EFFECTS OF VARYING FOREST FLOOR AND SLASH RETENTION ON SOIL NUTRIENT AND CARBON POOLS IN A REGENERATING DOUGLAS-FIR TREE FARM: NARA-SOILS

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TABLE OF CONTENTS

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Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

LIST OF FIGURES

FIGURE NO. | FIGURE TITLE | PAGE NO.

LIST OF TABLES

TABLE NO. | TABLE TITLE | PAGE NO.

LIST OF ACRONYMS

BO	bole-only harvest treatment
BOC	bole-only harvest+ compaction treatment
C	carbon
CO_2	carbon dioxide
DF	Douglas-fir
LTSP	long-term soil productivity
OM	organic matter
N	nitrogen
PNW	Pacific Northwest
PVC	poly-vinyl chloride
PWP	plant wilting point
REF	unharvested reference treatment
TT	total tree harvest treatment
TTC	total-tree harvest + compaction treatment
TTP	total-tree harvest + compaction + forest floor removal treatment
VWC	volumetric water content

EXECUTIVE SUMMARY

Forest harvesting intrinsically removes organic matter (OM) and associated nutrients; these exports may impact soil productivity and soil carbon stores of managed forests. Many studies have been conducted that use treatments ranging from bole-only removal to whole tree and forest floor removal to examine the impacts of OM removal on sustainability. Most forest floor removal studies that include a whole tree harvesting treatment have shown no significant effect on stand productivity or soil carbon. The process by which stand productivity and soil carbon resist change as a result of OM removal has been poorly explored. A release of nutrients from higher nutrient (e.g. N) mineralization rates, and by roots decaying at a faster rate, have been hypothesized due to higher soil moisture and temperature in harvested stands. While the hypothesis that decomposing roots are compensating soil carbon for organic matter losses has been around for many years, it has not been robustly tested. We monitored soil temperature, moisture, and respiration for two years after biomass harvesting, OM removal, and compaction treatments that bracketed the range of reality likely present in a biomass harvesting system. We also measured soil carbon, nitrogen, stable isotopes, and biomarkers in soils collected pre-, post-, and 2 years post-treatment. We found that average, maximum, and diel fluxes of soil temperature increased with increasing intensity of harvesting and organic matter removal treatments down to 100cm in depth. Soil respiration was not affected by changes in temperature, but was elevated as a result of leav-ing biomass on the site – possibly the result of a priming effect. Impacts of the treatments to soil temperature could have an effect on the soil carbon pool and availability of nutrients to trees. We found no apparent change in the size or con-centration of the soil carbon pool; however the C:N increased after treatment while the proportion of light fraction decreased. These results suggest that there were higher mineralization rates (reducing the light fraction) as well as a source of fresh material (with a high C:N). Biomarkers from the CuO oxidation procedure support this assertion that there were higher mineralization rates after harvesting and that the mineralized carbon was replaced by residual root carbon. These results suggest that residual surface biomass may not play as strong of a role in affecting the long-term soil productivity as widely believed and that we need to understand the role that residual roots play in supporting long-term soil productivity.

INTRODUCTION

Forest harvest residues and forest floor materials are thought to be significant sources of mineral soil organic matter and of nutrients for regenerating and establishing forests. These materials are often piled and burned and are currently being considered as a source of biofuel feedstock. We propose to examine the effects of varying harvest residue and forest floor levels on soil carbon and nutrient pools, tree productivity, and soil respiration on a recently established Long-term soil productivity experiment. Treatments include bole-only, total-tree, and total tree + forest floor removal in combination with and without moderate compaction. To achieve these goals we will examine Task 1) soil moisture, temperature, and respiration, Task 2) whole soils and density fractions pre-, post-, and 2 year post for elemental contents stable isotopic ratios, Task 3) Foliar response to soil changes, Task 4) Examine whole soils pre-, post-, and 2yr post for exchangeable nutrient and Task 5) Examine inputs of carbon and nutrients into mineral soils using pan lysimeters. This work will allow us to examine the soil's response to these intensive treatments and understand the subsequent stand's response.

TASK 1: MONITOR AND REPORT ON SOIL MOISTURE AND TEMPERATURE DATA AND EXAMINE SOIL CARBON CYCLING THROUGH SOIL RESPIRATION

Task Objectives

The goal of this research is to investigate the roles of harvest, its residues, and the forest floor on soil temperature, moisture, and respiration on an Oregon Douglas-fir stand where intensive forest management is practiced. The specific objectives of are 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.

Methodology

Site Description

The NARA Long-Term Soil Productivity (LTSP) study site is located approximately 30km east of Eugene, Oregon along the western side of the Cascades (Figure SNC-1.1). 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 (Figure SNC-1.2) (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. 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 form of snow, however there was no other period of snowfall 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 with a thinning treatment occurring mid-rotation (S. Holub, Personal Communication).

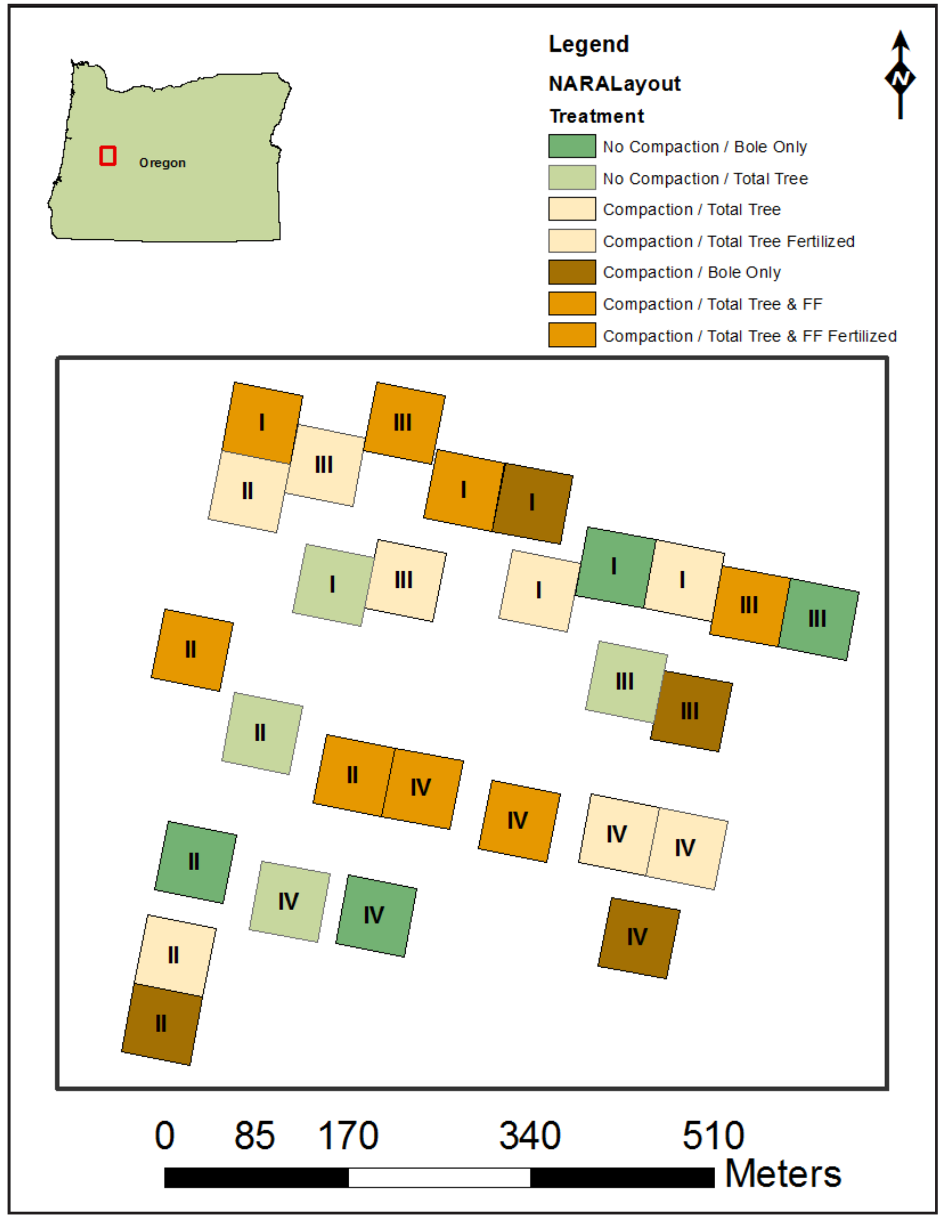

Figure SNC-1.1. Treatment layout of blocks and plots for at the LTSP affiliate study site in the western Oregon cascades located east of Springfield, OR.

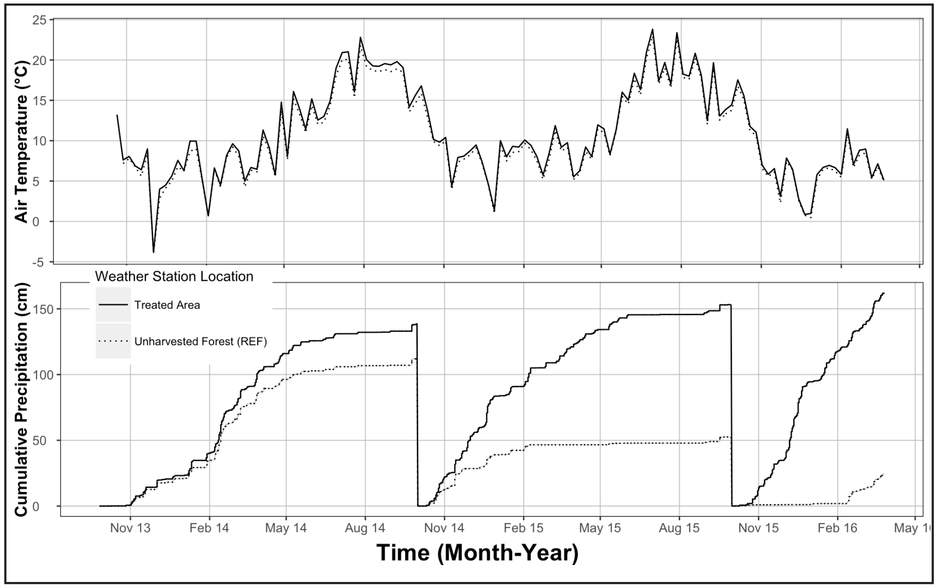

Figure SNC-1.2. Air temperature and cumulative precipitation of the treated area and the adjacent unharvested reference on a LTSP site near Springfield, OR.

Experimental Design

Plots were delineated prior to treatment application and run for elemental analysis to ensure similar site characteristics. 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 in 2014-2015 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.

Biomass Removal and Compaction Treatments

This is considered an 'affiliate' LTSP site because all nine-treatments are not present (Table SNC-1.1). 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. 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.

