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ORIGINAL ARTICLE

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Short-term effects of organic matter and compaction manipulations on soil temperature, moisture, and soil respiration for 2 years in the Oregon Cascades

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Abstract

Understanding the factors controlling nutrient dynamics can help guide forest management plans to promote their long-term productivity. We used experimental treatments with three levels of biomass removals and two levels of compaction to monitor the impacts to soil biophysical characteristics in an intensively managed forest. Soil temperature, moisture, and respiration observations began 6 mo after treatment installation completion and continued for 2 yr. Compaction had few consistent significant effects on measured variables, and there were negligible differences in volumetric soil water content between whole tree (WT) and bole only (BO) harvesting. Compared with BO, the 10-cm average and maximum growing season temperatures in WT significantly increased by 1.2 and 2.5 ˚C, respectively. The effects of WT removals resulted in whole profile (10–100 cm) increases in the average and maximum growing season soil temperatures. The WT removals resulted in an increase of 1.4 times more soil growing degree days (SGDD) at 10 cm and 1.6 times more at 100 cm compared with BO. Despite favorable temperature and moisture conditions, differences in soil respiration could not be explained by biomass or compaction treatments. The uncut reference forest was consistently cooler and drier, but respired more CO_2 throughout both years of observation compared with treated areas. The large physical disturbance of forest harvesting on the site likely masked any incremental treatment differences by homogenizing the microbial response in the ensuing 2-yr study period. Future research should continue to investigate whether these soil biophysical changes influence site productivity or more sensitive indices of soil C dynamics.

Abbreviations: BO, bole only harvesting; BOC, bole only harvesting with compaction; LTSP, long-term soil productivity; NARA, Northwest Advanced Renewables Alliance; PNW, Pacific Northwest; REF, unharvested forest reference; SGDD, soil growing degree days; VWC, volumetric water content; WT, whole tree harvesting; WTC, whole tree harvesting with compaction; WTFFC, whole tree harvesting plus forest floor removals with compaction.

1 | INTRODUCTION

Forests cover approximately one-third of earth's landmass and forest soils contain a majority of the terrestrial C (Binkley & Fisher, 2013; Nave et al., 2010). The combination of an increased demand for forest products (such as wood and biofuels) by a growing economy, and diminished land area available for fiber production, has led to the expansion of intensively managed forests (FAO, 2006). Intensively managed forests account for nearly 7% of all forests globally, but they contribute a large portion of the global wood and forest biomass supply. For example, the state of Oregon has 12 million hectares of forested land with about 34% of this held by large and small private landowners who contribute 76% of the harvested timber annually (Oregon Forest Resources Institute, 2021). Compared to federally owned forests, intensively managed forests typically have shorter time periods between forest harvests that may lead to greater removal of certain nutrients relative to natural disturbance regimes such as fire (Busse et al., 2019). This has caused many to question the long-term sustainability of this forest management strategy and the potential implications it could have for nutrient supply as stands enter successive rotations (Burger, 2009; Fox, 2000; Johnson & Curtis, 2001; Littke et al., 2020; Mainwaring et al., 2014; Perakis et al., 2013; Worrell & Hampson, 1997).

Within the constraints of climate, declines in long-term potential forest productivity due to active management can often, but not exclusively, be attributed to negative impacts on two ecosystem properties: site organic matter content and soil porosity (Powers, 1990). Harvest activities can compact soils and thus decrease total soil porosity, which negatively affects major physical processes such as water infiltration rates, plant available water, root growth potential, and oxygen diffusion gradients. Harvesting timber inherently removes biomass and often redistributes site organic matter. These disturbances can increase topsoil erosion potential and diminish long-term nutrient stores because much of the forest nutrition is concentrated in the upper mineral soil horizon. The intensity of forest harvesting can also influence long-term organic matter stores (James & Harrison, 2016), with nitrogen (N) being especially sensitive to whole tree harvesting (WT) because these nutrients are concentrated in the finer diameter woody debris and needle biomass (Hatten & Liles, 2019; Thiffault et al., 2011). Both erosional losses and removal of site organic matter can decrease soil cation exchange capacity leading to an immediate reduction in site carrying capacity. A site's total water holding capacity can be negatively affected with either removing organic matter or decreasing soil porosity, which is likely to affect the potential net primary productivity of successive rotations (Powers, 1990, 2006).

Within the constraints of a site's organic matter content and soil physical properties, soil temperature has first order control on potential plant productivity. As many other researchers

Core Ideas

- Bulk density increased 16–23% but compaction had no influence on soil moisture or soil respiration.
- As more biomass was removed, average growing season temperatures increased significantly from 10 to 100 cm in depth.
- At the 100-cm depth whole tree plus forest floor removals had three times more soil growing degree days.
- The uncut reference forest was consistently cooler and drier, but respired more CO_2 throughout the study period.
- The intense and temporally recent harvest disturbance obscured differences in soil respiration between treatments.

have found in the Pacific Northwest (PNW), soil temperatures increase as more surface biomass is removed; however, these measurements have been limited to surface mineral soils (0–20 cm) (Ares, Terry, Piatek, et al., 2007; Devine & Harrington, 2007; Roberts et al., 2005). Similar studies in Washington and Oregon found the average increase in soil temperature of whole tree removal treatments were between 0.6 and 3.0 ˚C (5–10 cm) higher than bole only removals during the growing season (Roberts et al., 2005; Slesak, Schoenholtz, et al., 2010). The quality of the days within the growing season, often measured as soil growing degree days (SGDD), can be predictive of fine-root growth productivity (Lopushinsky, 1990).

Soil moisture content can act as a control on both microbial activity and plant productivity. Surface biomass, in the form of harvest residuals and O-horizons, are a physical barrier from light, decreasing soil evaporative losses described as the "mulch effect" (Devine & Harrington, 2007; Lopushinsky et al., 1992). However, it can also intercept precipitation and limit the amount of water transferred to mineral soil (Jury & Horton, 2004). Due to the sensitivity of seedlings to soil moisture limitations, even a small change in below ground access to water and nutrients can affect tree productivity (Roberts et al., 2005). There is also strong evidence that soil moisture content, and its interplay with soil oxygen concentrations, is a main driving factor in the behavior and extent of soil respiration (Moyano et al., 2013; Skopp et al., 1990; Yuste et al., 2003).

Soil temperature can also act as a control on both microbial activity and plant productivity (Lloyd & Taylor, 1994). The breakdown of plant and animal debris produces smaller fragments of organic matter, soluble nutrients, and CO_2; this relationship allows researchers to use soil respiration as a proxy for these heterotrophic processes in soil (Coleman et al., 2004; Wardle, 2002). Similar to patterns in soil temperature, soil respiration was negatively correlated with biomass left on site during the growing season (Slesak, Schoenholtz, et al., 2010). The impact on soil C pools are directly affected by plant inputs, soil respiration, and microbial activity has also been correlated to mineralization rates necessary to understand nutrient dynamics (Coleman et al., 2004). By using the average soil respiration, we believe this can be an adequate proxy for soil nutrient mineralization rates important for long-term soil productivity.

Forest management can have a negative impact on tree biomass (Littke et al., 2020) and site C resources (Nave et al., 2010). However, these responses to harvests are soil specific with less weathered soils (e.g., Alfisols, Inceptisols) recovering mineral soil C much faster than highly weathered soils (e.g., Spodosols, Ultisols) (James & Harrison, 2016). A recent meta-analysis specific to PNW forests show soil organic C stocks are driven by vegetation, climate, and topography more so than land use history or management, but there was significant subregion variability (Nave et al., 2022). Although we cannot evaluate the long-term impacts of harvesting on a new study location, we can observe the immediate impacts of harvesting to better understand its potential trajectory.

