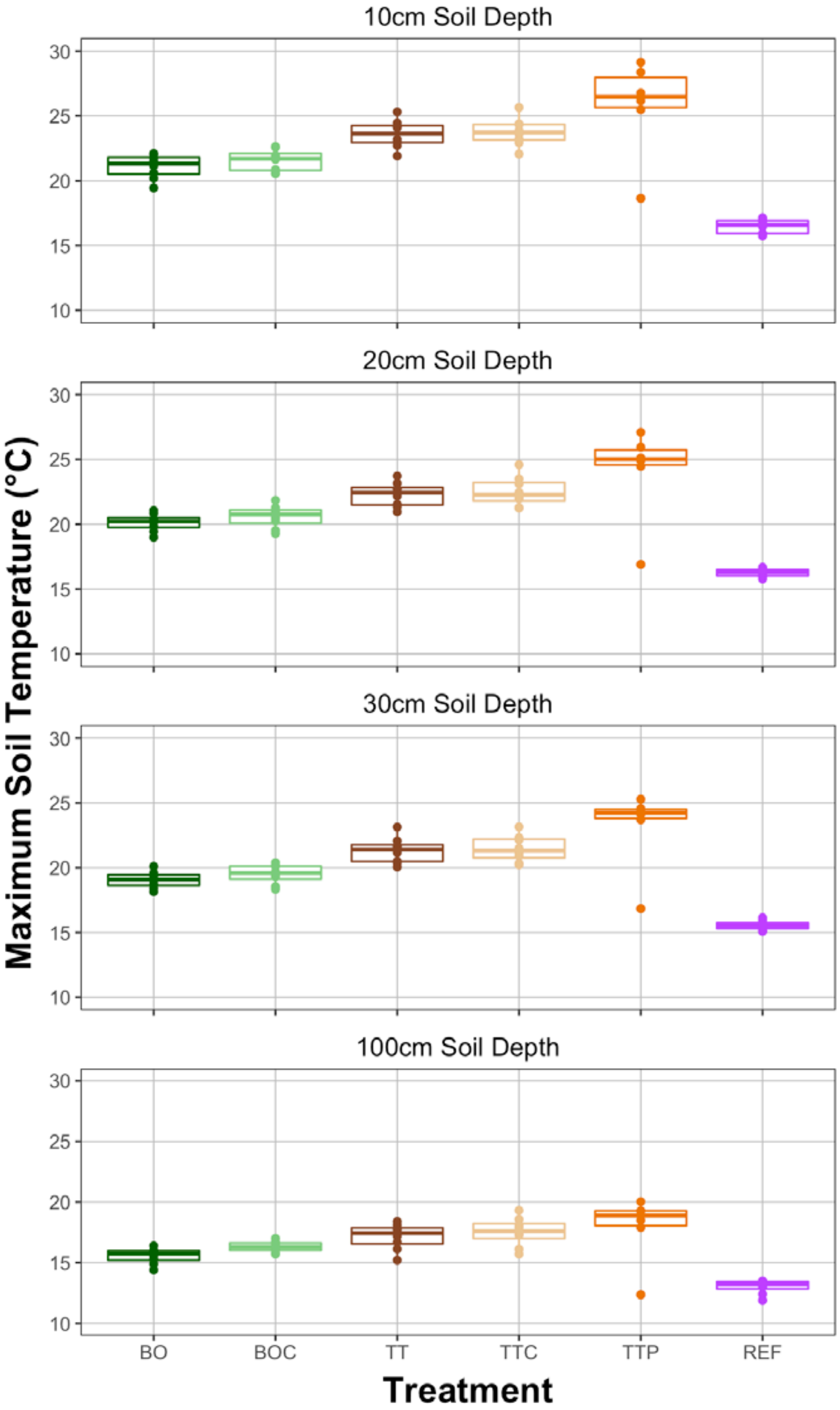


Figure 7. Maximum soil temperature for an LTSP site in Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction

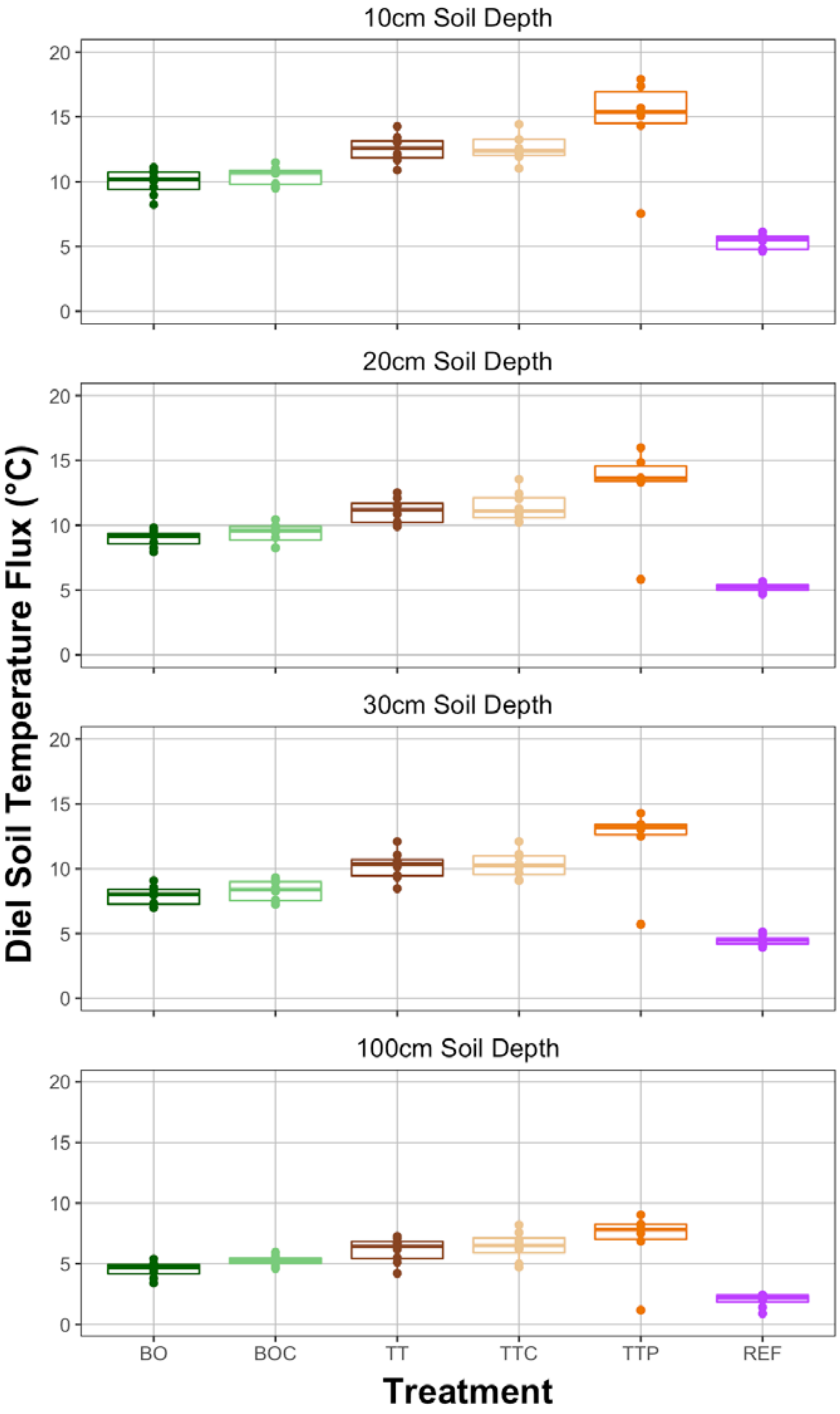


Figure 8. Diel soil temperature flux for an LTSP site near Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction

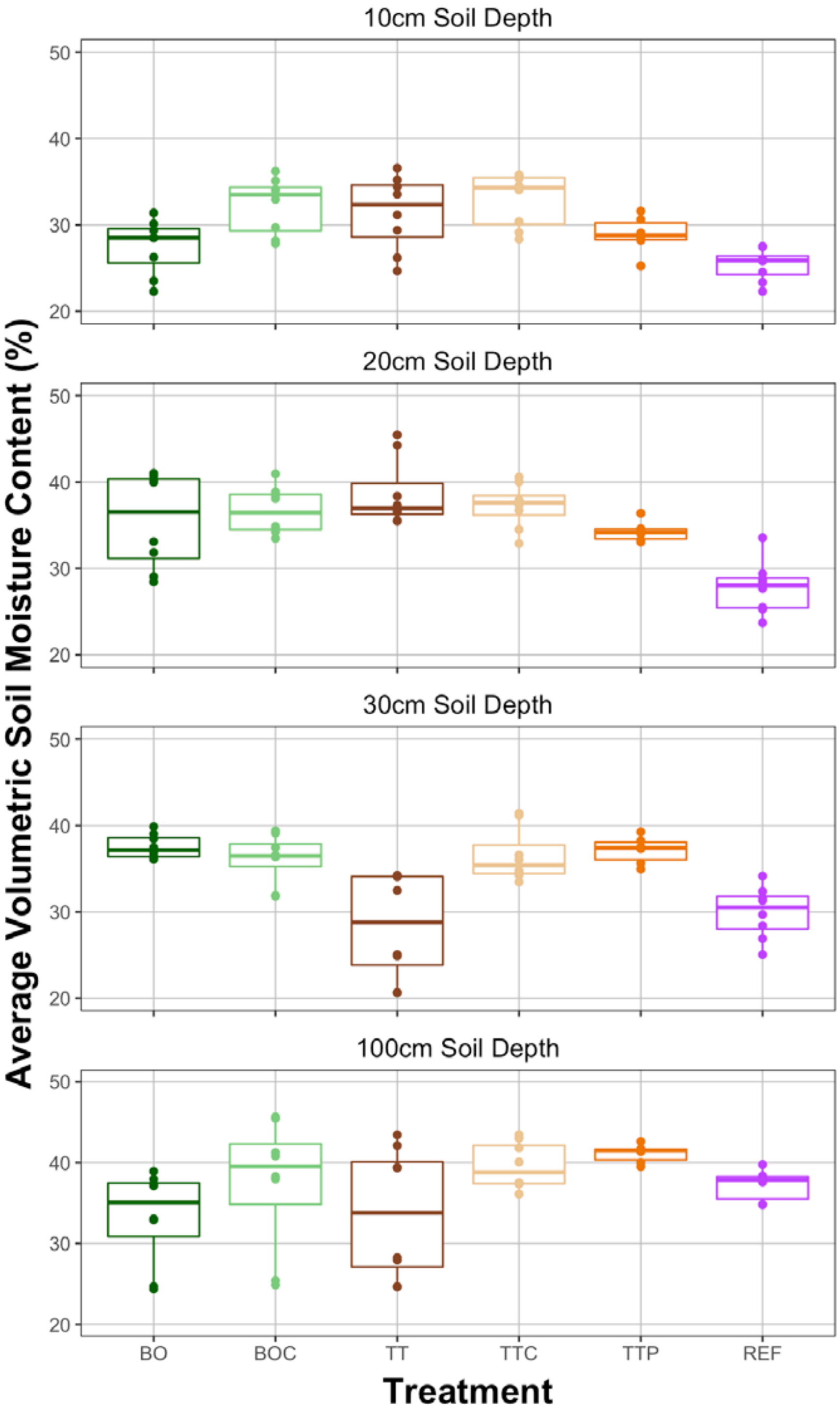


Figure 9. Average soil volumetric water content for an LTSP site near Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction

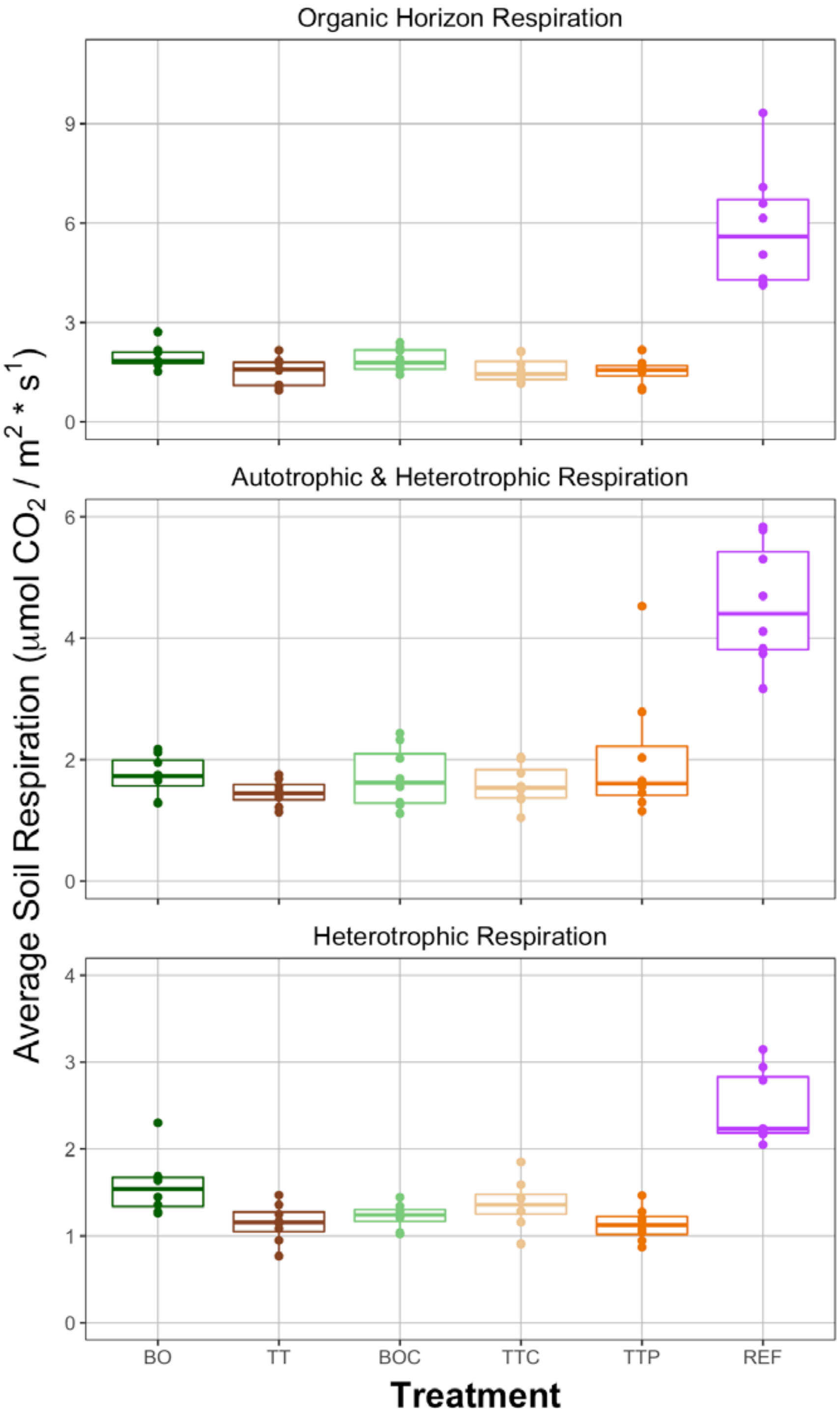


Figure 10. Average monthly soil respiration of multiple sources over two years at an LTSP site near Springfield, OR. Note the different Y-axis used between sources of respiration. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction

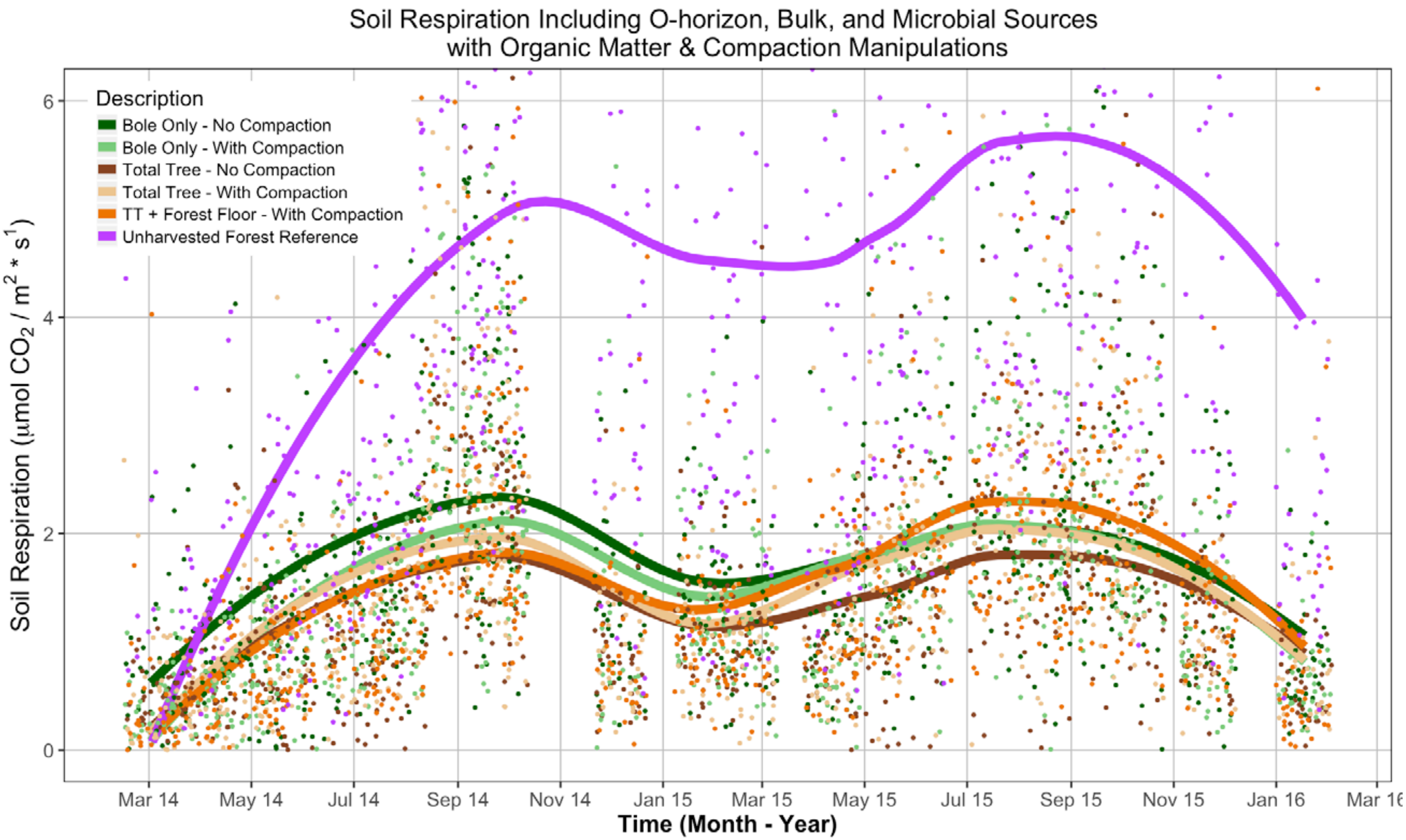


Figure 11. Observed soil respiration (including O-horizon, bulk, and microbial sources) over two years using a LiCOR 8100A on monthly intervals located on an LTSP site near Springfield, OR

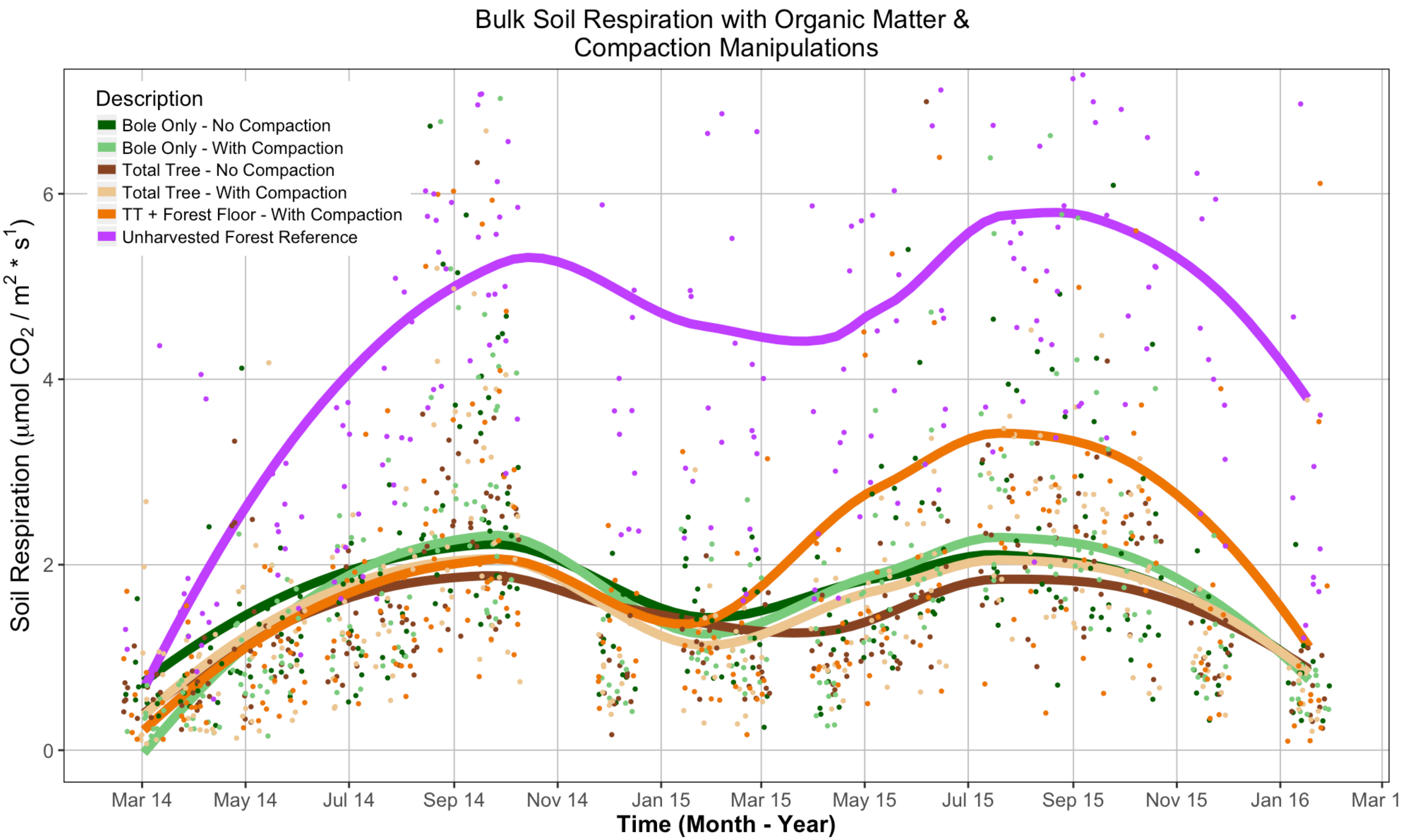


Figure 12. Observed bulk soil respiration patterns over two years using a LiCOR 8100A on monthly intervals located on an LTSP site near Springfield, OR