Table SNC-1.1. 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**

Instrumentation and Observation Frequency

Temperature and moisture data loggers

All plots (including 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.

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 was 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.

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's warm and moist enough to perform necessary biologic functions. Growing season length was calculated individually for the 10, 20, 30, and 100cm depths.

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; Zuur et al., 2008; Pinheiro et al., 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 α=0.10, was used to asses 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 ±1 day 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).

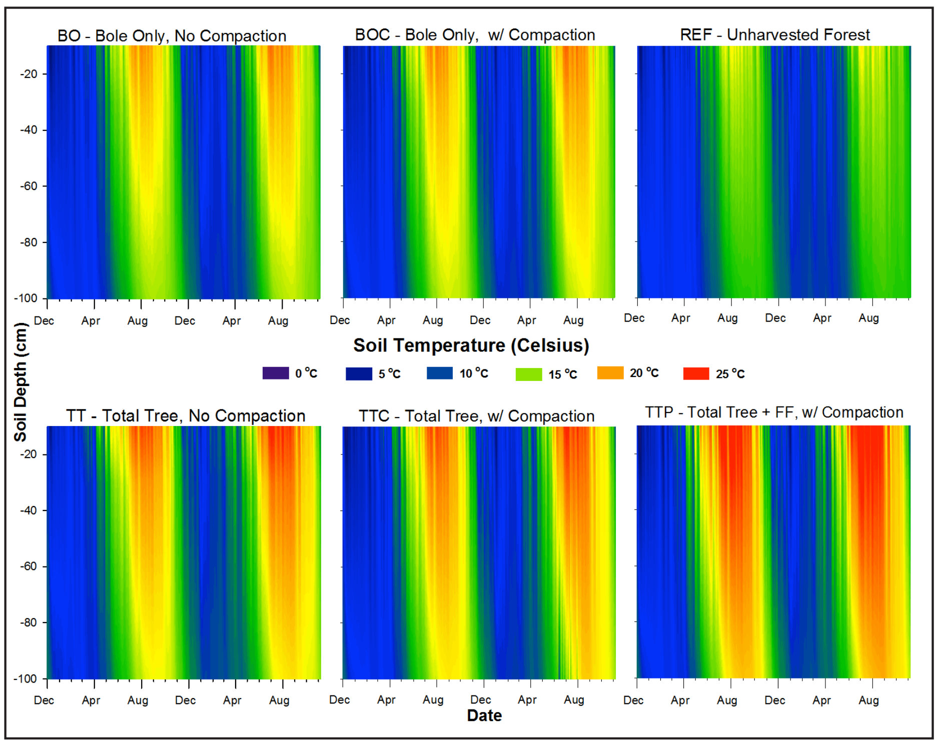

Figure SNC-1.3. Observed two-year soil temperature patterns following intensive organic matter and compaction manipulations at the Springfield, OR LTSP site. Soil probes were installed at 10, 20, 30, and 100cm mineral depth recorded hourly but represented on daily time steps. A linear average is used to interpolate between all probes.

Results

We 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 only examined over the entire two years to determine the effect of the treatments on soil carbon.

Growing Season Length

There were obvious differences in soil temperature and moisture patterns over the two years of data collection (Figures SNC-1.3 & SNC-1.4). Nearly all treatments, at all depths, accumulated between 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 SNC-1.5).

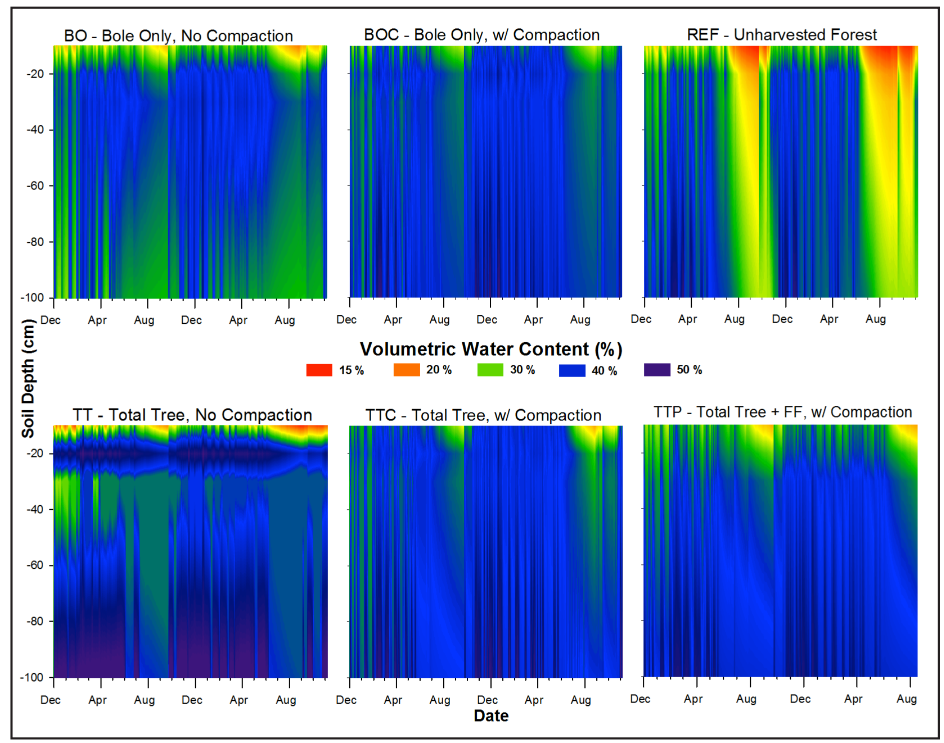

Figure SNC-1.4. Observed two-year soil volumetric water content (VWC) patterns following intensive organic matter and compaction manipulations at the Springfield, OR LTSP site. Soil probes were installed at 10, 20, 30, and 100cm mineral depth recorded hourly but represented on daily time steps.

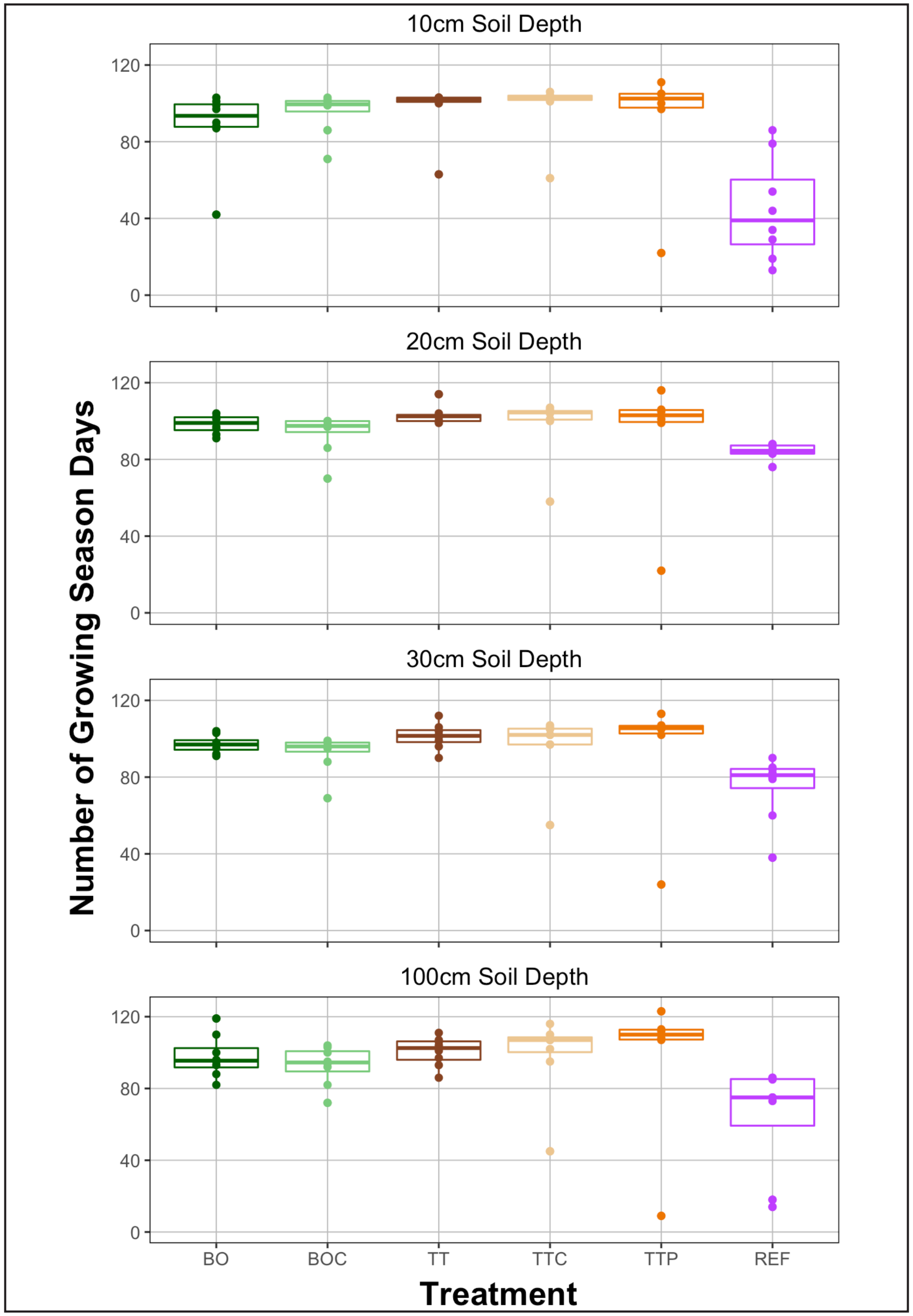

Figure SNC-1.5. Number of biologically defined growing season days for a LTSP site in Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction.

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) ($p<0.1$). 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.

There were very few significant differences in growing season length between biomass harvesting treatments. 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. 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. 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.

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 SNC-1.6). There was very strong evidence that the main effect of organic matter removal (OM) significantly influenced the average temperature at all soil depths ($p<0.1$). 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. 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.

The additive effect of 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. The additive effect of removing only the forest floor (TTC-TTP) increased the average growing season temperature approximately +1.6°C from 10-20cm, however this was only statistically significant and not biologically significant. Deeper than 30cm, no significantly different temperatures were observed for any treatments. 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. 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). 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.