The specific objectives were to determine if harvesting and changes in soil compaction or residual harvest biomass resulted in (a) soil temperature or moisture patterns sufficiently different to change the soil growing season characteristics and (b) changes in soil respiration over the first 2 yr. We hypothesized the following: (a) increasing the level of surface biomass removal would increase soil temperatures and promote higher quality growing seasons due to more solar radiation reaching the mineral soil; (b) compaction would result in lower soil macroporosity, have greater conduction of heat energy from increased contact with soil particles leading to higher soil temperature and soil moisture; and (c) treatments with higher quality growing seasons (higher temperature with adequate soil moisture) will have the most favorable conditions for microbial activity and thus highest rates of soil respiration.

2 | METHODS

2.1 | Site description

The study site was installed approximately 30 km East of Springfield, OR, along the western side of the Cascades with the support of the Northwest Advanced Renewables Alliance (NARA) to investigate the potential impacts of forest biomass harvesting for aviation fuel and other co-products. 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 and 17 million years old (Walter & Duncan, 1989). The soils of the area are best represented by the Kinney series described as fine-loamy, isotic, mesic Andic Humudept with clay and clay loam textural classes to 100-cm depth (Soil Survey Staff, 2015). The area is between 600- and 660-m elevation, has a simple convex-convex slope topography with approximately 15–25% slope. The region has a Mediterranean climate with mean annual temperature and precipitation of 11.4 ˚C and 170 cm, respectively, for the period between 1981 and 2010 (Wang et al., 2016). During the 2 yr of observation, 2014 and 2015, the mean annual temperature was 10 ˚C with a mean April–October air temperature of 16 ˚C. Approximately 130–140 cm of precipitation fell over each water year with most of the precipitation falling from November to May (Supplemental Figure S1). The surrounding area was logged in the mid- to late 1950s. We found evidence that the initial harvest was followed by a broadcast burn (abundant char on old stumps and charcoal in soils), which was a common site preparation practice of the mid-20th century. Douglas-fir was allowed to naturally regenerate with a thinning treatment occurring mid-rotation.

2.2 | Experimental design

This study used methods consistent with those of the Long-Term Soil Productivity (LTSP) network and is described herein as the "NARA LTSP" site. The LTSP framework was "the most broadly reviewed study plan ever produced by the USDA Forest Service" (Powers, 2006), with more than 100 installations focused on pulse disturbances and their effects. The intermediate compaction treatments, bole only and whole tree biomass removals were designed for the LTSP network to encapsulate the full range of potential management strategies, while simultaneously producing stepwise levels of nutrient removals that are disproportionate to biomass removals (Powers, 1990; Powers et al., 2005). However, the severe compaction treatment, and whole tree plus forest floor removals were meant to exceed any level of practical forest management technique and they should be considered a purely experimental product.

This is an LTSP-affiliate site, where five of the usual nine total LTSP treatments were installed (Table 1). Treatments include a bole only (BO) biomass removal, with (BOC) and without compaction (BO), a whole tree biomass removal, with (WTC) and without (WT) compaction, and a whole tree plus forest floor removal with compaction treatment (WTFFC) (Table 1). Bole only removal treatments had trees felled into the plot area and delimbed on plot to retain all non-merchantable tree biomass on the plot. Whole tree treatments had trees felled and delimbed off the plot where possible to

Soil Science Society of America Journal

TABLE 1 Summary of treatments from the overall long-term soil productivity experiment and this NARA affiliate site near Springfield, OR

Organic matter and compaction treatment levels	BO	WT	WTFF
No compaction	BO	WT	Not conducted[a]
Intermediate compaction	BOC	WTC	WTFFC
Severe compaction	Not conducted	Not conducted	Not conducted

Notes. BO, bole only harvest; BOC, bole only with compaction; WT, whole tree harvest; WTC, whole tree with compaction; WTFF, whole tree with forest floor removal.
[a]Treatments not installed on this site due to logistical and/or practical constraints.

TABLE 2 Summary of site and soil characteristics within each treatment (four plots per treatment) at the Northwest Advanced Renewables Alliance Long-Term Soil Productivity (NARA LTSP) site near Springfield, OR

Site property	Unit of measure	BO	BOC	WT	WTC	WTFF
Site Index	m	36.5 ± 1.9	37.4 ± 0.7	37.3 ± 0.5	36.6 ± 0.5	36.7 ± 1.3
Soil pH, 0–15 cm	–	5.2 ± 0.1	5.3 ± 0.1	5.2 ± 0.1	5.3 ± 0.1	5.2 ± 0.2
Soil C/N, 0–15 cm	–	23 ± 0.9	22.1 ± 1.4	22.2 ± 1	22.9 ± 0.5	21.4 ± 2.5
Rock fragments	%	1.9 ± 2.3	3.1 ± 3.2	1 ± 1.1	2.2 ± 2.5	2.6 ± 1.9
Soil carbon, forest floor to 100 cm	Mg ha^{-1}	230.5 ± 31.3	219 ± 14.6	218.9 ± 27.5	218.6 ± 28.4	222.1 ± 19.9
Soil nitrogen, forest floor to 100 cm	Mg ha^{-1}	11.4 ± 1.7	11.2 ± 0.9	11.3 ± 1.3	10.9 ± 1	11.5 ± 1.7
Forest floor biomass	Mg ha^{-1}	23.4 ± 4.7	26.2 ± 2	25.5 ± 4.2	22.7 ± 3.7	26.3 ± 4.9
Bulk density, 0–15 cm	g cm^{-3}	0.621 ± 0.037	0.594 ± 0.028	0.6 ± 0.03	0.598 ± 0.059	0.596 ± 0.065
Bulk density, 15–30 cm	g cm^{-3}	0.703 ± 0.052	0.728 ± 0.033	0.679 ± 0.021	0.739 ± 0.066	0.712 ± 0.043

Note. BO, bole only; BOC, bole only with compaction; WT, whole tree; WTC, whole tree with compaction; WTFF, whole tree with forest floor removal. Mean ± SD.

remove all aboveground tree material and any remaining tree biomass was subsequently removed as needed. The whole tree plus forest floor removal treatment was similar to the whole tree except additionally the forest floor material was removed to expose mineral soil. In this, and all treatments, tree stumps from the current and previous harvests remained intact on the plots. Compacted plots were trafficked by tracked equipment in three to five passes, or more, on more than 100% of the trafficable area of the plots. Where non-bole tree biomass remained, on the BO treatment, that material was windrowed such that the plot could be trafficked without the soil protection afforded by it. After compaction the windrowed material was redispersed on the plot. The compaction treatment on this site most closely resembles the C1 "intermediate compaction" treatment from previous LTSP studies (Powers, 1990). To test the effects of harvesting, we included four opportunistically placed intact forest reference plots (REF) on an adjoining hillslope. Although these reference plots did not undergo the same level of pre-harvest scrutiny (see elemental analysis below), the topography, soils, and vegetation were similar to those found on the treated areas.