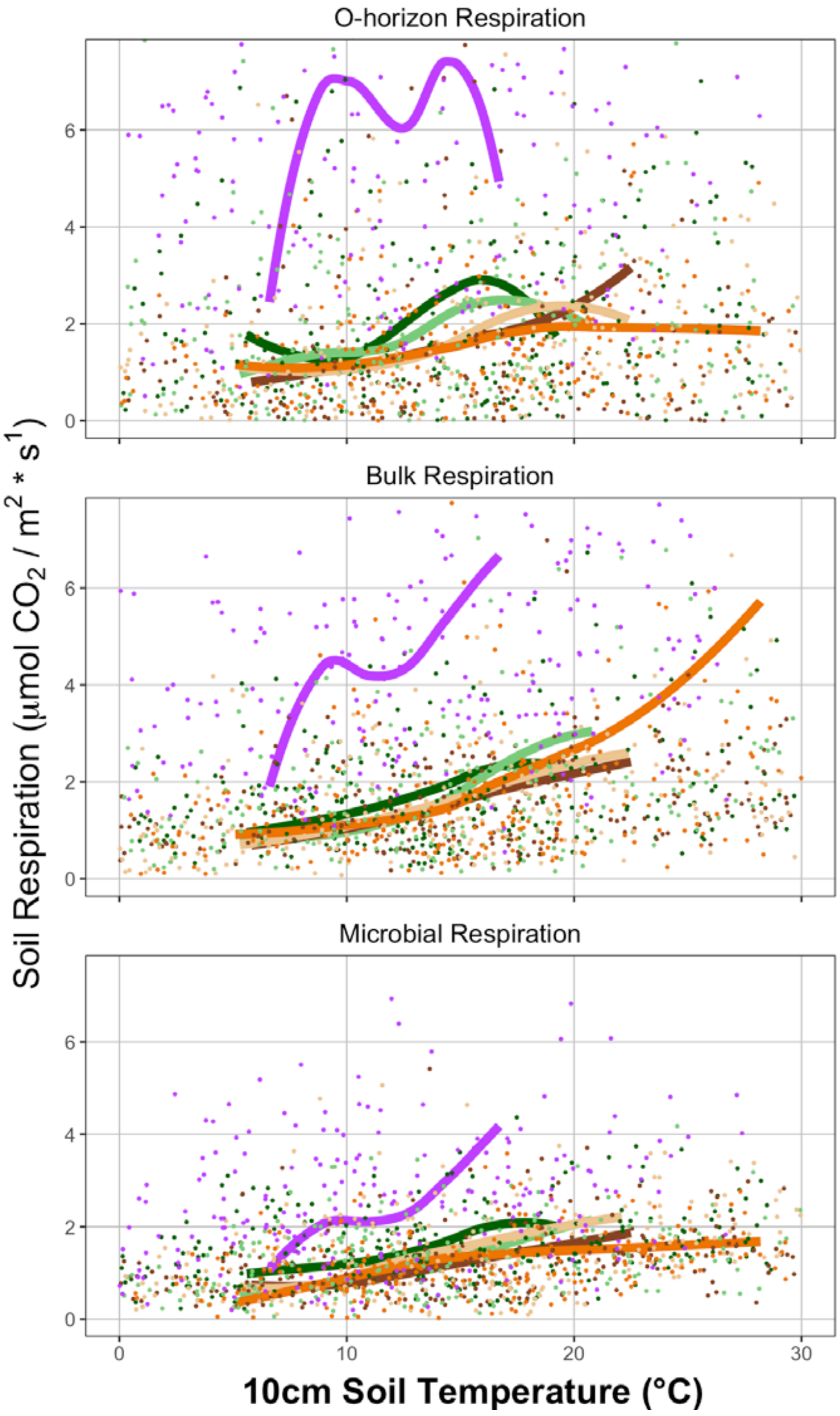


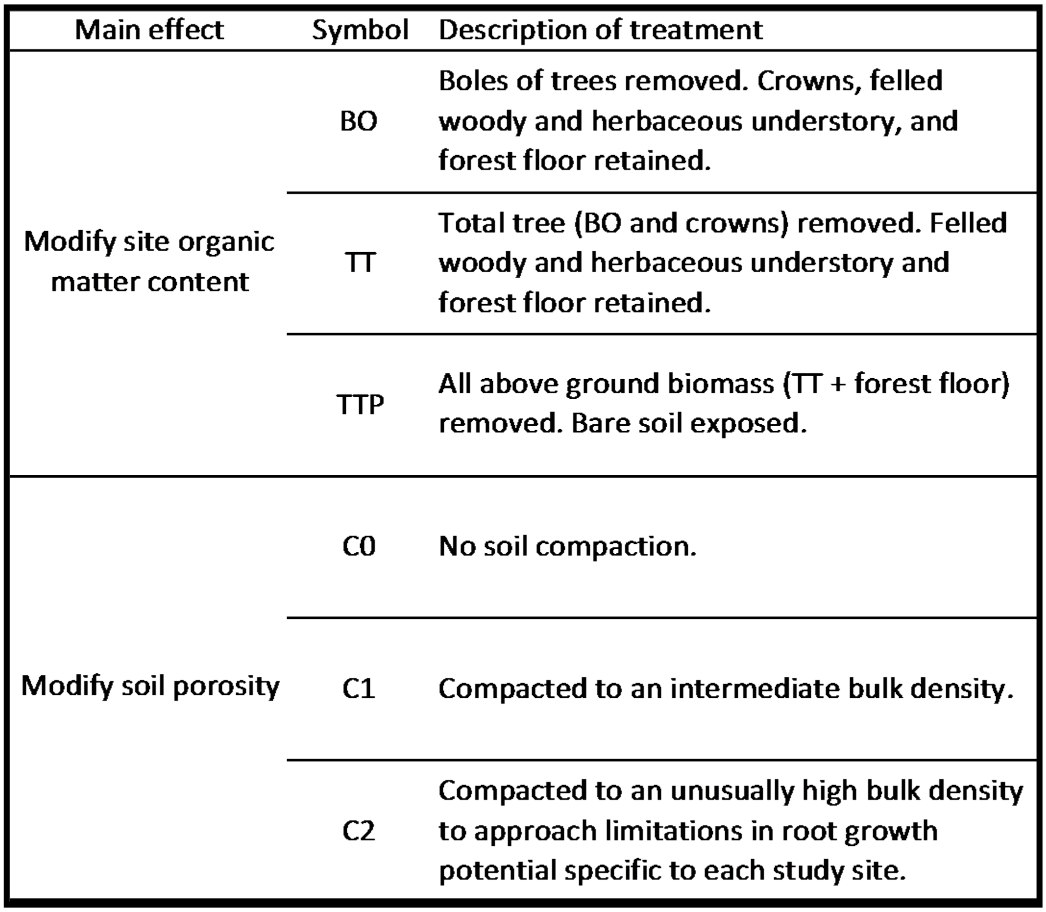
Figure 13. Soil respiration as a function of soil temperature for all observed sources. Data encompasses two years of observations with monthly measurement intervals located on an LTSP site near Springfield, OR

Figure 14. Potential amelioration of compaction treatments by frost heaving (A, B) and macrofauna activity (C) on an LTSP site near Springfield, OR.

Figure 15. Peak summer soil characteristics on forest floor removal and compaction treatment at an LTSP site in Springfield, OR. (A) Cracks were visible due to shrinking of soil only on forest floor removal plots, (B) evaporation due to direct solar radiation in August of 2014 (highest soil temperatures) only reached the upper 3cm.