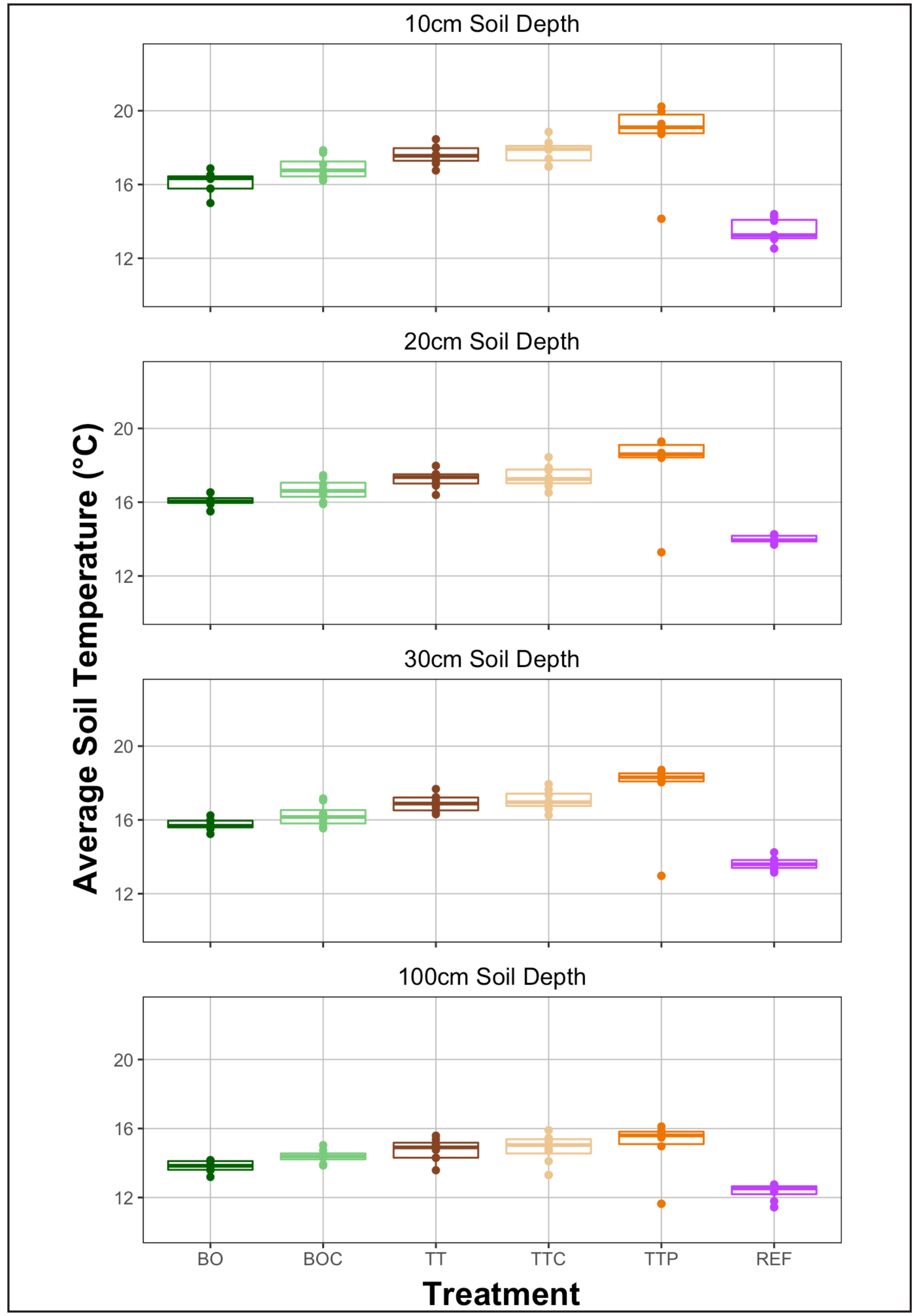

Figure SNC-1.6. Average soil temperature for a LTSP site in Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction.

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 SNC-1.7). 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. There was no evidence that the main effect of Compaction, nor the interaction (OM:Compaction), influenced the growing season maximum soil temperature. The strength of evidence 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. 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.

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. The additive effect of total tree and forest floor removal (BOC-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. 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.

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. 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).

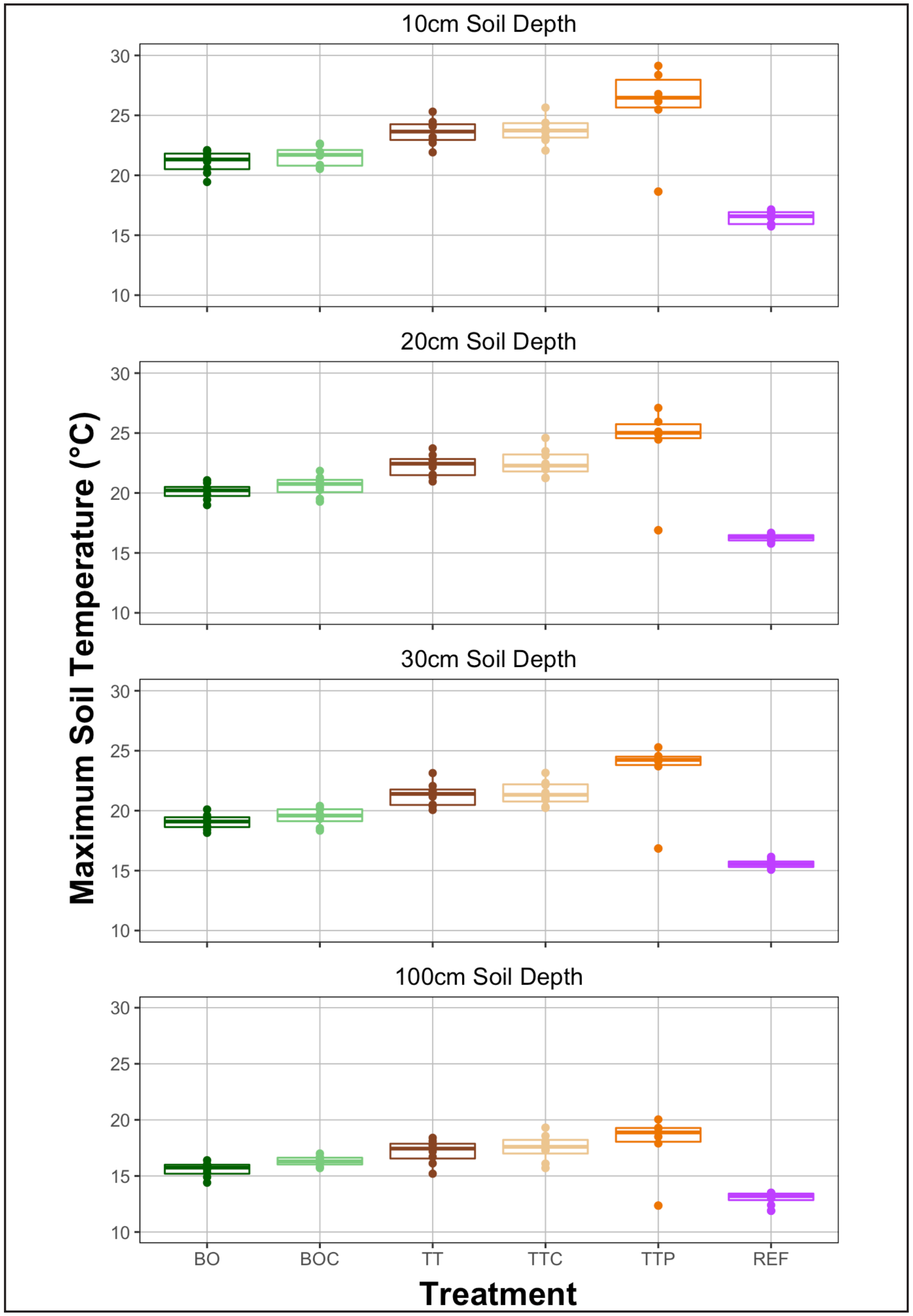

Figure SNC-1.7. Maximum soil temperature for a LTSP site in Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction.

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 (Figure SNC-1.8). 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. There was no evidence that the main effect of compaction influenced the growing season diurnal soil temperature.

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. 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.

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 (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.

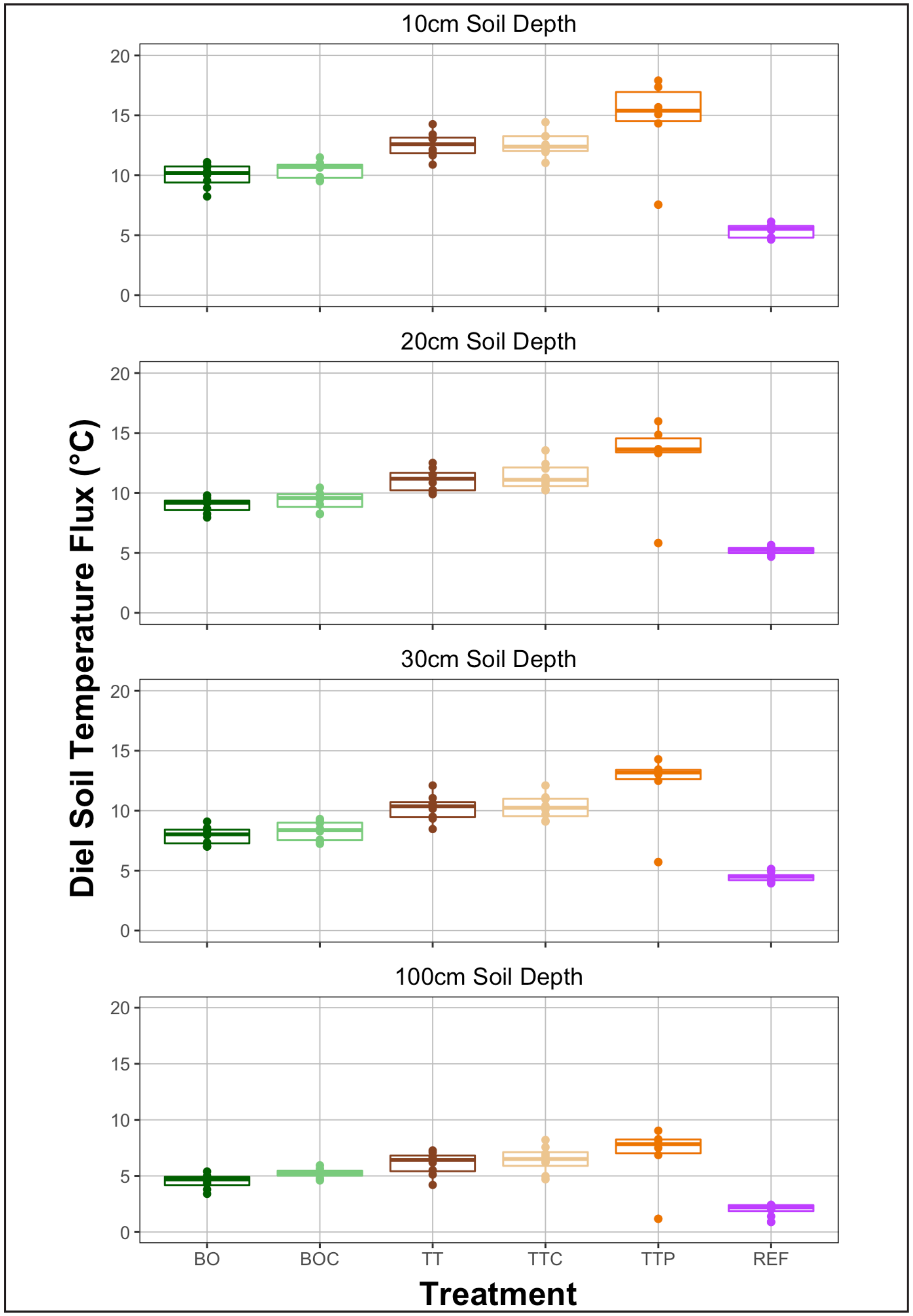

Figure SNC-1.8. Diel soil temperature flux for a LTSP site near Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction.