Plot boundaries were delineated and then sampled using 25 points per plot and run for elemental analysis to ensure similar site characteristics (Table 2). After soil chemistry data was available, treatments were assigned to the plots in a randomized complete block design consisting of four blocks based on soil N content of the upper 100 cm. Each plot ($n = 20$) was 0.4 ha, with an internal area of approximately 0.2 ha (0.05 acres) used as the measurement plot to limit any buffer effects. Treatment installation (harvesting, compaction, and/or forest floor removal if necessary) concluded during the late summer of 2013.

The area was fenced to prevent large herbivore activity on the treatment area and planted with Douglas-fir plug+1 0.7–0.9 cm double graded early in 2014 using 3.63-m hexagonal spacing (865 trees ha^{-1}). The plots and surrounding stand received a post-harvest herbicide treatment in the fall of 2013 as well as annual spring vegetation control for 2 yr (2014, 2015) using hexazinone and clopyralid, to keep competing vegetation below 30% coverage.

2.3 | Soil moisture and temperature observations

Soil moisture and temperature probes were installed at the approximate plot midpoint in the late fall of 2013 and were inserted at 10-, 20-, 30-, and 100-cm depth in mineral soil. To the best of the authors' knowledge, this is the first LTSP-affiliated study with these observations down to 100-cm depth. Soil moisture was measured as volumetric water content (VWC) with an accuracy of ± 3.0% and soil temperature has an accuracy of 0.1˚C (5TM Sensors, Decagon Devices, 2015). One weather station was installed at the highest point of the treated area, a minimum of one tree length away from the closest standing trees. Another weather station was located along the midpoint of a transect through the four REF plots beneath a canopy (Supplemental Figure S1). All soil probes and weather stations recorded data at the hourly scale.

2.4 | Growing season characteristics: A biologic approach

We used biologically relevant soil temperature and moisture thresholds for our tree species of interest to define the quality of the growing season, rather than a fixed period of time. Douglas-fir roots in the PNW do not become active until the subsoil reaches at least 10 ˚C with the greatest root and terminal bud growth rates at 20 ˚C (Lavender & Hermann, 2014; Lopushinsky, 1990). The estimated permanent wilting point for clay loam texture is approximately 18% VWC (Saxton & Rawls, 2006). At a minimum, the "growing season" requires the average daily values for individual plots to exceed 10 ˚C and 18% VWC to ensure it is warm and moist enough for Douglas-fir growth; we calculated the number of growing season days with those constraints for each depth and averaged across both years. However, the number of growing season days is not the best representation of the *quality* of those days. Therefore, we calculated the SGDD, which may be more sensitive to treatment differences.

Soil growing degree days were calculated from a modified version of Perala (1985); we only include days when the average VWC exceeded the permanent wilting point, but is otherwise calculated as:

$$\mathrm{SGDD} = \sum \left(T_{\mathrm{m}} - T_{\mathrm{b}}\right)$$

where T_m is the mean daily soil temperature. T_b is the threshold temperature for a given plant or crop; we used 10 ˚C because Douglas-fir root elongation has shown to be initiated at that temperature (Lavender & Hermann, 2014; Lopushinsky, 1990). We summed the SGDD for each plot-year combination independently (five treatments plus the unharvested forest reference [REF] plots, four blocks, 2 yr; $n = 48$), then averaged across years and blocks and reported cumulative degree centigrade. We also normalized this measure to the BO treatment, to interpret results more easily. We first normalized within each plot-year combination (e.g., 2014 WTFFC Block 1/2014 BO Block 1), then averaged across both years and all four blocks. Due to this initial within-block calculation, the normalized SGDD values are not directly calculated from the overall averaged SGDD seen in Table 3.

2.5 | Soil respiration

All observations were done with a Li-COR 8100A, using suggested base timing settings optimized for the 10-cm survey chamber (LI-COR Biogeosciences, 2012). Bulk soil respiration used PVC collars and were installed in December of 2013, but we allowed 3 mo after installation before the first observation to minimize disturbance artifacts (Kelting et al., 1998). The collars were beveled to minimize the influence of compaction along the internal walls. The PVC collars were inserted 2 cm in the mineral soil surface allowing for living roots to contribute to the respiration observations (Hanson et al., 2000). The placement of the PVC collars was a minimum of 50 cm away from any seedlings, with other vegetation in the vicinity hand-picked; because of the narrow rooting area of seedlings within these first 2 yr of seedling establishment we assumed there were no autotrophic contributions in treated areas. However, REF plots have active rooting systems that contributed to the respiration observations.

Each plot contained three random nests (pseudo-replicates) that were repeatedly measured on monthly intervals for 2 yr. At the time of each respiration observation, soil moisture of the 0-to-10-cm depth adjacent to the collar was recorded using an ECH2O probe (Decagon Devices). Soil temperature was collected from the plot-centered Decagon temperature probe at 10 cm to the nearest hour of when respiration was measured. Subsequent discussion centers on the growing season months (April–October) to focus on the months when differences were greatest. Each set of monthly observations required two full days to measure, these were done between the hours of 0500 and 1700 on successive days.

Due to the high degree of variability in soil respiration (both in space and time), the average respiration, from three pseudo-replicates, of each plot were used as the response variable. If any observation appeared to be inaccurate in the field (e.g., excessive wind), it immediately re-measured two additional times (triplicate observations) and the median value was used for further data aggregation.

2.6 | Statistics

Two sets of statistical comparisons were conducted for all response variables to leverage the complete 2 × 2 full-factorial design (BO, BOC, WT, WTC), and the additional two instrumented plots (WTFFC, REF). We use the 2 × 2 treatment design for testing the "main effects" of biomass harvesting from whole tree removals compared with bole only, and compaction vs. no compaction. To test the "treatment effects" all six instrumented plots were used and resulted in three statistical comparisons that include: (a) BO vs. REF tests the effect of forest harvesting and canopy removal, (b) BOC vs. WTFFC tests the additive effect of WT plus forest

TABLE 3 Summary data averaged over 2 yr at the Northwest Advanced Renewables Alliance Long-Term Soil Productivity (NARA LTSP) site near Springfield, OR