7. TABLES

Table 1. Long-Term Soil Productivity (LTSP) treatment levels. From Powers, R.F. 2006. Long-term soil productivity: genesis of the concepts and principles behind the program. Can. J. For. Res. 36:523. Copyright 2006 NRC Canada. Adapted without permission.

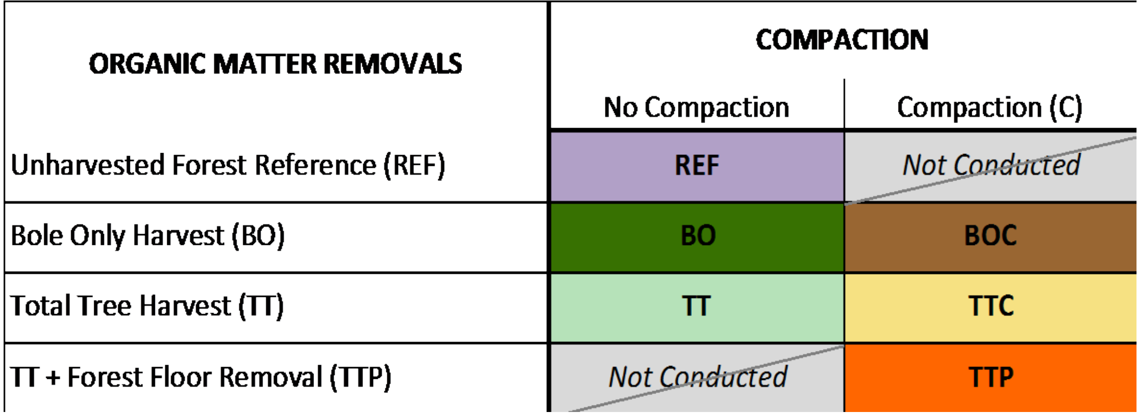


Main effect	Symbol	Description of treatment
Modify site organic matter content	BO	Boles of trees removed. Crowns, felled woody and herbaceous understory, and forest floor retained.
	TT	Total tree (BO and crowns) removed. Felled woody and herbaceous understory and forest floor retained.
	TTP	All above ground biomass (TT + forest floor) removed. Bare soil exposed.
Modify soil porosity	C0	No soil compaction.
	C1	Compacted to an intermediate bulk density.
	C2	Compacted to an unusually high bulk density to approach limitations in root growth potential specific to each study site.

Table 2. Climate data for the LTSP site near Springfield, OR. Data uses historical records from 1981-2010 at 628m elevation (Wang et al., 2016).

	Temperature (°C)			Precipitation (cm)	Solar Radiation (MJ $m^{-2}d^{-2}$)	Relative Humidity (%)
	Minimum	Maximum	Average			
January	0.8	8.2	4.5	23.1	4.1	75.0
February	1.7	10.4	6.0	17.4	7.4	71.0
March	2.4	12.0	7.2	18.2	10.9	68.0
April	4.2	14.9	9.5	15.0	15.2	66.0
May	6.6	18.8	12.7	11.7	18.7	62.0
June	10.1	22.0	16.0	8.0	21.7	64.0
July	12.0	26.5	19.3	2.2	24.3	58.0
August	12.3	26.6	19.5	2.3	21.1	58.0
September	11.0	23.8	17.4	5.6	15.5	62.0
October	7.4	17.0	12.2	13.8	8.2	69.0
November	3.4	10.8	7.1	27.2	4.3	75.0
December	1.5	8.2	4.9	26.0	3.3	77.0
Average	6.1	16.6	11.4	Mean Annual = 170cm	12.9	67.1

Table 3. Treatment matrix for the Springfield, OR Long-term Soil Productivity (LTSP) experiment. The full treatment matrix was not completed due to practical and management related. Color of treatment combinations remain consistent through all graphs.



ORGANIC MATTER REMOVALS	**COMPACTION**	
	No Compaction	Compaction (C)
Unharvested Forest Reference (REF)	**REF**	*Not Conducted*
Bole Only Harvest (BO)	**BO**	**BOC**
Total Tree Harvest (TT)	**TT**	**TTC**
TT + Forest Floor Removal (TTP)	*Not Conducted*	**TTP**

Table 4. Treatment level chemical and physical data pre and post-treatments at the LTSP site near Springfield, OR. Data provided by S. Holub Weyerhaeuser.

Soil Property	Treatment				
	BO	TT	BOC	TTC	TTP
Soil carbon forest floor to 100cm (Mg ha^{-1})	230.5	218.9	219.0	218.6	222.1
Soil carbon 0-15cm (Mg ha^{-1})	62.4	59.8	56.2	60.0	57.4
Soil carbon 15-30cm (Mg ha^{-1})	51.4	52.1	54.7	54.3	53.5
Soil carbon 30-100cm (Mg ha^{-1})	108.1	99.3	100.2	95.8	101.9
Soil nitrogen forest floor to 100cm (Mg ha^{-1})	11407.2	11327.1	11159.3	10897.3	11465.9
Soil nitrogen 0-15cm (Mg ha^{-1})	2721.3	2701.3	2540.9	2617.2	2739.6
Soil nitrogen 15-30cm (Mg ha^{-1})	2528.5	2545.9	2678.7	2592.0	2753.4
Soil nitrogen 30-100cm (Mg ha^{-1})	5966.3	5877.1	5745.9	5481.5	5735.9
Soil texture 0-15cm	Clay Loam	Clay Loam	Clay Loam	Clay Loam	Clay Loam
Roots 0-15cm (Mg ha^{-1})	5.5	5.2	6.1	5.2	4.1
Roots 15-30cm (Mg ha^{-1})	8.3	6.4	7.0	4.8	5.1
Roots 30-100cm (Mg ha^{-1})	20.4	10.2	25.0	13.6	18.9
Site Index by LiDAR (ft)	119.6	122.2	122.7	120.2	120.5
Site Index by HTN (ft)	121.9	125.9	123.6	123.5	123.1
PRE-treatment bulk density 0-15cm <2mm (g cm^{-3})	0.621	0.600	0.594	0.598	0.596
PRE-treatment bulk density 15-30cm <2mm (g cm^{-3})	0.703	0.679	0.728	0.739	0.712
PRE-treatment bulk density 30-100cm <2mm (g cm^{-3})	0.627	0.652	0.707	0.718	0.775
POST-treatment bulk density 0-15cm <4.75mm fraction (g cm^{3})	0.674	0.709	0.779	0.785	0.877
POST-treatment bulk density 15-30cm <4.75mm fraction (g cm^{3})	0.674	0.709	0.779	0.785	0.9
POST-treatment forest floor depth (cm)	17.0	7.3	13.1	6.4	1.2

Table 5. F-statistics on overall significance of predictor variables on the growing season length on an LTSP site near Springfield, OR. A growing season day is defined as average daily values of soil temperature >10°C and VWC>19%. Bold indicates significance, $F_{critical}$ (1,9) = 3.36 and $F_{critical}$ (1,15) = 3.07 with α =0.10.