Average Soil Moisture

There were no reliable significant differences between any treatments or depths over the two years of data collection (Figure SNC-1.9). 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 this data is called into question. Two soil moisture probes, both on TT treatments, experienced highly questionable read-ings 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 be inconsistently influenced by air pock-ets. 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 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. BOC and TTC had approx-imately 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. In summation, the only significant result was the main effect of total tree harvesting at 30cm depth, however the author cautions placing too much emphasis on this result.

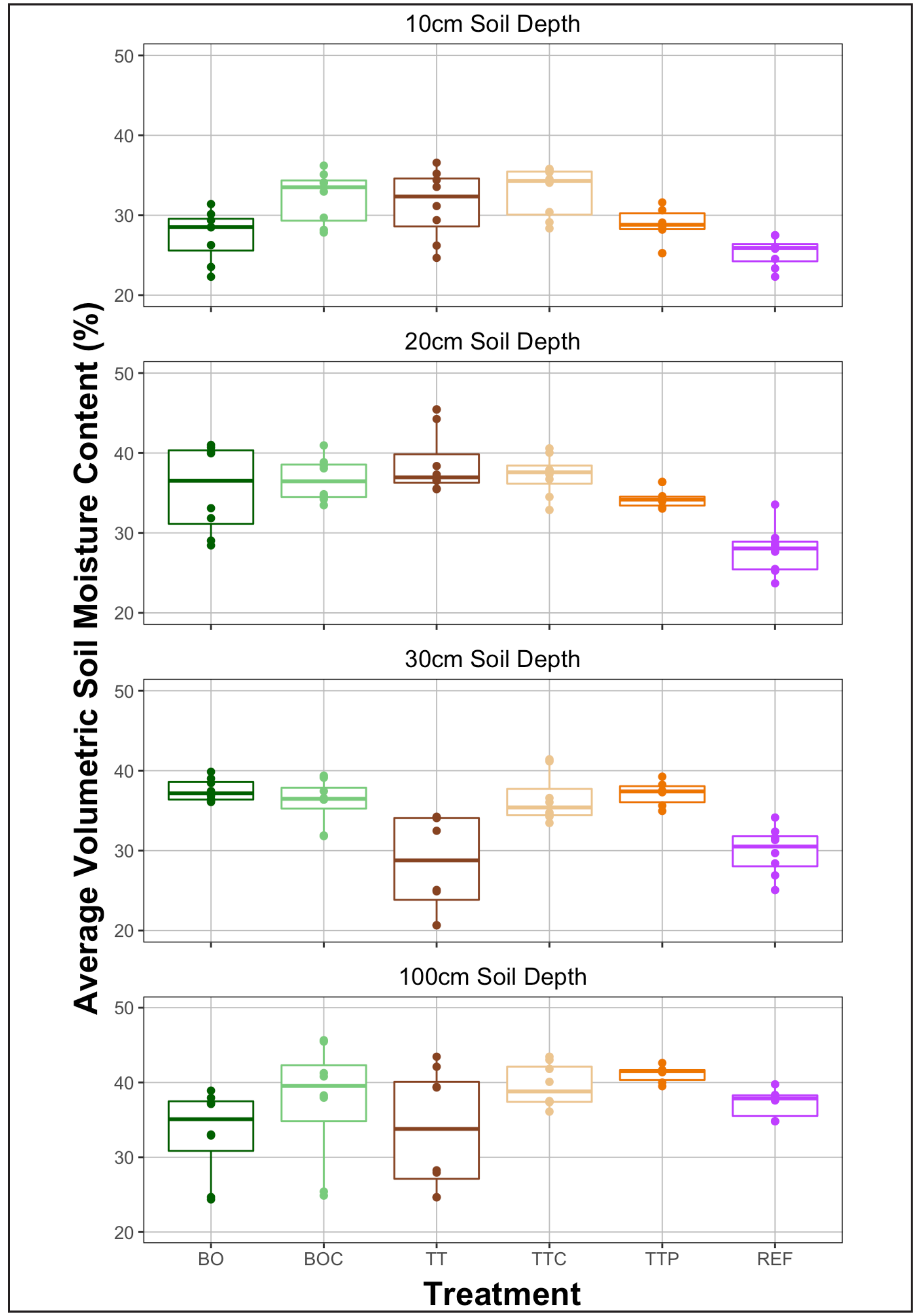

Figure SNC-1.9. Average soil volumetric water content for a LTSP site near Springfield, OR. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction.

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 (Figure SNC-1.10). 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. 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.

Total Tree Harvesting for the O-horizon and bulk soil show decreases in respiration with higher levels of organic matter removal. 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. 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}.

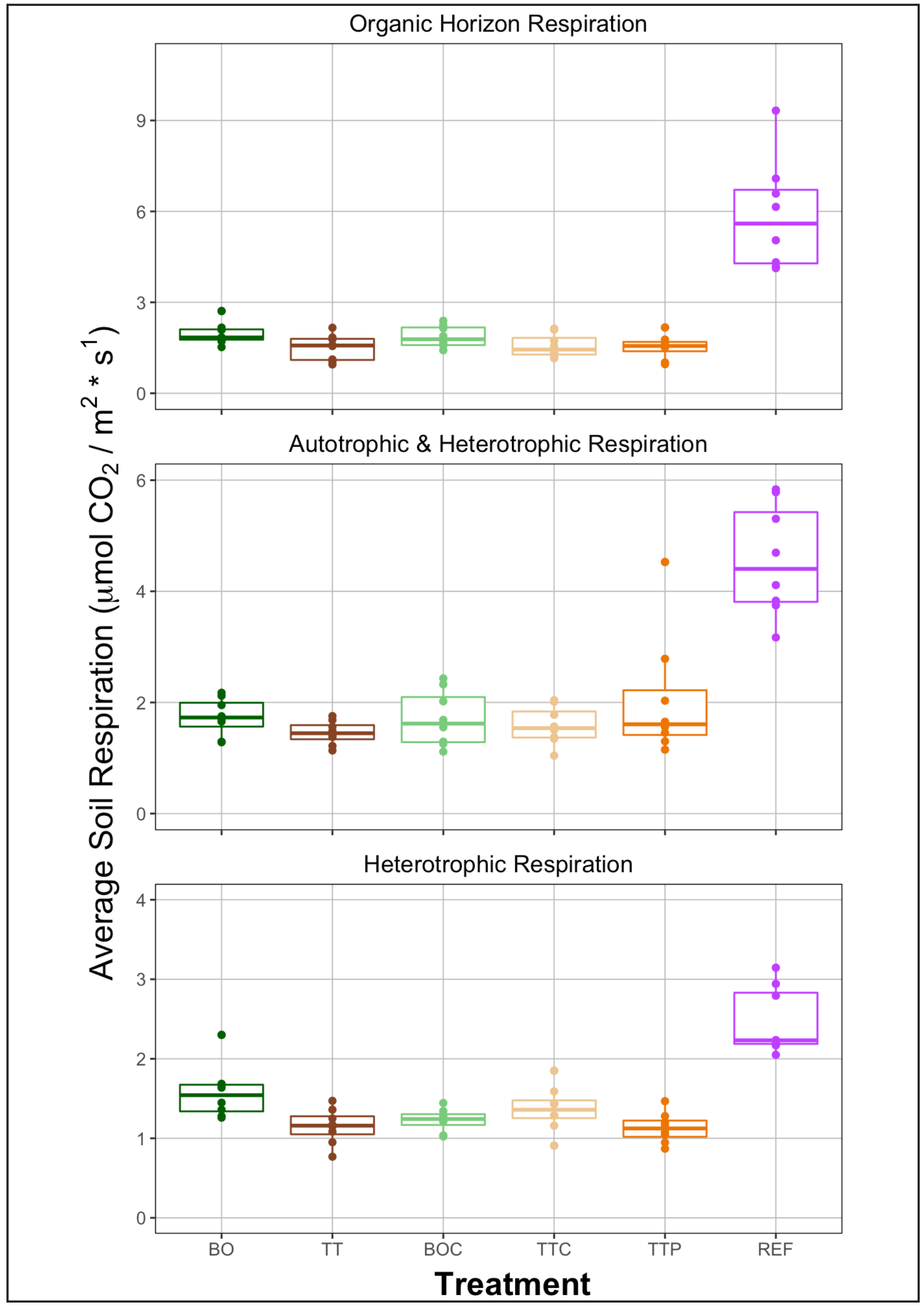

Figure SNC-1.10. Average monthly soil respiration of multiple sources over two years at a LTSP site near Springfield, OR. Note the different Y-axis used between sources of respiration. BO - Bole Only; BOC - Bole only with compaction; TT - Total tree harvest, TTC - total tree harvest with compaction, and TTP total tree and forest floor removal with compaction.

Conclusions/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 little 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.

Growing Season

There were nearly a complete absence of biologically significant differences in growing season length for any treatments (recall 'treatments' do not include the unharvested reference plots) and soil depths measured. 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 (Figure SNC-1.5). 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.

There are two distinctly different distributions of soil temperature that can be attributed to the dichotomous 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 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.

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 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 (Figure SNC-1.6, SNC-1.7, & SNC-1.8). 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. Soil temperatures of forest floor removal treatments reached the optimal range for nitrification rates. Fertilization applications should consider nutrient cycling pathways at these higher temperatures to ensure objectives are met.

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, however there is a general trend of a slightly higher average, maximum, and diel flux of soil temperature when compaction is present. To the authors' 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) water uptake, and nutrient mineralization. Effects of harvest residue management and other site preparation techniques on soil and air temperatures have previously been reported at the treatment level, but there is little information on temperature patterns in the various microsites created by these treatments. This study examines the effects of bole-only harvesting with and without vegetation control (BO + VC; BO - VC. We 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 (Figure SNC-1.6

& SNC-1.7). 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.