Response	Depth	REF	BO	BOC	WT	WTC	WTFF
	cm						
Daily temperature, °C	10	13.5 ± 0.2	16.1 ± 0.2	16.7 ± 0.1	17.6 ± 0.2	17.8 ± 0.2	19.4 ± 0.2
	20	13.1 ± 0.2	15.8 ± 0.2	16.3 ± 0.1	17.1 ± 0.2	17.4 ± 0.3	18.8 ± 0.2
	30	12.8 ± 0.3	15.4 ± 0.2	15.9 ± 0.1	16.7 ± 0.3	17.0 ± 0.2	17.8 ± 0.7
	100	11.7 ± 0.3	13.5 ± 0.3	14.3 ± 0.1	14.5 ± 0.3	14.9 ± 0.3	15.9 ± 0.1
Number of growing season days	10	45.6 ± 9.9	88.4 ± 7.0	100.1 ± 0.7	97.1 ± 4.9	103.1 ± 0.5	105.8 ± 2.0
	20	45.5 ± 9.9	88.4 ± 7.0	100.1 ± 0.7	97.1 ± 4.9	102.9 ± 0.6	105.8 ± 2.0
	30	45.0 ± 9.7	87.9 ± 6.9	98.8 ± 0.5	96.2 ± 4.9	102.1 ± 0.9	94.5 ± 10.5
	100	38.0 ± 9.6	80.9 ± 7.3	91.2 ± 1.2	89.1 ± 4.4	91.4 ± 5.8	99.7 ± 3.1
Soil growing degree days, °C	10	170.5 ± 46.8	550.9 ± 54.6	669.4 ± 14.1	739.6 ± 45.0	800.3 ± 25.7	997.3 ± 33.5
	20	151.3 ± 40.3	525.5 ± 52.9	635.4 ± 15.6	692.6 ± 44.5	760.8 ± 29.3	934.4 ± 27.3
	30	139.2 ± 40.5	484.5 ± 48.2	586.6 ± 15.1	651.9 ± 48.5	715.8 ± 29.3	782.3 ± 103.8
	100	80.4 ± 29.1	295.9 ± 39.2	392.5 ± 12.6	411.1 ± 43.6	458.2 ± 51.6	588.6 ± 30.4
Normalized soil growing degree days	10	0.3 ± 0.1	1.0 ± 0.0	1.4 ± 0.3	1.4 ± 0.1	1.7 ± 0.3	2.1 ± 0.5
	20	0.3 ± 0.1	1.0 ± 0.0	1.4 ± 0.3	1.4 ± 0.1	1.7 ± 0.4	2.1 ± 0.5
	30	0.3 ± 0.1	1.0 ± 0.0	1.4 ± 0.3	1.4 ± 0.1	1.8 ± 0.4	2.0 ± 0.6
	100	0.3 ± 0.1	1.0 ± 0.0	1.9 ± 0.7	1.6 ± 0.2	2.3 ± 0.8	3.0 ± 1.4
Volumetric water content, %	10	25.8 ± 0.3	28.0 ± 0.2	32.5 ± 0.2	31.7 ± 0.2	32.3 ± 0.2	28.7 ± 0.2
	20	31.9 ± 0.3	35.6 ± 0.2	36.9 ± 0.1	38.6 ± 0.2	37.0 ± 0.1	33.1 ± 0.1
	30	33.1 ± 0.2	37.6 ± 0.1	36.2 ± 0.1	27.9 ± 0.2	36.2 ± 0.1	36.3 ± 0.1
	100	28.4 ± 0.7	32.8 ± 0.2	36.9 ± 0.3	33.3 ± 0.3	39.5 ± 0.1	40.9 ± 0.1

Note. BO, bole only; BOC, bole only with compaction; REF, unharvested forest reference; WT, whole tree; WTC, whole tree with compaction; WTFF, whole tree with forest floor removal. Mean ± SE.

floor removal, keeping compaction constant, and (c) WTC vs. WTFFC tests the additive effect of forest floor removal, keeping compaction constant.

Linear mixed-effect models were used to fit all data and multiple comparisons of differences in means were done using paired two-sided *t* tests in RStudio statistical software (v.2022.02.03 +492) (Bates, 2005; Pinheiro et al., 2014; R Core Team, 2014; Zurr et al., 2008). All models included plots nested within blocks as random effects; both year and treatment were fixed effects and the interaction term between organic matter removals and compaction were tested. No attempt was made to differentiate effects between years.

Average and maximum daily soil temperatures exhibited heteroscedastic behavior requiring treatment groups to have non-constant variances to meet basic model assumptions of normality. Both years and 10-cm soil temperature were included in the soil respiration model as covariates, VWC data were not significant and were thus excluded from the final model. Soil respiration analysis required an autoregressive function to account for the repeated-monthly measures covariance matrix and to minimize the influence of seasonality on soil respiration. A family-wise Bonferroni adjustment was used for multiple comparisons, with $\alpha = .10$ used to assess statistical significance for all tests.

3 | RESULTS

3.1 | Soil compaction

Attempts were made to reach *severe* compaction (bulk density reaching 80% of the theoretical growth-limiting level) outlined by the original LTSP design (Powers, 1990). Operators repeatedly drove heavy equipment across the entire plot, although bulk density increased by approximately 16, 17, and 23% for the BOC, WTC, and WTFFC, respectively (Supplemental Table S1). As a result, these compaction treatments should be considered *intermediate* compaction treatments within the larger LTSP literature. The interaction term between levels of organic matter removal and compaction were not significant for any response variable, nor at any soil depth, and were thus excluded from further statistical analysis. Both the number of growing days, and SGDD appeared to increase for all soil depths because of compaction, although with large standard errors (Table 4).

3.2 | Soil moisture

We found no statistically significant differences in VWC between any treatments at any depth (data not shown). No harvest treatment reached the estimated permanent wilting point for clay loam soils (18% VWC) (Table 3). The REF plots did reach permanent wilting point at 10 cm, potentially limiting the growing conditions for some understory vegetation, but this was not seen at any deeper soil depth (Supplemental Figure S2).

3.3 | Soil temperature: Main effects

There were consistent and large differences in soil temperature throughout the year (Figure 1) and during the growing season due to organic matter removals (Table 3). Compared to bole only treatments, whole tree removals increased the average growing season temperature by 1.2 and 0.8 ˚C at 10- and 100-cm depths, respectively (Table 4). Whole tree removals increased the maximum growing season soil temperature by 2.4 and 1.5 ˚C at 10- and 100-cm depths, respectively (Table 4). Although the deep soil (100 cm) response is attenuated, to the best of our knowledge this is the first LTSP-affiliated study with these observations at this depth. While we found consistent and statistically significant differences in soil temperature due to whole removals down to 100 cm; we do not find any consistent evidence of changes in average or maximum soil temperature due to compaction at any soil depth. Although the average growing season temperature at 100 cm suggests a significant difference due to compaction, we believe this was an anomaly due to a single probe in one plot (Table 4).

3.4 | Soil temperature: Treatment effects

The effect of forest harvest and canopy removal (BO vs. REF) increased the average growing season soil temperature on BO treatments by 2.6 and 1.8 ˚C at 10- and 100-cm depths respectively (Table 5). Removing the forest floor and aboveground slash (BOC vs. WTFFC) had an increase of 2.5–2.7 ˚C in average growing season soil temperature from 10- to 30-cm depths on WTFFC plots. The removal of the forest floor (WTC vs. WTFFC) resulted in an increased average growing season soil temperature of 1.7 and 1.0 ˚C at 10- and 100-cm depths, respectively. For both the entire soil profile in forest floor removal (WTC vs. WTFFC) and slash and forest floor removal (BOC vs. WTFFC) treatments, the maximum soil temperature was nearly double of the average soil temperature (Table 5). For example, the average growing season temperature increases at 30 cm for BOC vs. WTFF and WTC vs. WTFFC were 2.5 and 1.4 ˚C, but the maximum soil temperature increases for the same depths was 4.8 and 2.9 ˚C, respectively.