Response variable	Soil Depth (cm)	Overall F-test Comparison	DF	F-value	p-value	Statistically Significant
Number of Growing Season Days	10	**(Intercept)**	**1 , 15**	**21094.4**	**<.0001**	*
		OM	1 , 9	**24.8**	**0.001**	*
		Compaction	1 , 9	**3.6**	**0.091**	*
		Year	1 , 15	1.4	0.263	
		OM:Compaction	1 , 9	0.4	0.533	
	20	**(Intercept)**	**1 , 15**	**12612.6**	**<.0001**	*
		OM	**1 , 9**	**9.8**	**0.012**	*
		Compaction	1 , 9	0.1	0.817	
		Year	**1 , 15**	**13.8**	**0.002**	*
		OM:Compaction	1 , 9	0.0	1.000	
	30	**(Intercept)**	**1 , 15**	**1942.2**	**<.0001**	*
		OM	1 , 9	**6.9**	**0.028**	*
		Compaction	1 , 9	2.7	0.132	
		Year	**1 , 15**	**61.6**	**<.0001**	*
		OM:Compaction	1 , 9	0.0	0.987	
	100	**(Intercept)**	**1 , 15**	**722.2**	**<.0001**	*
		OM	1 , 9	1.0	0.354	
		Compaction	1 , 9	0.6	0.450	
		Year	**1 , 15**	**86.4**	**<.0001**	*
		OM:Compaction	1 , 9	0.1	0.793	

Table 6. Comparisons of treatment effects on the number of growing season days at an LTSP site near Springfield, OR. Bold indicates biological significance (α = 0.10; minimum difference ±1°C). Note the direction of all statistical comparisons are always the difference between the less intensive to more intensive treatments and the sign (±) of coefficients reflect this directionality.

Response variables	Main & Treatment Effects	Soil Depth (cm)	Comparison	Estimate	Std. Error	DF	p-value	Confidence Intervals		Significance	
								Lower	Upper	Statistical	Biological
Number of Growing Season Days	Main Effects	10	Compaction	-6.00	5.18	9	0.277	-17.72	5.72		
			Total Tree Harvesting	-8.75	8.85	9	0.349	-28.77	11.27		
		20	Compaction	-0.38	2.34	9	0.876	-5.67	4.92		
			Total Tree Harvesting	-4.88	2.39	9	0.072	-10.29	0.54		
		30	Compaction	4.88	7.03	9	0.505	-11.02	20.77		
			Total Tree Harvesting	-4.13	1.78	9	0.046	-8.15	-0.10	*	
		100	Compaction	1.88	10.25	9	0.859	-21.32	25.07		
			Total Tree Harvesting	-2.75	6.24	9	0.670	-16.87	11.37		
	Treatment Effects	10	**BO - REF**	**42.75**	**12.35**	**15**	**0.003**	**13.83**	**71.67**	*	*
			BOC - TTP	-5.63	2.08	15	0.016	-10.50	-0.75	*	
			TTC - TTP	-2.63	2.09	15	0.228	-7.51	2.26		
		20	**BO - REF**	**13.38**	**2.32**	**15**	**0.000**	**7.95**	**18.80**	*	*
			BOC - TTP	**-8.00**	**2.31**	**15**	**0.003**	**-13.41**	**-2.59**	*	*
			TTC - TTP	-3.13	2.32	15	0.198	-8.57	2.32		
		30	**BO - REF**	**22.38**	**6.21**	**14**	**0.003**	**7.72**	**37.03**	*	*
			BOC - TTP	0.88	14.85	14	0.953	-34.15	35.92		
			TTC - TTP	4.88	16.07	14	0.766	-33.04	42.81		
		100	**BO - REF**	**33.88**	**12.66**	**14**	**0.018**	**4.00**	**63.75**	*	*
			BOC - TTP	-2.58	21.66	14	0.907	-53.69	48.53		
			TTC - TTP	3.42	22.67	14	0.882	-50.08	56.92		

Table 7. F-statistics on overall significance of predictor variables on soil temperature characteristics during the growing season on an LTSP site near Springfield, OR. Bold indicates significance, $F_{critical}$ (1,9) = 3.36 and $F_{critical}$ (1,15) = 3.07 with α =0.10.

Response variable	Soil Depth (cm)	Overall F-test Comparison	DF	F-value	p-value	Statistically Significant
Daily Average Temperature During Growing Season	10	**(Intercept)**	**1 , 15**	**23712.5**	**<.0001**	*
		OM	**1 , 9**	**27.4**	**0.001**	*
		Compaction	1 , 9	2.1	0.178	
		Year	**1 , 15**	**35.5**	**<.0001**	*
		OM:Compaction	1 , 9	0.7	0.419	
	20	**(Intercept)**	**1 , 15**	**25600.4**	**<.0001**	*
		OM	**1 , 9**	**29.1**	**0.000**	*
		Compaction	1 , 9	1.0	0.348	
		Year	**1 , 15**	**150.6**	**<.0001**	*
		OM:Compaction	1 , 9	0.8	0.390	
	30	**(Intercept)**	**1 , 15**	**22216.1**	**<.0001**	*
		OM	**1 , 9**	**23.0**	**0.001**	*
		Compaction	1 , 9	3.5	0.096	
		Year	**1 , 15**	**97.0**	**<.0001**	*
		OM:Compaction	1 , 9	1.0	0.352	
	100	**(Intercept)**	**1 , 15**	**10199.3**	**<.0001**	*
		OM	**1 , 9**	**11.2**	**0.009**	*
		Compaction	1 , 9	2.7	0.138	
		Year	**1 , 15**	**16.6**	**0.001**	*
		OM:Compaction	1 , 9	1.4	0.266	
Daily Maximum Temperature During Growing Season	10	**(Intercept)**	**1 , 15**	**10541.3**	**<.0001**	*
		OM	**1 , 9**	**28.8**	**0.001**	*
		Compaction	1 , 9	0.5	0.506	
		Year	**1 , 15**	**389.8**	**<.0001**	*
		OM:Compaction	1 , 9	0.1	0.714	
	20	**(Intercept)**	**1 , 15**	**10529.9**	**<.0001**	*
		OM	**1 , 9**	**24.5**	**0.001**	*
		Compaction	1 , 9	0.7	0.416	
		Year	**1 , 15**	**244.1**	**<.0001**	*
		OM:Compaction	1 , 9	0.1	0.797	
	30	**(Intercept)**	**1 , 15**	**10855.9**	**<.0001**	*
		OM	**1 , 9**	**29.4**	**0.000**	*
		Compaction	1 , 9	0.6	0.473	
		Year	**1 , 15**	**221.3**	**<.0001**	*
		OM:Compaction	1 , 9	0.1	0.712	
	100	**(Intercept)**	**1 , 15**	**5655.5**	**<.0001**	*
		OM	**1 , 9**	**10.1**	**0.011**	*
		Compaction	1 , 9	1.7	0.226	
		Year	**1 , 15**	**205.4**	**<.0001**	*
		OM:Compaction	1 , 9	0.2	0.688	
Diel Soil Temperature During Growing Season	10	**(Intercept)**	**1 , 15**	**2587.2**	**<.0001**	*
		OM	1 , 9	**27.0**	**0.001**	*
		Compaction	1 , 9	0.5	0.519	
		Year	**1 , 15**	**201.5**	**<.0001**	*
		OM:Compaction	1 , 9	0.3	0.591	
	20	**(Intercept)**	**1 , 15**	**2430.9**	**<.0001**	*
		OM	1 , 9	**24.7**	**0.001**	*
		Compaction	1 , 9	0.9	0.371	
		Year	**1 , 15**	**69.3**	**<.0001**	*
		OM:Compaction	1 , 9	0.0	0.878	
	30	**(Intercept)**	**1 , 15**	**1904.6**	**<.0001**	*
		OM	1 , 9	**25.1**	**0.001**	*
		Compaction	1 , 9	0.4	0.526	
		Year	**1 , 15**	**97.0**	**<.0001**	*
		OM:Compaction	1 , 9	0.2	0.683	
	100	**(Intercept)**	**1 , 15**	**638.6**	**<.0001**	*
		OM	1 , 9	**10.0**	**0.012**	*
		Compaction	1 , 9	1.6	0.244	
		Year	**1 , 15**	**222.7**	**<.0001**	*
		OM:Compaction	1 , 9	0.2	0.683	

Table 8. Comparisons of treatment effects on soil temperature characteristics during the growing season at an LTSP site near Springfield, OR. Bold indicates biological significance (α = 0.10; minimum difference ±1°C).