Impacts to Douglas-fir seedlings

Douglas-fir seedlings are susceptible to mortality if the site reach extremes 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 is often used to define lethal temperatures for Douglas-fir roots, however this study used a soil depth of 4.5cm in a relatively small-volume container to reach these conclusions (Lopushinsky, 1990).

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. 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. 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 undamaged 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. The relatively low D_b 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 SNC-1.8). 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. 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 in Hillel, 2004).

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 SNC-1.9). 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. This is with the caveat that these sites had complete vegetation control to minimize seedling competition for water, light and nutrients.

Soil Respiration

We observed a wide range in soil temperatures but did not observe a proportional change in respiration rates to these increases in soil temperatures (Figure SNC-1.10). Basic biologic principles predict the highest rates of activity occur as temperature increase (Lloyd and Taylor, 1994). We found significant increases in the growing season average, maximum, and diel flux of soil temperature without any evidence to suggest a moisture limitation. 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.

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. Soil respiration rates at the LTSP site in Springfield, OR through Year-2 are reflected in Figures SNC-1.11-SNC-1.13.

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, 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)I have considered the latest studies and tried to identify the most important needs for future research. Recent publications have shown that the increase or decrease in soil organic matter mineralization (measured as changes of CO2 efflux and N mineralization. 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 treatment.

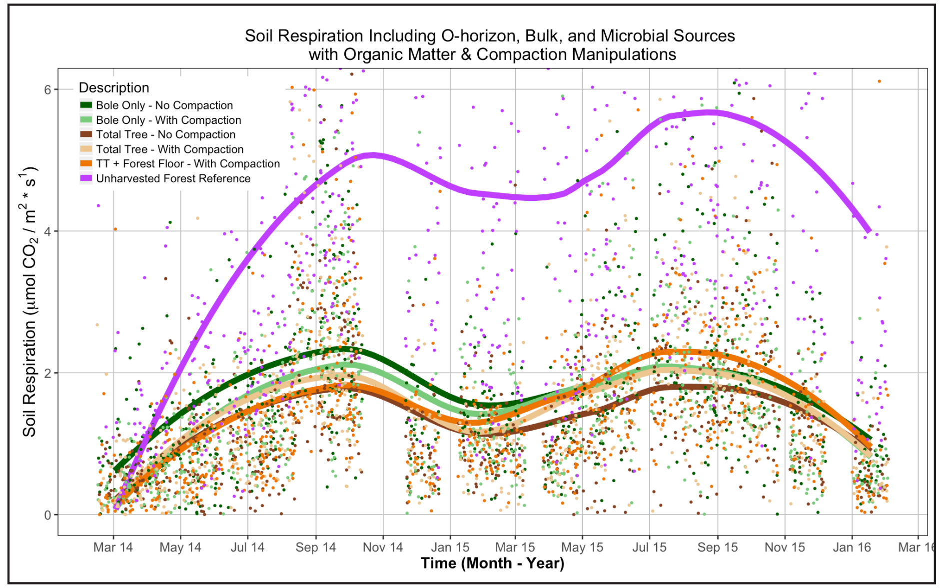

Figure SNC-1.11. Observed soil respiration (including O-horizon, bulk, and microbial sources) over two years using a LiCOR 8100A on monthly intervals located on a LTSP site near Springfield, OR.

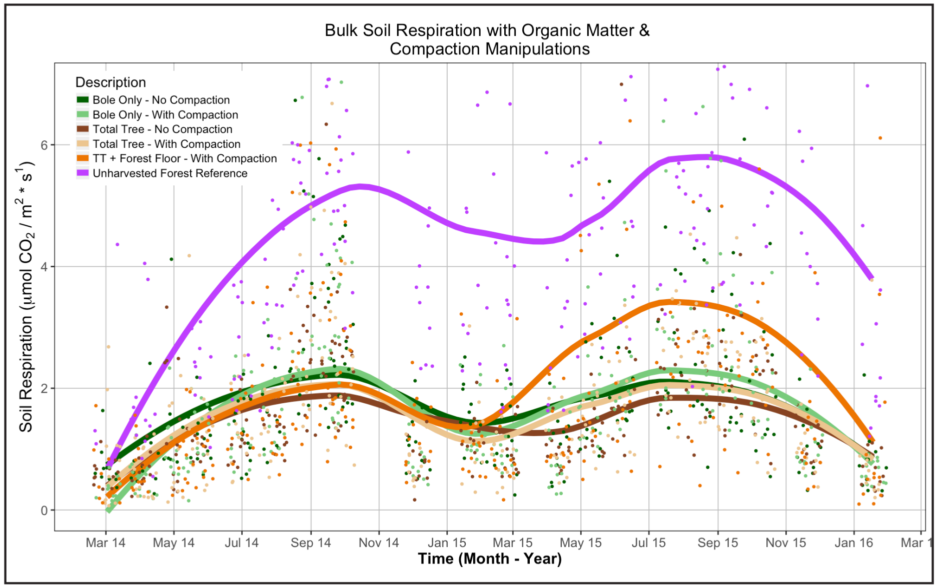

Figure SNC-1.12. Observed bulk soil respiration patterns over two years using a LiCOR 8100A on monthly intervals located on a LTSP site near Springfield, OR.

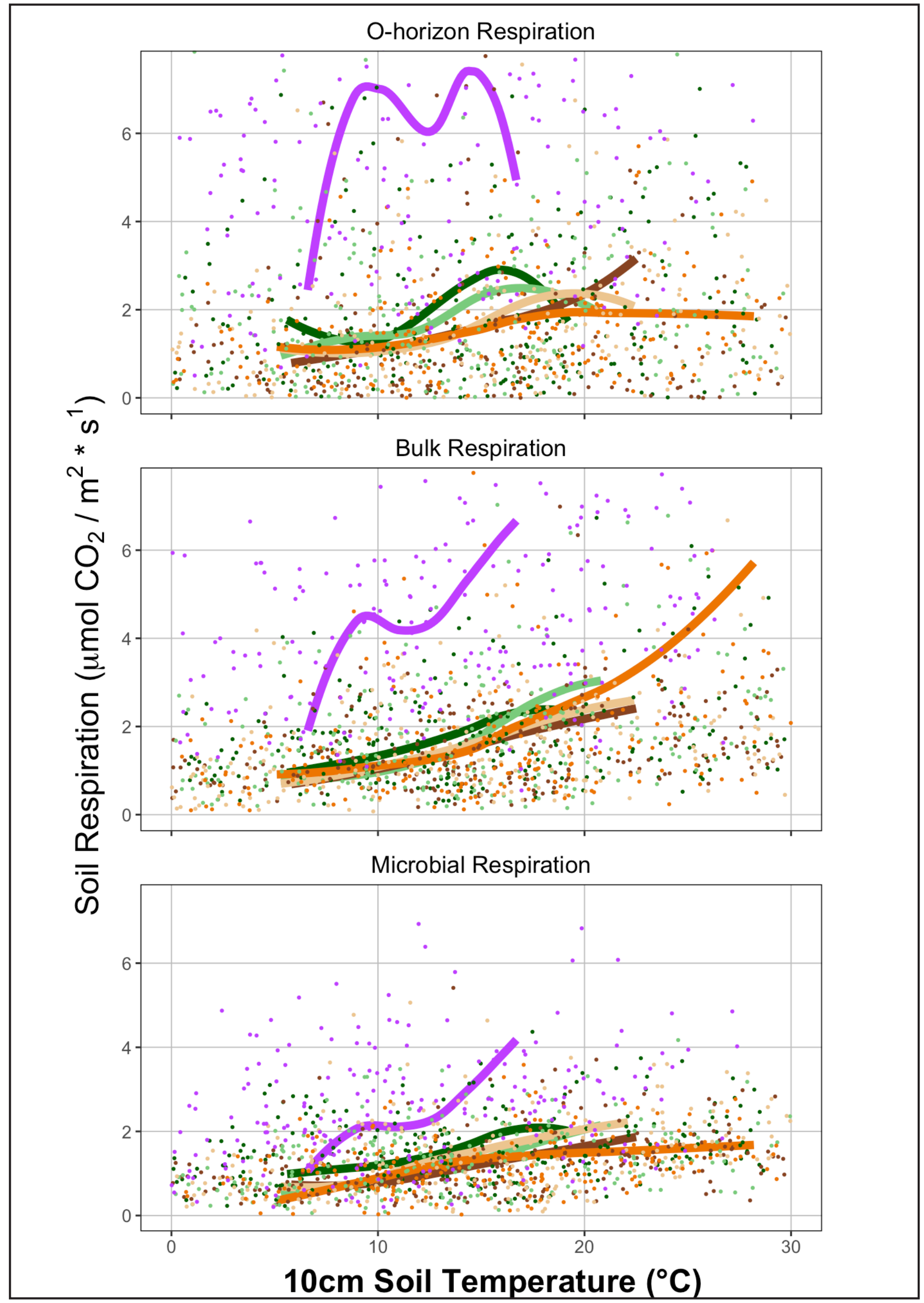

Figure SNC-1.13. Soil respiration as a function of soil temperature for all observed sources. Data encompasses two years of observations with monthly measurement intervals located on a LTSP site near Springfield, OR.

TASK 2: ANALYZE WHOLE SOILS AND DENSITY FRACTIONS PRE-, POST-, AND 2-YEAR-POST FOR ELEMENTAL CONTENTS AND STABLE ISOTOPIC RATIOS.

Task Objective

Forest harvesting intrinsically removes organic matter (OM) and associated nutrients; these exports may impact soil productivity and soil carbon stores of managed forests. Many studies have been conducted that use treatments ranging from bole-only removal to whole tree and forest floor removal to examine the impacts of OM removal on sustainability. Most forest floor removal studies that include a whole tree harvesting treatment have shown no significant effect on stand productivity or soil carbon (Powers et al. 2005, Ponder et al. 2012). The North American long-term soil productivity (LTSP) network found no significant differences in tree productivity at age 10 after whole tree harvesting and floor removal on 18 sites across North America and minor reductions in soil carbon in soils with very low or very high carbon contents (Powers et al. 2005).

The process by which stand productivity and soil carbon resists change as a result of OM removal has been poorly explored. A release of nutrients from higher nutrient (e.g. N) mineralization rates and by roots decaying at a faster rate have been hypothesized due to higher soil moisture and temperature in harvested stands (Powers et al. 2005, Van Lear et al. 2000, Li et al. 2003, Roberts et al. 2005, Sanchez et al. 2006, Slesak et al. 2009, Slesak et al. 2010, Slesak et al. 2011). While the hypothesis that decomposing roots are compensating soil carbon for organic matter losses has been around for many years, it has not been robustly tested as far as I know.

The objectives of this study were to:

1. Determine the effect of organic matter removal and compaction on soil carbon pools. We hypothesize that soil carbon will be unaffected by either organic matter or compaction manipulations.