TABLE 4 Statistical results of the linear mixed effects analysis for the main effects of whole tree removals (bole only [BO] and bole only with compaction [BOC] vs. whole tree [WT] and whole tree with compaction [WTC]) and compaction (BO and WT vs. BOC and WTC) on soil temperature properties at the Northwest Advanced Renewables Alliance Long-Term Soil Productivity (NARA LTSP) site near Springfield, OR

Depth	Main effect comparison	Difference in average growing season temperature		Difference in maximum growing season temperature		Difference in soil growing degree days		Difference in number of growing days	
		Estimate	P value	Estimate	P value	Estimate	P value	Estimate	P value
cm		˚C		˚C		˚C			
10	Whole tree removals	**1.2 ± 0.2**	**<.01**	**2.4 ± 0.4**	**<.01**	**140.9 ± 33.8**	**<.01**	**3.0 ± 0.6**	**<.01**
	Compaction	0.3 ± 0.2	.170	0.3 ± 0.4	.491	**85.2 ± 44.1**	**.082**	**8.0 ± 4.1**	**.08**
20	Whole tree removals	**1.1 ± 0.3**	**<.01**	**2.1 ± 0.4**	**<.01**	**134.4 ± 37.9**	**<.01**	**2.8 ± 0.6**	**<.01**
	Compaction	0.4 ± 0.3	.169	0.4 ± 0.4	.329	**86.6 ± 45.6**	**.087**	7.8 ± 4.2	.10
30	Whole tree removals	**1.1 ± 0.3**	**<.01**	**2.2 ± 0.4**	**<.01**	**137.2 ± 36.1**	**<.01**	**3.5 ± 1.2**	**.02**
	Compaction	0.4 ± 0.3	.198	0.4 ± 0.4	.383	**81.9 ± 44.4**	**.095**	7.6 ± 4.1	.11
100	Whole tree removals	**0.8 ± 0.3**	**.022**	**1.4 ± 0.4**	**<.01**	**86.9 ± 40.0**	**.055**	2.7 ± 5.0	.60
	Compaction	**0.7 ± 0.3**	**.036**	0.7 ± 0.4	.139	**81.9 ± 36.9**	**.051**	6.4 ± 5.4	.26

Note. Bold indicates statistically significant effect ($p < .01$).

TABLE 5 Statistical results of the linear mixed effects analysis for the treatment comparisons between the unharvested forest reference (REF), bole only (BO), whole tree with compaction (WTC), and whole tree with forest floor removals with compaction (WTFFC) on soil temperature properties at the Northwest Advanced Renewables Alliance Long-Term Soil Productivity (NARA LTSP) site near Springfield, OR

Depth	Comparisons of treatment effects	Difference in average growing season temperature		Difference in maximum growing season temperature		Difference in soil growing degree days		Difference in number of growing days	
		Estimate	P value	Estimate	P value	Estimate	P value	Estimate	P value
cm		˚C		˚C		˚C			
10	BO vs. REF	**−2.6 ± 0.4**	**<.01**	**−4.6 ± 0.7**	**<.01**	**−380.5 ± 83.6**	**<.01**	−42.8 ± 0.6	**<.01**
	BOC vs. WTFFC	**2.7 ± 0.3**	**<.01**	**5.5 ± 0.6**	**<.01**	**327.9 ± 51.4**	**<.01**	5.6 ± 4.1	.082
	WTC vs. WTFFC	**1.7 ± 0.4**	**<.01**	**3.3 ± 0.6**	**<.01**	**196.9 ± 50.7**	**<.01**	**2.6 ± 0.6**	**<.01**
20	BO vs. REF	**−2.7 ± 0.4**	**<.01**	**−4.5 ± 0.7**	**<.01**	**−374.2 ± 79.3**	**<.01**	−42.9 ± 4.2	**.089**
	BOC vs. WTFFC	**2.5 ± 0.4**	**<.01**	**4.8 ± 0.6**	**<.01**	**298.9 ± 49.2**	**<.01**	**5.6 ± 1.2**	**.015**
	WTC vs. WTFFC	**1.4 ± 0.4**	**<.01**	**2.9 ± 0.6**	**<.01**	**173.6 ± 48.9**	**<.01**	2.9 ± 4.1	**.090**
30	BO vs. REF	**−2.7 ± 0.4**	**<.01**	**−4.5 ± 0.7**	**<.01**	**−345.4 ± 74.8**	**<.01**	−42.9 ± 5.0	.600
	BOC vs. WTFFC	**2.5 ± 0.4**	**<.01**	**4.8 ± 0.6**	**<.01**	195.6 ± 115.4	.111	−4.2 ± 5.4	.262
	WTC vs. WTFFC	**1.4 ± 0.4**	**<.01**	**2.9 ± 0.6**	**<.01**	66.5 ± 115.5	.573	**−7.6 ± 0.2**	**<.01**
100	BO vs. REF	**−1.8 ± 0.4**	**<.01**	**−2.3 ± 0.7**	**<.01**	**−215.5 ± 58.8**	**<.01**	−42.9 ± 0.2	.170
	BOC vs. WTFFC	**1.6 ± 0.3**	**<.01**	**2.9 ± 0.6**	**<.01**	**196.1 ± 45.0**	**<.01**	**8.4 ± 0.3**	**<.01**
	WTC vs. WTFFC	**1.0 ± 0.4**	**.031**	**1.6 ± 0.7**	**.026**	**130.3 ± 62.5**	**.056**	8.3 ± 0.3	.169

Note. Bold indicates statistically significant effect ($p < .01$).

3.5 | Growing season characteristics

The number of growing days, and the SGDD increased as more surface organic matter was removed that resulted in whole-profile differences (Tables 4 and 5). The effect of WT removal compared with BO resulted in a statistically significant increase of 141 and 137 SGDD at 10- and 30-cm depths, respectively (Table 4). The effect of removing the forest floor (WTC vs. WTFFC) resulted in an increase of 196 and 173 SGDD at 10- and 20-cm depth, respectively. At 100-cm depth,