Response variables	Main & Treatment Effects	Soil Depth (cm)	Comparison	Estimate	Std. Error	DF	p-value	Confidence Intervals		Significance	
								Lower	Upper	Statistical	Biological
Daily Average Temperature During Growing Season	Main Effects	10	Compaction	-0.16	0.31	9	0.621	-0.87	0.55		
			Total Tree Harvesting	-1.47	0.36	9	0.003	-2.28	-0.65	*	
		20	Compaction	-0.02	0.30	9	0.938	-0.70	0.65		
			Total Tree Harvesting	-1.34	0.30	9	0.002	-2.02	-0.66	*	
		30	Compaction	-0.20	0.33	9	0.569	-0.95	0.56		
			Total Tree Harvesting	-1.30	0.31	9	0.002	-2.00	-0.61	*	
		100	Compaction	-0.02	0.56	9	0.969	-1.28	1.24		
			Total Tree Harvesting	-1.54	0.43	9	0.006	-2.52	-0.56	*	
	Treatment Effects	10	**BO - REF**	**2.64**	**0.40**	**15**	**0.000**	**1.70**	**3.59**	*	*
			BOC - TTP	**-2.73**	**0.34**	**15**	**0.000**	**-3.53**	**-1.93**	*	*
			TTC - TTP	-1.66	0.36	15	0.000	-2.50	-0.82	*	
		20	**BO - REF**	**2.05**	**0.28**	**15**	**0.000**	**1.40**	**2.71**	*	*
			BOC - TTP	**-2.58**	**0.29**	**15**	**0.000**	**-3.25**	**-1.90**	*	*
			TTC - TTP	-1.62	0.30	15	0.000	-2.31	-0.93	*	
		30	**BO - REF**	**2.26**	**0.27**	**14**	**0.000**	**1.63**	**2.90**	*	*
			BOC - TTP	**-1.19**	**1.01**	**14**	**0.259**	**-3.57**	**1.19**	*	*
			TTC - TTP	-0.34	1.01	14	0.743	-2.72	2.05	*	
		100	**BO - REF**	**2.00**	**0.42**	**14**	**0.000**	**1.02**	**2.98**	*	*
			BOC - TTP	-0.95	0.63	14	0.157	-2.44	0.55		
			TTC - TTP	-0.24	0.73	14	0.751	-1.95	1.48		
Daily Maximum Temperature During Growing Season	Main Effects	10	Compaction	-0.15	0.61	9	0.816	-1.52	1.23		
			Total Tree Harvesting	**-2.52**	**0.61**	**9**	**0.003**	**-3.91**	**-1.13**	*	*
		20	Compaction	-0.24	0.60	9	0.697	-1.60	1.11		
			Total Tree Harvesting	-2.16	0.59	9	0.005	-3.51	-0.82	*	
		30	Compaction	-0.14	0.56	9	0.809	-1.41	1.13		
			Total Tree Harvesting	**-2.26**	**0.55**	**9**	**0.003**	**-3.51**	**-1.01**	*	*
		100	Compaction	-0.38	0.64	9	0.560	-1.82	1.05		
			Total Tree Harvesting	-1.59	0.62	9	0.031	-3.00	-0.18	*	
	Treatment Effects	10	**BO - REF**	**4.59**	**0.66**	**15**	**0.000**	**3.04**	**6.14**	*	*
			BOC - TTP	**-5.51**	**0.62**	**15**	**0.000**	**-6.96**	**-4.06**	*	*
			TTC - TTP	**-3.33**	**0.61**	**15**	**0.000**	**-4.76**	**-1.90**	*	*
		20	**BO - REF**	**3.85**	**0.54**	**15**	**0.000**	**2.58**	**5.12**	*	*
			BOC - TTP	**-4.84**	**0.54**	**15**	**0.000**	**-6.10**	**-3.58**	*	*
			TTC - TTP	**-2.90**	**0.54**	**15**	**0.000**	**-4.16**	**-1.63**	*	*
		30	**BO - REF**	**3.51**	**0.51**	**15**	**0.000**	**2.32**	**4.70**	*	*
			BOC - TTP	**-3.72**	**1.08**	**15**	**0.004**	**-6.25**	**-1.19**	*	*
			TTC - TTP	-1.76	1.08	15	0.124	-4.30	0.77		
		100	**BO - REF**	**2.55**	**0.60**	**14**	**0.001**	**1.14**	**3.96**	*	*
			BOC - TTP	**-2.85**	**0.63**	**14**	**0.000**	**-4.33**	**-1.37**	*	*
			TTC - TTP	-1.63	0.64	14	0.023	-3.14	-0.12	*	
Diurnal Soil Temperature During Growing Season	Main Effects	10	Compaction	-0.05	0.63	9	0.938	-1.49	1.38		
			Total Tree Harvesting	**-2.57**	**0.63**	**9**	**0.003**	**-4.01**	**-1.14**	*	*
		20	Compaction	-0.32	0.60	9	0.602	-1.67	1.03		
			Total Tree Harvesting	-2.11	0.59	9	0.006	-3.45	-0.77	*	
		30	Compaction	-0.10	0.60	9	0.872	-1.45	1.25		
			Total Tree Harvesting	-2.29	0.60	9	0.004	-3.65	-0.93	*	
		100	Compaction	-0.36	0.63	9	0.586	-1.79	1.07		
			Total Tree Harvesting	-1.58	0.62	9	0.032	-2.99	-0.17	*	
	Treatment Effects	10	**BO - REF**	**4.57**	**0.66**	**15**	**0.000**	**3.03**	**6.11**	*	*
			BOC - TTP	**-5.45**	**0.62**	**15**	**0.000**	**-6.90**	**-4.00**	*	*
			TTC - TTP	**-3.38**	**0.61**	**15**	**0.000**	**-4.81**	**-1.94**	*	*
		20	**BO - REF**	**3.79**	**0.53**	**15**	**0.000**	**2.55**	**5.02**	*	*
			BOC - TTP	**-4.79**	**0.55**	**15**	**0.000**	**-6.07**	**-3.51**	*	*
			TTC - TTP	**-2.81**	**0.55**	**15**	**0.000**	**-4.11**	**-1.51**	*	*
		30	**BO - REF**	**3.45**	**0.56**	**15**	**0.000**	**2.14**	**4.77**	*	*
			BOC - TTP	**-3.76**	**1.11**	**15**	**0.004**	**-6.36**	**-1.16**	*	*
			TTC - TTP	-1.83	1.11	15	0.120	-4.43	0.77		
		100	**BO - REF**	**2.53**	**0.59**	**14**	**0.001**	**1.13**	**3.94**	*	*
			BOC - TTP	**-2.89**	**0.63**	**14**	**0.000**	**-4.37**	**-1.41**	*	*
			TTC - TTP	-1.68	0.64	14	0.019	-3.18	-0.18	*	

Table 9. F-statistics on overall significance of predictor variables on average Volumetric Water Content (VWC) at multiple depths on an LTSP site near Springfield, OR. Bold indicates significance, $F_{critical}$ (1,9) = 3.36 and $F_{critical}$ (1,15)= 3.07 with α =0.10.