2. Determine the mechanisms of resilience of tree growth and soil carbon to changes after organic matter manipulations and compaction. We hypoth esize that higher mineralization rates as a result of higher soil moisture and temperature mediate any reduction in nutrient availability caused by removing organic matter. Furthermore, we hypothesize that residual roots replace native soil carbon causing there to be no net loss in total soil carbon.

Methodology

Site Description

See Task 1: Monitor and report on soil moisture and temperature data and examine soil carbon cycling through soil respiration

Soil Sampling

Soils were sampled using coring methods to 100cm in depth (0-15, 15-30, and 30-100cm) at 26 locations within each plot. Soils were composited by depth (1 depth per plot). We focused on the 0-15 and 15-30cm depths for this study. Soils were dried and sieved to 2mm.

Density fractionations were conducted using the methods of Crow et al. (2007) on soils collected pre- and 2 years post-harvest. Density fractions and whole soils were ground using a roller grinder, and the stable isotopic (^{13}C and ^{15}N) plus C and N composition of all whole soils and density fractions were determined. C and N concentration was determined by dry combustion using a Thermo FlashEA 1112 Series, and stable isotopes were determined at the CEOAS Stable Isotope Lab using a DeltaPlusXL. CuO oxidation was conducted on whole soils and density fractions pre- and 2yrs post using the methods of (Goñi and Montgomery, 2000).

Results and Discussion

These results should be considered preliminary (as such, no statistical tests have been conducted). In general, the data show that there is no difference between C, N, or C:N of the treatment plots during the pre-treatment (Table SNC-2.1). There also does not appear to be any difference among the treatments stable isotopic composition or bulk density. Immediately post-treatment there doesn't appear to be much effect on the C and N contents between the treatments, but *there does appear to be an increase in %C and concomitant increase in the C:N of the 0-15cm and 15-30 mineral soil* suggesting that some fresh organic matter has made its way into the soil from dead roots or mixing of harvest residues and O-horizon into the mineral soil (Table SNC-2.2). C and N concentrations of both mineral soil horizons have appeared to decrease across most treatments between the post- and 2 year post-treatments sampling periods. Many of the treatments' C:N of both mineral soil horizons have decreased during the 2-years post-treatment. *This suggests that the lack of inputs and/or higher rates of mineralization have decreased the OM content of* *the 0-15 and 15-30cm soil horizons between the post- and 2 years post-treatment harvest sampling dates.* However, there does not appear to be any differences in the ^{13}C of whole soils between pre-treatment and 2 –years post harvest. Detailed analysis of density fractions (this study – see below) as well as soil respiration, temperature, and moisture (associated study) will elucidate if any of these hypothesized process are occurring.

In the surface mineral soil horizon it appears as if the proportion of the whole soil made up by the light fraction decreased with the intermediate and heavy fraction both increased (Table SNC-2.3). This suggests that the lack of inputs and/or higher rates of mineralization have decreased the light fraction content of this surface soil horizons between the pre- and 2 years post-treatment harvest sampling dates. However, the C:N content of the light fraction appears to increase over this time period suggesting that it was influenced by fresh OM inputs from roots or slash. The ^{13}C content appears to be unaffected in any fraction by the harvest or any of the treatments in either the 0-15 or 15-30cm horizon (Table SNC-2.4). On the other hand ^{15}N of the light fraction appears to become more depleted after harvesting with the strongest effect occurring on the C treatment, which may have had fresh slashed (depleted ^{15}N signature) mixed in with the surface soil during het compaction process.

Furthermore, we found that there was a stronger contribution of belowground sources (roots) post-treatment in the 0-15cm horizon (Figure SNC-2.1). Roots have a higher cinnamyl (C) phenol and syringyl (S) phenol than branches or needles. A higher concentration of these biomarkers relative to vanillyl (V) phenols (C:V and S:V, respectively) suggests that there was a higher proportion of root carbon in the whole soil samples of the 0-15cm soils. However, whole soils from the 0-15cm horizon also appeared to have a higher contribution of degraded organic matter (Figure SNC-2.2). Para-hydroxy benzoic acids (P) and 3,5-dihydroxy benzoic acid (3,5-Bd) are both degradation products of lignin and used to determine the relative degra-dation state of organic matter. The ratio of these two compounds to V (P:V and 3,5-Bd:V) correct for any differences in extraction. 2-yrs post-treatment the soil organic matter in the 0-15cm appears to be more degraded. Interestingly there does not appear to be an effect of any of the treatments on the SOM composition – the main effect appears to be the harvest.

Table SNC-2.1. Pre-treatment (2012) whole soil organic matter characteristics and bulk density.

	N (%)		C (%)		C:N		^{13}C		^{15}N		Bulk Density (g cm^{-3})	
	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d
0-15 cm												
A	0.33%	0.09%	7.60%	1.66%	27.6	2.1	-25.8	0.2	4.0	0.5	0.61	0.04
B	0.30%	0.02%	7.51%	0.96%	28.9	1.7	-25.5	0.6	3.6	0.0	0.60	0.03
C	0.31%	0.05%	6.53%	0.56%	25.1	2.8	-25.8	0.1	4.0	0.1	0.59	0.02
D	0.31%	0.04%	6.82%	1.07%	25.5	1.3	-25.9	0.3	3.8	0.3	0.60	0.05
E	0.33%	0.05%	7.48%	1.06%	26.1	1.8	-26.1	0.2	3.9	0.1	0.60	0.06
15-30 cm												
A	0.23%	0.06%	4.86%	1.20%	24.8	3.3	-25.6	0.2	5.0	0.5	0.70	0.05
B	0.24%	0.02%	5.20%	0.40%	25.2	2.3	-25.5	0.0	5.1	0.2	0.68	0.02
C	0.24%	0.03%	4.93%	0.61%	23.7	2.3	-25.7	0.5	4.8	0.2	0.73	0.03
D	0.21%	0.02%	4.55%	0.57%	24.9	2.5	-25.6	0.2	4.6	0.3	0.74	0.06
E	0.25%	0.07%	5.55%	1.74%	26.0	0.9	-25.7	0.0	5.1	0.5	0.71	0.04

Table SNC-2.2. Post-treatment (2013) and 2 years post-treatment (2015) whole soil organic matter characteristics and bulk density.

	N (%)		C (%)		C:N		^{13}C		^{15}N		Bulk Density (g cm^{-3})	
	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d
2013: Immediate Post-treatment												
0-15cm												
A	0.31%	0.06%	7.93%	0.83%	30.6	3.0	-25.8	0.2	3.6	0.2	0.63	0.05
B	0.30%	0.04%	7.75%	1.76%	30.0	3.9	-25.5	0.2	3.6	0.5	0.65	0.03
C	0.29%	0.07%	7.79%	1.56%	31.3	1.4	-25.6	0.7	4.4	1.0	0.71	0.06
D	0.30%	0.07%	7.11%	2.04%	28.0	2.1	-25.8	0.1	3.4	0.4	0.72	0.04
E	0.28%	0.05%	8.17%	0.68%	35.4	5.9	-25.7	0.1	3.8	0.3	0.78	0.04
A	0.22%	0.09%	5.75%	1.65%	32.3	6.8	-25.5	0.2	4.6	0.5	0.67	0.03
B	0.23%	0.05%	5.62%	1.03%	29.7	5.3	-25.4	0.1	4.5	0.6	0.71	0.04
C	0.22%	0.05%	5.34%	0.91%	28.3	3.2	-25.5	0.3	4.8	0.4	0.78	0.05
D	0.21%	0.04%	4.94%	1.09%	28.0	2.6	-25.4	0.2	4.6	0.2	0.79	0.05
E	0.21%	0.04%	4.91%	0.69%	27.7	2.7	-25.4	0.1	4.5	0.8	0.88	0.03
2015: 2yrs Post-treatment												
15-30cm												
A	0.30%	0.05%	6.77%	0.84%	26.8	3.3	-25.9	0.1	4.1	0.4	0.63	0.05
B	0.28%	0.04%	8.25%	3.22%	35.3	17.4	-25.6	0.2	4.2	0.2	0.65	0.03
C	0.24%	0.05%	6.37%	0.59%	32.3	5.2	-25.9	0.2	4.4	0.3	0.71	0.06
D	0.23%	0.05%	6.42%	1.19%	32.6	2.1	-25.8	0.1	4.3	0.4	0.72	0.04
E	0.23%	0.04%	5.83%	0.57%	29.6	3.0	-25.6	0.2	4.5	0.3	0.78	0.04
A	0.21%	0.05%	4.58%	0.95%	25.7	1.9	-25.4	0.1	5.3	0.3	0.67	0.03
B	0.19%	0.05%	4.14%	0.73%	26.7	9.3	-25.4	0.1	5.1	0.3	0.71	0.04
C	0.18%	0.06%	4.22%	0.40%	29.5	5.9	-25.5	0.2	5.7	0.3	0.78	0.05
D	0.20%	0.02%	4.13%	0.49%	25.0	1.9	-25.4	0.1	5.3	0.2	0.79	0.05
E	0.17%	0.03%	3.82%	0.40%	26.5	2.2	-25.3	0.2	5.6	0.5	0.88	0.03

Table SNC-2.3. Organic matter characteristics of density fractions from the 0-15cm mineral soil horizon.