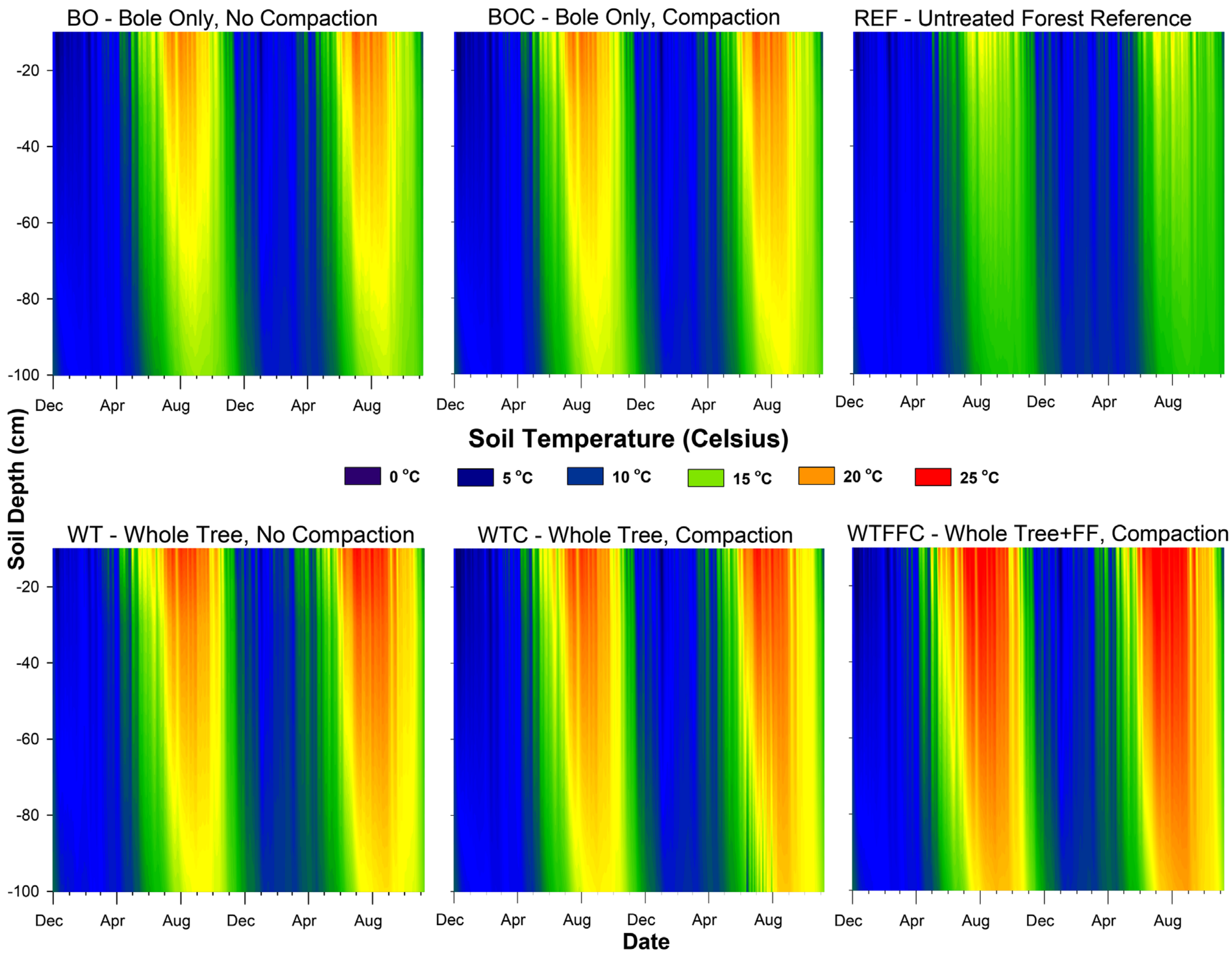

FIGURE 1 Observed 2-yr (2014 and 2015) soil temperature patterns following intensive organic matter and compaction manipulations at Northwest Advanced Renewables Alliance Long-Term Soil Productivity (NARA LTSP) site near Springfield, OR. Soil probes were installed at 10-, 20-, 30-, and 100-cm mineral depths and recorded hourly but represented on daily time steps. A linear average is used to interpolate between all probes

the effect size remained large (+130 SGDD) when removing the forest floor (WTC vs. WTFFC).

Although the number of growing season days at the surface increased as more biomass was removed, these increases were only +3 d for whole tree removal (Table 4) and +2.6 d for removing the forest floor compared with only whole tree removals (Table 5). When we normalize the SGDD to the BO treatment, the additional effects of WT and WTFFC removal resulted in an increase of 1.4 and 2.1 times more SGDD at 10 cm, respectively (Table 3). This effect increases down the soil profile; at 100-cm depth WT and WTFFC had 1.6 and 3.0 times more SGDD compared with BO, respectively. The increase in SGDD down the entire soil profile, as well as increases in the average daily and maximum soil temperatures, should encourage the microbial community occupying those more favorable soil profiles to also increase their activity.

3.6 | Soil respiration

There were no significant differences in treatments due to compaction or organic matter removals over the 2-yr study period (Table 6). Using the 10 cm soil temperature was predictive of soil respiration across both years of measurement; but the temperature increases within each treatment did not result in differential responses. We believe the +0.69 μmol CO_2 m^{-1} s^{-1} increase in 2015 from whole tree removals (Table 6) was possibly due to a faster soil warming during early spring, but the effect dissipated once all plots were warmed during the growing season (Supplemental Figure S3). Although the second-season observations suggest WTFFC treatments resulted in higher rates of soil respiration than any other treatments (Supplemental Table S2), the differences were not significant (Table 6). The REF showed nearly 2.5 times higher soil respiration throughout the study period

TABLE 6 Statistical results of the linear mixed effects analysis of monthly soil respiration (μmol CO_2 m^{-1} s^{-1}) from the main effects of whole tree removals (bole only [BO] and bole only harvesting with compaction [BOC] vs. whole tree [WT] and whole tree + compaction [WTC]), compaction (BO and WT vs. BOC and WTC), and individual treatment comparisons at the NARA LTSP site near Springfield, OR

Year	Main effects and treatment comparisons	Difference in average monthly bulk soil respiration		Difference in growing season bulk soil respiration	
		Estimate	P value	Estimate	P value
2014	Whole tree removals	0.29 ± 0.39	.287	0.48 ± 0.33	.180
	Compaction	−0.13 ± 0.25	.617	−0.13 ± 0.33	.694
	BO vs. REF	**−2.82 ± 0.39**	**<.01**	**−3.39 ± 0.48**	**<.01**
	BOC vs. WTFFC	−0.35 ± 0.44	.441	−0.08 ± 0.44	.866
	WTC vs. WTFFC	−0.47 ± 0.44	.296	−0.45 ± 0.44	.321
2015	Whole tree removals	**0.69 ± 0.26**	**.027**	0.60 ± 0.34	.107
	Compaction	0.18 ± 0.26	.512	−0.01 ± 0.34	.980
	BO vs. REF	**−2.54 ± 0.38**	**<.01**	**−2.99 ± 0.50**	**<.01**
	BOC vs. WTFFC	0.23 ± 0.34	.506	0.33 ± 0.47	.492
	WTC vs. WTFFC	0.08 ± 0.34	.820	−0.05 ± 0.47	.923

Note. REF, unharvested forest reference; WTFFC, whole tree harvesting with compaction. Bold indicates statistically significant effect ($p < .01$). The individual comparisons include: BO vs. REF testing the effect of forest harvesting and canopy removal, BOC vs. WTFFC testing the additive effect of WT plus forest floor removal keeping compaction constant, and WTC vs. WTFFC testing the additive effect of forest floor removal keeping compaction constant.

when compared with all treated plots (Supplemental Figure S3).

4 | DISCUSSION

From these results we find that biomass manipulations influenced nearly all response variables while compaction treatments appeared to have little effects. Our first hypothesis was confirmed; less residual biomass promotes higher soil temperatures, longer and higher quality growing seasons as interpreted by SGDD calculations. Our second hypothesis, that compaction would increase soil temperature and moisture, was rejected because neither were sufficiently changed due to compaction. Finally, our third hypothesis was also rejected; treatments with higher quality growing seasons did not have the highest rates of soil respiration. We posit the lack of differences in soil moisture is likely due to low water demands from seedlings, and the imprinting of harvest activities was a major disturbance that superseded any incremental biomass manipulations such that soil respiration was indistinguishable across treatments.

4.1 | Soil compaction

While there was no statistically significant impact of compaction on any response variable, there was a general trend of a slightly higher average and maximum soil temperatures, and greater SGDD with compaction. The compaction treatment's modest effect is consistent with other studies that have found higher average soil temperatures, although these are typically restricted to the upper 30 cm and with few statistically significant findings (Fleming et al., 2006; Li et al., 2003; Page-dumroese et al., 2006). This is expected because as bulk density increases, so too does soil thermal conductivity due to greater contacts between soil particles promoting more efficient heat transfer (Jury & Horton, 2004).

Other studies also find compaction had either a modest influence on soil moisture (Zabowski et al., 2000) or even a positive influence on soil moisture content (Ares et al., 2005; Gomez et al., 2002; Holub et al., 2013). However, the LTSP network has an overrepresentation of soils that are either more resilient to compaction (e.g., well-drained) or can actually increase their plant available water as a result of compacting coarse-textured soils Ponder et al. (2012).