Response variable	Soil Depth (cm)	Overall F-test Comparison	DF	F-value	p-value	Statistically Significant
Daily Average VWC During Growing Season	10	**(Intercept)**	**1 , 15**	**756.8**	**<.0001**	*
		OM	1 , 9	1.5	0.257	
		Compaction	1 , 9	3.2	0.106	
		Year	**1 , 15**	**58.1**	**<.0001**	*
		OM:Compaction	1 , 9	1.5	0.248	
	20	**(Intercept)**	**1 , 15**	**576.4**	**<.0001**	*
		OM	1 , 9	1.0	0.343	
		Compaction	1 , 9	0.0	0.918	
		Year	**1 , 15**	**11.6**	**0.004**	*
		OM:Compaction	1 , 9	0.9	0.374	
	30	**(Intercept)**	**1 , 15**	**612.8**	**<.0001**	*
		OM	**1 , 9**	**7.0**	**0.026**	*
		Compaction	**1 , 9**	**3.4**	**0.098**	*
		Year	**1 , 15**	**10.3**	**0.006**	*
		OM:Compaction	**1 , 9**	**7.0**	**0.027**	*
	100	**(Intercept)**	**1 , 15**	**437.7**	**<.0001**	*
		OM	1 , 9	0.1	0.718	
		Compaction	1 , 9	2.0	0.189	
		Year	**1 , 15**	**19.5**	**0.001**	*
		OM:Compaction	1 , 9	0.1	0.762	

Table 10. Comparisons of treatment effects on soil moisture characteristics during the growing season at an LTSP site near Springfield, OR. Bold indicates biological significance (α = 0.10; minimum difference ±3% Volumetric Water Content - VWC).

Response variables	Main & Treatment Effects	Soil Depth (cm)	Comparison	Estimate	Std. Error	DF	p-value	Confidence Intervals		Significance	
								Lower	Upper	Statistical	Biological
Daily Average VWC During Growing Season	Main Effects	10	Compaction	-0.93	2.31	9	0.696	-6.16	4.30		
			Total Tree Harvesting	-3.89	2.23	9	0.116	-8.94	1.16		
		20	Compaction	1.70	2.31	9	0.481	-3.53	6.92		
			Total Tree Harvesting	-3.15	2.30	9	0.204	-8.36	2.06		
		30	Compaction	-7.91	2.49	9	0.011	-13.55	-2.28	*	
			Total Tree Harvesting	**9.27**	**2.48**	**9**	**0.005**	**3.68**	**14.87**	*	*
		100	Compaction	-6.04	4.94	9	0.252	-17.21	5.13		
			Total Tree Harvesting	-0.22	4.93	9	0.966	-11.37	10.94		
	Treatment Effects	10	BO - REF	2.14	2.17	15	0.339	-2.94	7.22		
			BOC - TTP	3.82	2.25	15	0.111	-1.46	9.09		
			TTC - TTP	3.66	2.26	15	0.126	-1.63	8.96		
		20	BO - REF	7.79	2.32	15	0.004	2.35	13.23	*	
			BOC - TTP	3.75	2.19	15	0.107	-1.38	8.87		
			TTC - TTP	3.84	2.19	15	0.100	-1.29	8.97		
		30	BO - REF	7.64	2.55	15	0.009	1.67	13.61	*	
			BOC - TTP	-0.43	2.50	15	0.867	-6.29	5.43		
			TTC - TTP	-0.44	2.52	15	0.865	-6.33	5.46		
		100	BO - REF	-0.21	4.55	14	0.963	-10.96	10.53		
			BOC - TTP	-3.47	4.87	14	0.487	-14.95	8.01		
			TTC - TTP	-1.08	4.87	14	0.828	-12.58	10.42		

Table 11. F-statistics on overall significance of predictor variables including average monthly soil respiration (O-horizon, bulk, microbial) and growing season soil respiration (bulk) on an LTSP site near Springfield, OR. Bold indicates significance, $F_{critical}$ (1,9) = 3.36 and $F_{critical}$ (1,15) = 3.07 with α =0.10.

Response variable	Overall F-test Comparison	DF	F-value	p-value	Statistically Significant
Average Monthly O horizon Respiration	**(Intercept)**	**1 , 15**	**853.8**	**<.0001**	*
	OM	**1 , 9**	**16.2**	**0.003**	*
	compaction	1 , 9	0.1	0.806	
	year	**1 , 15**	**43.1**	**<.0001**	*
	OM:compaction	1 , 9	0.6	0.463	
Average Monthly Bulk Soil Respiration	**(Intercept)**	**1 , 15**	**318.8**	**<.0001**	*
	OM	1 , 9	1.3	0.280	
	compaction	1 , 9	0.1	0.783	
	year	**1 , 15**	**37.5**	**<.0001**	*
	OM:compaction	1 , 9	0.2	0.664	
Average Monthly Microbial Respiration	**(Intercept)**	**1 , 15**	**371.3**	**<.0001**	*
	OM	1 , 9	0.5	0.490	
	compaction	1 , 9	0.0	0.961	
	year	**1 , 15**	**44.4**	**<.0001**	*
	OM:compaction	**1 , 9**	**6.0**	**0.037**	*
Growing Season Bulk Rs	**(Intercept)**	**1 , 158**	**322.3**	**<.0001**	*
	OM	1 , 9	1.1	0.320	
	compaction	1 , 9	0.3	0.579	
	year	1 , 158	2.5	0.116	
	10cm Soil Temp	**1 , 158**	**39.3**	**<.0001**	*
	OM:compaction	1 , 9	0.0	0.843	

Table 12. Comparisons of treatment effects on two-year average monthly soil respiration sources (O-horizon, bulk, and microbial), and growing season microbial respiration at an LTSP site near Springfield, OR. Bold indicates biologic significance (α = 0.10).

Response variables	Main & Treatment Effects	Comparison	Estimate	Std. Error	DF	p-value	Confidence Intervals		Significance	
							Lower	Upper	Statistical	Biological
Average Monthly O-Horizon Respiration	Main Effects	Compaction	-0.06	0.14	9	0.699	-0.38	0.26		
		Total Tree Harvesting	**0.45**	**0.16**	**9**	**0.020**	**0.09**	**0.82**	*	*
	Treatment Effects	**BO - REF**	**-3.89**	**0.56**	**15**	**0.000**	**-5.22**	**-2.57**	*	*
		BOC - TTP	**0.34**	**0.12**	**15**	**0.014**	**0.05**	**0.63**	*	*
		TTC - TTP	0.04	0.14	15	0.804	-0.30	0.37		
Average Monthly Bulk Soil Respiration	Main Effects	Compaction	-0.13	0.25	9	0.617	-0.71	0.44		
		Total Tree Harvesting	0.29	0.26	9	0.287	-0.29	0.87		
	Treatment Effects	**BO - REF**	**-2.82**	**0.39**	**15**	**0.000**	**-3.74**	**-1.89**	*	*
		BOC - TTP	-0.35	0.44	15	0.441	-1.38	0.68		
		TTC - TTP	-0.47	0.44	15	0.296	-1.50	0.55		
Average Monthly Microbial Respiration	Main Effects	Compaction	-0.22	0.14	9	0.158	-0.54	0.10		
		Total Tree Harvesting	**0.43**	**0.18**	**9**	**0.043**	**0.02**	**0.84**	*	*
	Treatment Effects	**BO - REF**	**-0.89**	**0.22**	**15**	**0.001**	**-1.41**	**-0.37**	*	*
		BOC - TTP	0.10	0.15	15	0.514	-0.24	0.44		
		TTC - TTP	0.24	0.14	15	0.115	-0.09	0.57		
Growing Season Bulk Rs	Main Effects	Compaction	-0.13	0.33	9	0.694	-0.88	0.61		
		Total Tree Harvesting	0.48	0.33	9	0.180	-0.27	1.22		
	Treatment Effects	**BO - REF**	**-3.39**	**0.48**	**15**	**0.000**	**-4.51**	**-2.27**	*	*
		BOC - TTP	-0.08	0.44	15	0.866	-1.11	0.95		
		TTC - TTP	-0.45	0.44	15	0.321	-1.49	0.58		

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