	N (%)		C (%)		C:N		^{13}C		^{15}N	
	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d
2012: Pre-treatment										
Heavy										
A	0.11%	0.01%	1.47%	0.14%	16.4	0.8	-24.8	0.2	5.1	1.0
B	0.11%	0.01%	1.45%	0.13%	16.1	1.5	-24.7	0.1	6.0	0.6
C	0.10%	0.02%	1.48%	0.24%	18.2	2.6	-24.8	0.1	5.8	1.1
D	0.10%	0.02%	1.51%	0.16%	18.9	3.6	-24.9	0.1	5.8	0.2
E	0.10%	0.01%	1.48%	0.09%	16.7	1.4	-24.8	0.1	5.5	0.7
Intermediate										
A	0.30%	0.05%	5.24%	0.77%	20.5	1.0	-25.5	0.2	4.6	0.7
B	0.28%	0.03%	4.73%	0.55%	19.6	0.6	-25.3	0.1	5.1	0.1
C	0.28%	0.07%	4.90%	0.89%	20.6	1.2	-25.5	0.1	5.1	0.3
D	0.27%	0.05%	4.73%	0.98%	20.1	1.4	-25.6	0.2	4.7	0.3
E	0.28%	0.05%	4.69%	0.63%	19.9	1.4	-25.4	0.1	4.9	0.7
Light										
A	0.80%	0.07%	32.29%	2.09%	47.1	4.4	-26.4	0.3	0.8	1.0
B	0.81%	0.06%	34.13%	1.81%	49.4	3.8	-26.2	0.2	0.5	1.3
C	0.82%	0.06%	32.56%	2.09%	46.5	5.1	-26.5	0.2	1.8	0.4
D	0.76%	0.09%	32.59%	1.72%	50.7	7.9	-26.3	0.2	1.1	1.0
E	0.84%	0.07%	31.84%	2.03%	44.8	6.1	-26.4	0.1	1.2	0.6
2015: Post-treatment										
Heavy										
A	0.09%	0.01%	1.36%	0.08%	18.3	1.7	-24.7	0.1	6.0	0.7
B	0.08%	0.01%	1.17%	0.16%	16.6	2.3	-24.6	0.1	6.0	0.5
C	0.09%	0.01%	1.38%	0.28%	18.4	2.1	-24.5	0.1	5.7	1.1
D	0.08%	0.03%	1.35%	0.34%	21.8	5.9	-24.5	0.2	6.0	0.4
E	0.08%	0.00%	1.18%	0.07%	18.2	1.0	-24.4	0.2	6.3	0.6
Intermediate										
A	0.27%	0.05%	4.43%	0.63%	19.2	1.2	-25.2	0.1	5.3	0.5
B	0.29%	0.03%	4.39%	0.73%	17.5	1.1	-25.2	0.0	5.1	0.4
C	0.27%	0.03%	4.88%	0.05%	20.9	2.3	-25.5	0.2	4.6	0.5
D	0.25%	0.05%	4.26%	1.12%	20.0	1.3	-25.3	0.2	5.1	0.5
E	0.23%	0.04%	3.54%	0.49%	18.2	0.5	-25.2		5.0	
Light										
A	0.72%	0.18%	34.44%	0.45%	58.5	12.0	-26.4	0.1	0.7	0.7
B	0.73%	0.08%	36.04%	1.73%	58.2	6.4	-26.3	0.2	0.3	0.7
C	0.70%	0.11%	35.19%	2.38%	60.0	9.3	-26.5	0.2	0.3	0.6
D	0.68%	0.09%	34.47%	0.91%	60.3	8.7	-26.4	0.1	0.9	0.5
E	0.74%	0.03%	35.13%	1.46%	55.4	4.5	-26.3	0.2	1.2	1.0

Table SNC-2.4. Organic matter characteristics of density fractions from the 15-30cm mineral soil horizon.

	N (%)		C (%)		C:N		^{13}C		^{15}N	
	mean	s.d	mean	s.d	mean	s.d	mean	s.d	mean	s.d
2012: Pre- Treatment										
Heavy										
A	0.10%	0.02%	1.28%	0.16%	16.1	1.2	-24.4	0.2	6.5	0.7
B	0.09%	0.01%	1.23%	0.08%	15.9	0.8	-24.3	0.1	7.3	0.2
C	0.09%	0.02%	1.34%	0.20%	17.9	2.1	-24.4	0.1	6.7	0.3
D	0.10%	0.01%	1.41%	0.31%	17.1	2.5	-24.4	0.1	7.1	0.3
E	0.09%	0.02%	1.22%	0.14%	16.9	3.3	-24.4	0.1	6.7	0.3
Intermediate										
A	0.22%	0.05%	3.66%	0.72%	19.3	1.2	-25.1	0.1	5.5	0.9
B	0.21%	0.01%	3.70%	0.39%	20.1	1.9	-25.1	0.2	6.0	0.5
C	0.23%	0.05%	3.82%	0.79%	19.6	2.6	-25.3	0.2	5.8	0.6
D	0.23%	0.03%	4.13%	0.96%	21.3	3.4	-25.3	0.2	5.5	0.5
E	0.22%	0.03%	3.50%	0.69%	19.0	2.4	-25.0	0.1	6.3	0.6
Light										
A	0.75%	0.09%	34.11%	1.67%	54.2	10.1	-26.4	0.2	1.9	0.9
B	0.76%	0.10%	34.54%	0.99%	54.1	7.7	-26.2	0.1	1.3	1.0
C	0.66%	0.12%	34.17%	1.02%	62.0	13.8	-26.4	0.0	2.1	0.3
D	0.74%	0.07%	34.40%	1.61%	55.0	5.1	-26.4	0.1	1.3	0.7
E	0.83%	0.08%	33.25%	2.20%	47.0	3.9	-26.4	0.1	1.6	0.9
2015: Post-treatment										
Heavy										
A	0.06%	0.02%	1.03%	0.15%	20.7	6.4	-24.1	0.0	6.7	0.0
B	0.08%	0.02%	1.02%	0.22%	15.3	1.3	-23.9		7.6	
C	0.08%	0.02%	1.02%	0.27%	16.1	2.8	-24.1	0.1	7.2	0.2
D	0.08%	0.01%	1.15%	0.12%	17.0	1.2	-24.1	0.1	7.6	0.0
E	0.07%	0.01%	0.95%	0.14%	15.9	1.3	-23.9	0.3	7.3	0.5
Intermediate										
A	0.21%	0.05%	3.58%	0.83%	19.9	1.8	-25.1	0.1	5.8	0.7
B	0.20%	0.04%	3.16%	0.80%	18.4	0.8	-24.8	0.0	6.8	0.3
C	0.19%	0.05%	3.23%	0.93%	20.0	3.1	-25.1	0.4	5.8	0.3
D	0.19%	0.04%	3.11%	0.77%	19.2	2.0	-25.0	0.1	6.1	0.3
E	0.17%	0.04%	2.76%	0.24%	19.6	3.4	-25.0		6.1	
Light										
A	0.62%	0.07%	31.74%	0.75%	60.8	8.6	-26.3	0.2	1.9	0.4
B	0.66%	0.06%	32.64%	0.35%	58.6	5.9	-26.4	0.4	1.9	0.4
C	0.66%	0.08%	33.43%	0.94%	60.0	6.6	-51.5	35.3	0.7	0.9
D	0.62%	0.09%	32.18%	1.75%	62.3	9.4	-26.2	0.1	2.0	0.3
E	0.63%	0.04%	33.00%	1.98%	61.5	7.5	-26.4	0.1	2.2	0.3

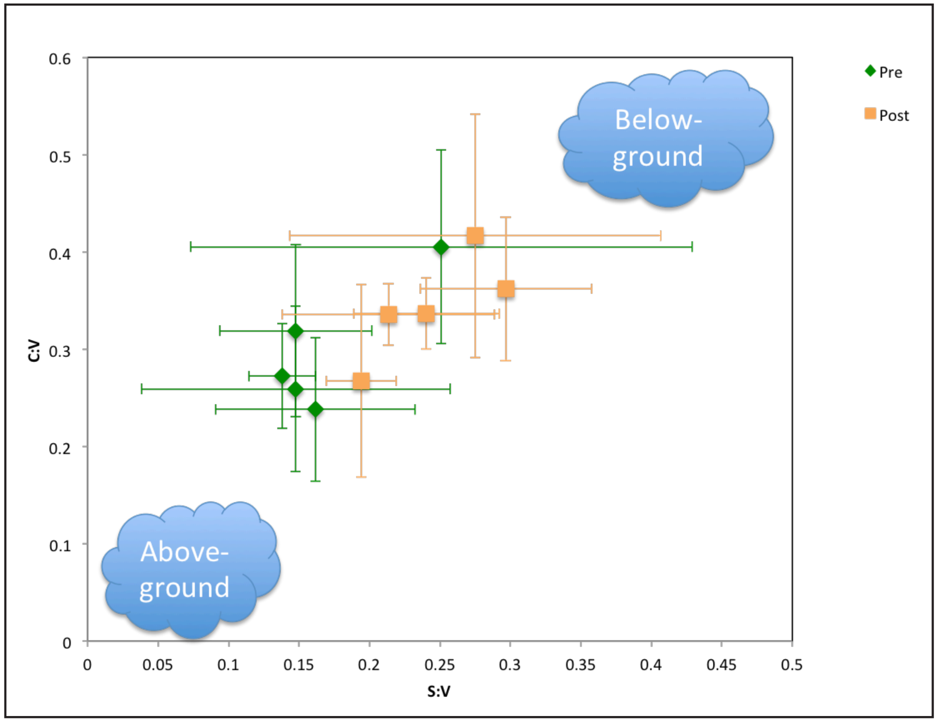

Figure SNC-2.1. C:V and S:V of whole soils from 0-15cm from immediately pre- to 2-yrs post-treatment. C:V is generally a biomarker of woody versus non-woody, while S:V is generally used as a marker of angiosperm versus gymnosperm. Typically though, roots have a higher C:V and S:V relative to their aboveground counterparts, so we are using that trend to show that 2-yrs post-treatment there appears to be a higher contribution of root carbon to the SOM pool. Further probing of biomarker results will likely strengthen this preliminary assessment.

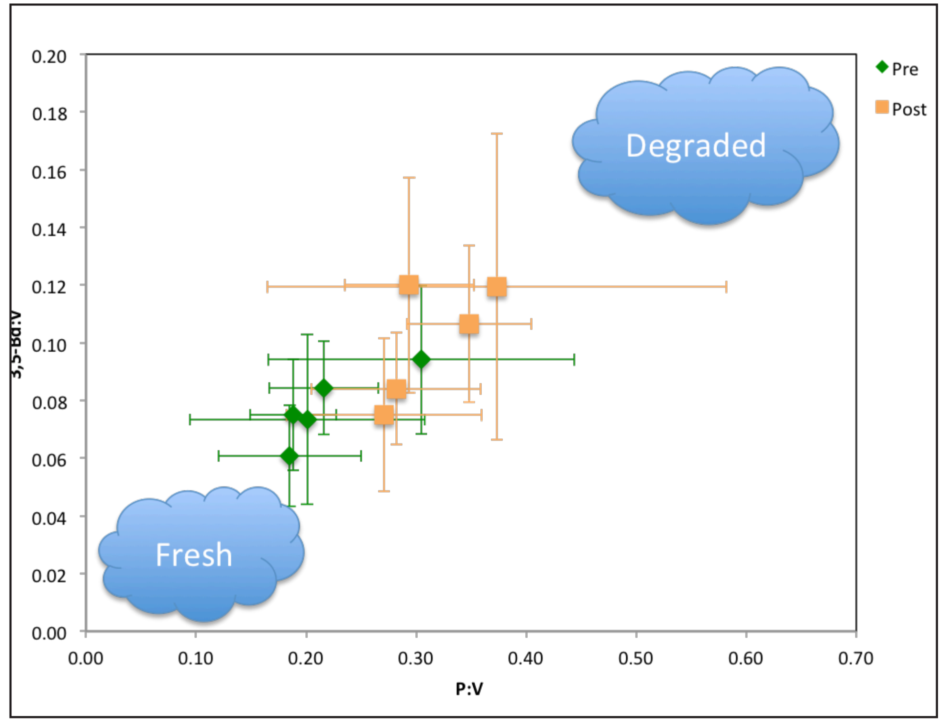

Figure SNC-2.2. P:V and 3,5-Bd:V of whole soils from 0-15cm from immediately pre- to 2-yrs post-treatment. Both of these ratios have a positive relationship with relative degradation. These preliminary results suggest that the soil organic matter was more degraded after 2 years. This is probably a result of the lack of fresh litter and root inputs from a well-developed forest as well as higher mineralization and OM transformation rates occurring as a result of higher soil temperature and moisture.