Biomass manipulation studies in the PNW are overrepresented by Inceptisols with andic properties (this study, Slesak, Schoenholtz, et al., 2010; Zabowski et al., 2000), or Andisols (Ares et al., 2005; Strahm et al., 2005). Andisols or andic influenced soils have unique mineralogy, allophane and imogolite, which provide them relatively high specific surface area, cation exchange capacity, water holding capacity (Singh et al., 2018), abnormally low bulk density (0.60–0.85 g cm^{-3}) (Brady & Weil, 2010), and a high site resilience to dissolved N losses (Strahm & Harrison, 2006) and mineral soil C losses following harvest (James & Harrison, 2016). Thus, it unlikely the compaction effort on these andic soils would have approached root restrictive levels (~1.5 g cm^{-3}) (Powers, 1990). Extreme caution should be taken extrapolating these compaction results to other sites and locations with different mineralogy or different harvest techniques because Andisols have been shown to be the only soil order with increases in mineral soil C following harvests (James & Harrison, 2016).

Additionally, three locations along Willapa Bay in Washington had similar soils (Inceptisols with andic soil properties) but were harvested when soils were between saturation and field capacity resulting in ruts, displaced soil, and skid trails with bulk densities 86% greater than non-skid trails (Miller et al., 1996).

4.2 | Soil moisture

The range of VWC throughout the 2 yr of observation were almost entirely constrained to 28–37% VWC for all treated plots and all depths (Table 3). This is a narrower range than the similarly located Fall River LTSP site with ranges between 30 and 50% VWC (Roberts et al., 2005). However, that study began its observation period 2 yr after seedlings were planted, whereas this study began observations within 6 mo of treatment application and nearly synchronous when seedlings were planted. The narrow range in VWC at the NARA and Fall River LTSP sites may be due to a variety of factors including low water use demands from newly planted seedlings, high soil water holding capacity of fine-textured and/or andic mineralogy soils (Littke et al., 2018), and substantial rainfall saturating the profile during the winter months (Supplemental Figure S2).

There did not appear to be any negative effects of compaction on soil infiltration, despite post-treatment 0–15 cm bulk density increasing by approximately 16, 17, and 23% for BOC, WTC, and WTFFC, respectively (Supplemental Table S1). When comparing weather data during high rain events, VWC did not appear to lag between compaction treatments nor due the quantity of surface biomass left on site, which corroborates visual observations. However, it is possible the amount of infiltrated water, inferred from changes in VWC, were affected but were not captured from the hourly intervals of data collection. Although erosion is a common concern when exposing bare mineral soil (e.g., WTFFC), the slopes were gentle enough that no erosion was observed.

The LTSP sites in the PNW generally show growing season soil moisture to be negatively correlated with increasing biomass coverage, although with small effect sizes. For example, the growing season VWC at Fall River LTSP sites was between 2 and 4% lower in BO compared with WTFFC (Roberts et al., 2005), and 80% logging debris coverage at Matlock decreased VWC by 4% compared with 40% debris coverage in the 2nd year of observation (Slesak, Schoenholtz, et al., 2010). Early in a stand history the lack of differences in soil moisture across compaction or biomass retention treatments is consistent with other PNW biomass manipulation studies (Zabowski et al., 2000), with most researchers finding the presence of understory vegetation has a larger impact on soil water content (Ares, Terry, Harrington, et al., 2007; Harrington et al., 2013; Slesak, Harrington, et al., 2010) and soil matric potential (Lopushinsky et al., 1992).

Visual observations of WTFFC treatments during both summers qualitatively show the upper 0–5 cm of soil was drier than any other treatments. However, because the drying front did not reach the 10-cm soil moisture probe, we lack the quantitative data to suggest there were soil moisture differences between treatments. A final consideration is the effect size from treatments would need to exceed the accuracy of the moisture probes used in this study (±3% VWC) to be considered statistically significant. It is likely that the 0-to-5-cm depths were excessively dry in the WTFFC plots, and that VWC was influenced at 10 cm, but it was not a large enough change to have been statistically significant.

It is unlikely differences in soil moisture will become biologically significant until seedlings' water demand increases. For example, other PNW LTSP sites (Matlock and Mollala) with older trees have VWC reaching as low as 15% VWC in the growing season (Slesak et al., 2010a). Other studies across the PNW with higher stand density (500–1,800 trees ha^{-1}) found the 50-cm depth to reach 5% VWC or less during the summer (Littke et al., 2018). As trees approach canopy closure, and evapotranspiration demands approach the water inputs to the site, water limitations may become more apparent than they currently are. In this study, the untreated forest reference plots (REF) with ~55-yr-old trees and intact understory reached 15% VWC in the 10-cm depth and 30% VWC in the 100-cm depth during summer months indicating high water use demand by the overstory and understory vegetation (Gallo, 2016).

4.3 | Soil temperature

Other PNW LTSP sites have recorded summer month average temperature increases between 0.6 and 1.5 ˚C at 10-cm soil depth when comparing bole only vs. whole tree plus forest floor removal plots (Devine & Harrington, 2007; Roberts et al., 2005). This NARA LTSP site shows increases in the 10-cm daily average growing season soil temperature by 1.2 ˚C due to whole tree removals (Table 4), and 2.7 ˚C due to whole tree plus forest floor removals (Table 5). At a warmer California LTSP site, whole tree plus forest floor removal increased the summer soil temperature by 4–6 ˚C in the upper 30 cm (Paz, 2001), resulting in a robust shift towards a more drought-tolerant soil microbiological community 16 yr after harvests (Wilhelm et al., 2017). Although the NARA LTSP site did not exhibit as extreme a temperature shift, it is plausible that the extreme dryness in the 0–5 cm soil in the WTFFC plots could promote a microbial community shift.

Whole tree removals increase the maximum growing season deep soil (100 cm) temperature by 1.4 ˚C (Table 4). The additive effect of removing the forest floor compared with whole tree harvesting (WTC vs. WTFFC) increased deep average soil temperature by only 1.0 ˚C, but the growing season increased by approximately eight additional days, which is three times more than the 10-cm response (+2.6 d) (Table 5). The deep-soil response is notable because soil temperature has not been measured this deep on any LTSP-affiliated sites.

The greater effect size on soil temperature at this NARA LTSP site, compared with PNW Fall River LTSP site, may be due to the more southerly latitude of these sites and the southerly aspect of the hillslope promoting soil heating from increased solar radiation. These warmer soils could feasibly promote higher rates of nutrient cycling. Combined with the lack of moisture limitations from the VWC data, we expected a strong effect on microbial activity.

4.4 | Soil respiration

Elevated soil temperatures have been shown to have measurable effects on soil respiration in mesocosm experiments of newly added organic matter (Lin et al., 1999) and conifer root-litter additions (Chen et al., 2000). On other PNW LTSP sites, the peak growing season soil respiration rates correlated to peak soil temperatures, but was constrained when soil moisture content was lowest (Slesak et al., 2010b). This suggests a relatively simple relationship between temperature, moisture, and soil respiration; however, we did not find such relationships at this LTSP site.

Despite favorable conditions for microbial activity on plots containing less residual biomass (i.e., higher soil temperatures without evidence of moisture limitations), soil respiration rates were not statistically different across any treatment. This contrary finding may be, among other possibilities, a result of the intense and temporally recent disturbance effect on *all* plots (i.e., harvesting) that superseded the incremental differences in biomass retention, compaction, and the resulting influences on soil temperature (Levy-Varon et al., 2012; Rastetter et al., 2013). Similar results were identified by Martin (2019) using soils from this same location; rates of soil respiration in a mesocosm experiment showed no differences between treatments 3 mo post-treatment, and only small differences between treatments 3 yr later. Martin (2019) also noted microbial composition varied more between sample periods, than between treatments. Prior LTSP study sites (Matlock and Molalla) began their soil respiration observation period nearly 2 yr *after* harvest (Slesak et al., 2010b), whereas this current study began observations 6 mo after harvests concluded.