Preliminary Conclusions

Our working hypothesis is that the there is a lack of fresh inputs and higher mineralization rates, which is combining to increase the relative degradation state of the soil organic matter 2-years post-treatment. These higher mineralization rates are driven by higher soil moisture and temperature in all the treated soils relative to the reference (see Task 1: Monitor and report on soil moisture and temperature data and examine soil carbon cycling through soil respiration). Higher moisture and temperatures did no result in higher soil respiration (see Task 1: Monitor and report on soil moisture and temperature data and examine soil carbon cycling through soil respiration), and was only significantly different in the treatments with residual slash (possible soil priming effect). Further analysis of the biomarker and stable isotope data should elucidate whether there is indeed a soil priming effect occurring in these treatments with residual slash. Our preliminary results suggest that the contribution *of residual roots to the soil carbon pool appears to be buffering the loss of soil C caused by the higher mineralization*. Further analysis of the biomarker, and stable isotope data should strengthen this conclusion.

TASK 3: FOLIAR RESPONSE TO SOIL CHANGES AND EXAMINE WHOLE SOILS PRE-, POST-, AND 2-YEAR POST FOR EXCHANGEABLE NUTRIENT POOLS

Task Objective

1. Determine if exchangeable pools of nutrients are being depleted by compaction and intensive biomass removal
2. Determine if tree nutrition is affected by compaction and intensive biomass removal

Methodology

Foliar samples were collected winter of 2016 from the NARA LTSP site (see site description in Task 1: Monitor and report on soil moisture and temperature data and examine soil carbon cycling through soil respiration). Foliar samples have been dried (40 degrees C) and ground. Soils were collected pre- and post-treatment, dried, sieved, and ground. Mineral soil pH was determined in deionized water using the 2:1 method (Thomas, 1996). C and N were determined on dried and ground O-horizon, mineral soil, and foliar material using dry combustion on a Thermo FlashEA 1112. Mineral soils were extracted using 1M NH4Cl to extract the exchangeable pools of cations, while O-horizons and foliar samples were digested using 30% H2O2 and a 1:10 nitric-hydrochloric (HNO3-HCL) acid digestion of organic matter in conjunction with external heating (EPA method 3050; Benton and Wolf, 1997). Digests and extracts were analyzed for Ca, K, Na, Mg, B, Al, Cu, Fe, Mn, Mo, P, S, and Zn on an inductively coupled plasma atomic emission spectrometry (ICP-AES) using a Thermo Scientific ICP-OES 61E. The stable isotopic compositions of foliar samples ($\delta^{13}C$ and $\delta^{15}N$) will be determined using high- temperature combustion coupled with isotope ratio mass spectrometry.

Results

None to date. Samples have been collected and analyzed for metals, and are slated for CN and stable isotope analysis once transferred to OSU.

Conclusions/Discussion

Once these samples have been analyzed we will use the results to determine if further analyses on soil nutrient pools are necessary.

ASK 4: EXAMINE INPUTS OF CARBON AND NUTRIENTS INTO MINERAL SOILS USING PAN LYSIMETERS.

Task Objective

Determine the importance of the O-horizon and forest residuals in affecting soil carbon, nitrogen, and phosphorus stocks.

Methodology

Pan lysimeters were installed on all plots at the NARA LTSP site. Lysimter solutions were collected after every major rain event. These solutions will be analyzed for dissolved organic carbon, dissolved nitrogen (total), and dissolved phosphorus (total).

Results

None to date. Samples have been collected, frozen and are slated for analysis once deemed necessary from analysis of soil carbon and foliar nutrition.

Conclusions/Discussion

Once these samples have been analyzed we will use the results to determine if further analyses on soil nutrient pools are necessary.

NARA OUTPUTS

Publications

In-preparation (planned submission prior to November 30, 2016)

Gallo, Adrian C., Jeff A. Hatten, Scott Holub, others. In-preparation. Effects on soil temperature, moisture, and respiration two years following intensive organic matter and compaction manipulations in the Oregon Cascades. Forest Ecology and Management.

Littke, Kim, Adrian C. Gallo, Jeff A. Hatten, Scott Holub, Rob Harrison, Jason James In-preparation. Predicting deep soil nutrients from shallow soil measurements in the Douglas-fir region. Forest Ecology and Management.

Gallo, Adrian C., Jeff A. Hatten, Scott Holub, others. In-preparation. Effects of organic matter and compaction manipulations on soil carbon in the Oregon Cascades. Forest Ecology and Management.

Theses and Graduate Students

Adrian Gallo (2013-2016 MS, 2016-present PhD)

Gallo, Adrian C. 2016. Effects on soil temperature, moisture, and respiration two years following intensive organic matter and compaction manipulations in the Oregon Cascades. MS Thesis. Oregon State University. 81pp.

Invited Presentations

Hatten, J.A., J. Mack, S. Roberts, E.B. Sucre, S.M. Holub, J. Dewey, A.C. Gallo. 2015. Assessing Long Term Soil Productivity in Intensively Managed Loblolly Pine and Douglas-Fir Forests. Society of American Foresters Annual Meeting. Baton Rouge, Louisiana. November 3-6, 2015.

Hatten, J.A. 2014. Long-term soil productivity of managed forests: Mechanisms of apparent resilience after intensive biomass removal. Western Region Council on Forest Engineering Seminar. Eugene, Oregon. January 16.

Academic Seminars

Hatten, J.A., J. Mack, S. Roberts, E.B. Sucre, S.M. Holub, J. Dewey, A.C. Gallo. 2016. Assessing "Long-Term" Soil Productivity and Soil Carbon in Intensively Man aged Forests. Wood Lunch in the Department Wood Science and Engineering, Oregon State University. Corvallis, Oregon. March 8, 2016.

Hatten, J.A., J. Mack, S. Roberts, E. Sucre, Z. Leggett, S. Holub, A. Gallo*. 2013. Apparent resiliency of soil carbon and stand productivity to organic matter manipulations in a loblolly pine plantation. Department of Crop and Soil Sciences Fall Seminar Series 2013. Oregon State University. Corvallis, Oregon. December 2, 2013.

Conference Presentations

Hatten, J.H., A.C. Gallo, and S.M. Holub, 2015. Soil Organic Matter Dynamics in an Intensively Managed Douglas-fir Forest. Soil Science Society of America Annual Meeting. Minneapolis, Minnesota. November 15-18. (Poster)

Gallo, A., J.A. Hatten. 2015. Biophysical responses in soil following intensive bio mass removal. Western Forestry Graduate Research Symposium. Corvallis, Oregon. April 27-28, 2015. (Oral) Best overall oral presentation

Gallo, A., J.A. Hatten. 2015. Immediate response mechanisms to account for sustained tree growth following intensive biomass removal on LTSP sites. Northwest Forest Soils Council. Hood River, Oregon. March 14, 2015. (Oral)

Gallo, A., J.A. Hatten. 2014. Immediate response mechanisms to account for sustained tree growth following intensive biomass removal on Long-Term Soil Productivity (LTSP) sites. Soil Science Society of America Annual Meeting. Long Beach, California. November 3-6. (Poster)

Holub, S., R. Harrison, and J. Hatten. 2014. How do removals affect long-term productivity?: Long-term Soil Productivity (LTSP) studies. Northwest Advanced Renewables Annual Meeting. Seatac, Washington. September 16-18. (Oral)

Holub, S., N. Meehan, R. Meade, G. Johnson, R. Harrison, M. Menegale, J. Hatten, and A. Gallo. 2014. NARA Long-term Soil Productivity (LTSP) Project – 2014 Update. Northwest Advanced Renewables Annual Meeting. Seatac, Washington. September 16-18. (Poster)

Gallo, A., J.A. Hatten. 2014. Long-term soil productivity on managed forests: Mechanisms of apparent resilience after intensive biomass removal. Western Forestry Graduate Research Symposium. Corvallis, Oregon. April 21-22. (Poster)

Hatten, J.A., J. Mack, S. Roberts, E. Sucre, Z. Leggett, J. Dewey. 2013. Effect of Forest Harvest Residue Manipulations on Soil Organic Matter Content and Composition of a Loblolly Pine Plantation in the Southeastern United States. American Geophysical Union Fall Meeting. San Francisco, California. December 9-15. (Poster)

Hatten, J., E. Sucre, Z. Leggett, J. Mack, J. Zerpa, S. Roberts, B. Strahm. 2013. Explaining the Apparent Resiliency of Loblolly Pine Plantation to Organic Matter Removal. Biannual Southern Silviculture Conference. Shreveport, Louisiana. March 4-7. (Oral)

Webinar

Webinar "Long-term soil productivity and sustainability of forest harvest residue harvesting" J.A. Hatten and S.M. Holub. NARA Wood-to-Biofuels Webinar Series. October 30, 2015. https://youtu.be/Bkho8fsrZGA

Physical Collections

Soil samples and density fractions from pre-, post-, and 2yrs post-treatment of the NARA LTSP site. Location: OSU Forest Soils Lab

Databases

Total C, N, stable isotopes, and biomarker measurements from soil samples and density fractions from pre-, post-, and 2yrs post-treatment of the NARA LTSP site. Location: OSU Forest Soils Lab

NARA OUTCOMES

Change in knowledge

- Average, maximum, and diel fluxes of soil temperature were affected by organic matter removal treatments down to 100cm in depth.
- Soil respiration was not affected by changes in temperature, but was elevated as a result of increased biomass – possibly the result of a priming effect.
- Impacts of the treatments to soil temperature could have an effect on the soil carbon pool.
- No apparent change in the size or concentration of the soil carbon pool
- The C:N increased after treatment while the proportion of light fraction decreased. These results suggest that there were higher mineralization rates (reducing the light fraction) as well as a source of fresh material (with a high C:N)
- Biomarkers support this assertion that there were higher mineralization rates after harvesting and that the mineralized carbon was replaced by residual root carbon.
- These results suggest that we need to understand the role that residual roots play in supporting long-term soil productivity.

FUTURE DEVELOPMENTS

We are pursing future work in the area of the role of roots, deep soils, and soil temperature I affecting post harvest soil carbon dynamics. Currently planning a meta-analysis of other Long-term Soil Productivity Experiments in order to explore the ubiquity of residual roots buffering losses in soil carbon.

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