One idea of the rapid monitoring of soil respiration following harvests was to examine hypotheses set forth by Powers et al. (2005) attempting to explain a decade worth of LTSP results. They noticed mineral soil C stocks generally decreased when the forest floor was removed but mineral soil C stocks either stayed the same, or sometimes increased, when only harvest slash was removed. They posit three possible explanations including (a) biased sampling near stumps, (b) rapid heterotrophic respiration leading to soil particle settling and densification, or (c) increases in root fragmentation and decomposition following harvests leading to an apparent increase in mineral soil C. The authors dispense with the first explanation, lend some credence to the second hypothesis, and provide considerable evidence to support their third explanation. While we cannot address the third hypothesis, we can address the second; although soil microclimate appears more favorable in plots with less surface biomass (WT, WTC, and WTFFC treatments), it did not result in an accelerated rate of mineral soil respiration compared with bole only harvesting. As time since disturbance increases, possibly exhausting senesced root-derived C and aboveground labile organic matter additions, temperature and moisture conditions may predict soil efflux and nutrient mineralization rates in the long term.

Alternatively, soil respiration may have been uniformly diminished across all treatments due to the application of herbicides (e.g., Velpar, Transline, and Glyphosate) as seen for vegetation control in agricultural settings (Nguyen et al., 2016) and in forest settings (Slesak et al., 2010b). Forest applications of herbicide at this study location were much lower (∼10 mg kg^{-1}) compared with experimental agricultural rates (∼200 mg kg^{-1}). Martin (2019) showed treatments had similar cumulative CO_2 respired in mesocosm experiments using 3-mo and 3-yr post-treatment samples, the latter sample point is 1 yr after herbicide application ended at this NARA site. Therefore, it is unlikely that herbicide application had a differential effect between treatments on overall soil respiration observations.

4.5 | Implications for tree growth

Even after a decade following complete removal of boles, harvest residues, O-horizon, and coarse woody debris, Powers et al. (2005) found that there was no discernable unambiguous impact on tree growth across LTSP installations. A recent analysis of seedling growth shows this NARA LTSP site had the greatest 0–3-yr seedling response of any of the PNW LTSP sites (Littke et al., 2021). This overperformance in the initial few years could be attributed to several factors specific to this NARA LTSP site including: a 25–50% lower planting density, more robust vegetation control, improved seedling genetics, and/or a warmer climate without moisture limitations. However, after the first 0–3 yr, the seedling growth rates slowed compared with the Fall River LTSP site.

Within this NARA site, Littke et al. (2021) also found that WTFFC had the largest seedling growth response and the BO treatment had the lowest seedling performance. Although bole only treatments (BO, BOC) have similar levels of surface biomass retained (Table 2), the BOC treatments had 40% more SGDD compared with BO, which is similar to whole tree treatments (WT, WTC) (Table 3). This suggests compaction on BOC treatments increased the soil thermal conductivity that may have offset the "mulch effect"-induced cooling from additional harvest residues. As noted above, the soil temperatures on WTFFC were the highest of all treatments. They approached temperature optimums for nitrification, but also threshold temperatures for seedling mortality.

Douglas-fir seedling response to soil temperature have been well documented (Lavender & Hermann, 2014) and we might expect a decrease in root growth, or even mortality, when rooting temperatures exceed 25 ˚C. Based on monthly field visual observations over 2 yr and site visits, there is no excessive seedling mortality on WTFFC treatments even though the 10-cm depth regularly exceed 25 ˚C (Figure 1). This likely because seedlings were planted at depths deeper than those receiving these lethal temperatures. Interestingly, the 25–35 ˚C soil temperature range corresponds to optimized nitrification rates in forest soils (Brady & Weil, 2010), which is one possible explanation for higher foliar N content in the WTFFC treatment (Littke et al., 2021).

The excessive drying of exposed mineral soil in the WTFFC plots may cause decreases in long-term site productivity. The PNW is commonly associated with andic-influenced soils containing allophane and imogolite, but their meta-stable nanocrystalline structures depends on retaining at least some moisture to remain stable (Churchman et al., 2012). These forests typically have an O-horizon, preventing excessive drying that may de-water allophane and imogolite, permanently collapsing their structures and forming halloysite or kaolinite (Chadwick et al., 2003). These secondary minerals have one to two orders of magnitude less effective surface area compared with allophane or imogolite (Singh et al., 2018), thereby permanently decreasing the water holding capacity (Karube & Abe, 1998) and potential cation exchange capacity of the site. Because the upper mineral layer in forest soils have a disproportionate amount of organic matter and nutrient reserves, any reduction in cation exchange capacity of these upper few centimeters could have an outsized negative consequence on the WTFFC treatment that may not be realized until higher demands from soil resources occurs later in stand development. The uniqueness of this NARA LTSP site (low soil bulk density, moderate slopes, high soil organic matter, and water holding capacity) may be providing an early-stage resilient response, but continued monitoring is necessary to ensure the long-term productivity of this western cascade forest.

5 | CONCLUSIONS

We found that increasing the level of organic matter removal did promote higher soil temperatures, but soil moisture was unaffected by any biomass or compaction treatment. Bulk density of compacted treatments increased by 16–23%, but we found no robust evidence that compaction negatively affected any response variable measured. As a result, greater organic matter removals corresponded to higher quality soil growing conditions throughout the profile due to temperature increases without facing moisture limitations. To the best of the authors' knowledge, this is the first LTSP study with temperature observations down to 100-cm depth. Treatments with the largest and smallest SGDD, corresponded with the maximum and minimum seedling growth (WTFFC and BO, respectively). Soil temperatures on WTFFC treatments reached the optimal window for nitrification rates and approached the higher end of fine-root growing temperatures (25–30 ˚C). Although seedling performance could change with an additional few degrees of warming illustrating the precarious nature of extrapolating these results elsewhere.

Despite adequate soil moisture and statistically significant increases in soil temperature throughout the entire soil profile (0–100 cm) as more organic matter was removed, we found no statistically significant differences in soil respiration during the first 2 yr of observation. These soil respiration results run counter to other, more established, LTSP findings. The uniformity in soil respiration may be a result of the intense and temporally recent disturbance effect on all plots (i.e., harvesting) that superseded the incremental differences in biomass retention, compaction, and the resulting influences on soil temperature. Furthermore, this study occurs on soils with abnormally low bulk density and a high soil nutrient status such that early site resilience seen here may not be maintained through the canopy closure phase or be applicable to other locations. Future research should continue to investigate the apparent resilience in seedling growth and changes in soil C dynamics to identify potential growth limitations as the site approaches canopy closure and soil resources face higher demands.

AUTHOR CONTRIBUTIONS

Adrian C. Gallo: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Visualization; Writing – original draft; Writing – review & editing. Scott M. Holub: Conceptualization; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing – review & editing. Kim Littke: Data curation; Investigation; Resources; Supervision; Validation; Writing – review & editing. Kate Lajtha: Supervision; Writing – review & editing. Doug Maguire: Supervision; Validation;

Writing – review & editing. Jeff A. Hatten: Conceptualization; Data curation; Funding acquisition; Investigation; Methodology; Project administration; Supervision; Validation; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

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