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Effects of forest harvesting and biomass removal on soil carbon and nitrogen: Two complementary meta-analyses

Jason James[a,*], Deborah Page-Dumroese[b], Matt Busse[c], Brian Palik[d], Jianwei Zhang[e], Bob Eaton[f], Robert Slesak[g], Joanne Tirocke[b], Hoyoung Kwon[h]

[a] Exponent Inc. Bellevue, WA 98007, USA
[b] Rocky Mountain Research Station, US Forest Service, Moscow, ID 83843, USA
[c] Pacific Southwest Research Station, US Forest Service, Davis, CA 95618, USA
[d] Northern Research Station, US Forest Service, Grand Rapids, MN 55714, USA
[e] Pacific Southwest Research Station, US Forest Service, Redding, CA 96002, USA
[f] Southern Research Station, US Forest Service, Research Triangle Park, NC 27709, USA
[g] Department of Forest Resources, University of Minnesota, St. Paul, MN 55108, USA
[h] Systems Assessment Center, Energy Systems Division, Argonne National Laboratory, Lemont, IL 60439, USA

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ABSTRACT

Forest residues and logging slash from pre-commercial forest thinning and regeneration harvests are a potential feedstock for bioenergy production but there has been a concern about the impact of residue removal on forest soil C and N. This study aimed to address such by conducting two meta-analyses using the data available from published literature and an independent dataset compiled from the North American Long-Term Soil Productivity (LTSP) study.

For the meta-analysis using literature, we categorized forest harvesting and biomass removal into i) no harvest control, ii) bole-only (BO, partial or clearcut) regular harvests, iii) BO with partial removal of logging slash and/or O horizon (BO+Removal), iv) whole tree harvests (WTH), and v) WTH with slash and O horizon removal (WTH+Removal). Accordingly, we compiled soil C and N data and key statistics (e.g., standard deviation) from 142 scientific articles published since 1979. We compared the results from this meta-analysis with data from 22 installations of the LTSP study where three levels of organic matter removal - BO, WTH, and WTH plus forest floor (+FF, O horizon) removal - as well as an additional vegetation control (+VC) were measured for two decades in either completely randomized or randomized block design.

In the literature meta-analysis, BO+Removal (-19.2%), WTH (-15.4%) and WTH+Removal (-24.9%) contained significantly less soil C than no-harvest controls across combined soil depths, while BO had no difference. Within individual mineral soil horizons, only BO+Removal and WTH+Removal treatments contained significantly less carbon than controls. There was a high degree of heterogeneity in treatment response between studies in the literature. The analyses from the LTSP dataset showed no significant difference in combined soil depths for WTH or WTH+VC relative to BO harvest, but there was significantly less soil C in BO+VC (-3.6%), WTH+FF (-8.5%) and WTH+FF+VC (-15.3%). These treatment effects declined over time since harvest, particularly the most intensive treatments. Soil N results largely mirrored soil C in both meta-analyses with smaller estimated effects for most treatments at equivalent depths (except for WTH+Removal and WTH+FF+VC, which remain about the same). There were no significant differences in soil N for combined soil depths between WTH and no-harvest control (in the literature analysis) or BO harvest (for both analyses).

Since the most severe losses of soil C and N involved FF removal, WTH that accounts for modest removals (<80%) of harvesting residues may provide a sustainable source of biomass for bioenergy production without additional soil impacts compared to BO harvesting practices.

* Corresponding author.
E-mail address: jamesj@exponent.com (J. James).

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1. Introduction

Bioenergy production has the potential to reduce fossil fuel used for heating and transportation (Popp et al., 2014). Growing interest in woody biomass feedstocks for bioenergy production has stimulated studies from U.S. Forest Service (White, 2010) and U.S. Department of Energy (Langholtz et al., 2016) that assess the resource potential of biomass growth and production from managed forests at national and regional levels. In such assessments, scenarios are often developed to evaluate the economic, ecological, landscape, and technical impacts of biomass yields, biomass to bioenergy conversion efficiencies, and management regimes on bioenergy wood production. For example, forest restoration thinning is now actively practiced on national forest lands to reduce tree densities and wildfire hazard, and this means that woody residues are either moved off-site for bioenergy production or burned in slash piles (Goerndt et al., 2012; Skog and Barbour, 2006).

In recent years, forest residues (i.e. logging residues and pre-commercial forest thinnings) have been proposed as a feedstock for cellulosic biofuels along with corn stover and dedicated energy crops (Williams et al., 2009). Historically, forest residues have been underutilized as a source of biomass feedstock because of low market demands and high transportation costs (Oswalt and Smith, 2014). Recent cost-benefit analyses, however, suggest that as much as 65% of all forest residues could theoretically serve as a source for national biofuel production (Perlack et al., 2011).

Studies have investigated life-cycle energy consumption and greenhouse gas (GHG) emissions for biofuels produced from forest residues via either a thermo- or biochemical biomass conversion process, and found potential for GHG offsets from woody biofuel production (Zanchi et al., 2012). However, the environmental impacts of removing forest residues from forestlands have not been well quantified in life-cycle analyses. In fact, forest residues can increase wood decay rates in the mineral soil (Page-Dumroese et al. this issue) or on the soil surface (Finér et al. 2016), providing important ecosystem services such as maintaining site productivity (McKinley et al., 2011), minimizing erosion (Berhe et al., 2018), and preserving forest diversity (Attiwill and Adams, 1993; Buchholz et al., 2014). Forest residues also play a key role in the carbon cycle in forest soils, resulting in the storage of significant quantities of soil C (Achat et al., 2015). As a result, harvesting forest residues for bioenergy or biofuel could have long-term impacts on soil C, potentially reducing the net benefit of GHG offsets.

Several meta-analyses have assessed the impacts of harvesting and residue removal on soil C (Achat et al., 2015; James and Harrison, 2016; Johnson and Curtis, 2001; Nave et al., 2010). In meta-analysis, results from many studies that apply similar treatments are statistically analyzed to provide cumulative answers that may not have been evident within individual sites (Hedges et al., 1999; Lajeunesse, 2011). Using this approach, Achat et al. (2015) showed that intensive harvests led to soil C losses in all layers of forest soils. Similarly, James and Harrison (2016) found that harvesting reduced soil C, on average, by 11.2% and there was substantial variation between responses in different soil depths, with greatest losses occurring in the O horizon.

While meta-analysis is a powerful tool, the process of data synthesis combines many different treatments and study designs from across the peer-reviewed literature, which sacrifices the fine distinctions in treatment implementation for greater generalizability. Ideally, a more comprehensive approach where an independent synthesis and meta-analysis are conducted using a separate dataset should be taken to provide consistent study design in a wide variety of forests. This can be accomplished through the North American Long-Term Soil Productivity (LTSP) study in which a similar experimental design was implemented across a wide variety of forest soils (Powers, 2006). In our study, we conducted meta-analyses on two different datasets – one of published literature and the other of an independent dataset compiled from the LTSP study. The latter includes soil C and N data to quantify the consequences of pulse soil disturbance on forest productivity through research and monitoring (Powers, 2006). Since 1989, the LTSP sites, located across the US and Canada, have provided valuable long-term data for forest research and results for forest management. One key finding from the first decade of the experiment was that complete removal of surface organic matter (including O horizon) led to declines in soil C and nutrient concentrations to a depth of 20 cm in the mineral soil (Powers et al., 2005). By replicating the same study design across many forests, the LTSP network provides a powerful dataset to quantify the effects of forest residue removal on forest C and N cycling as well as aboveground vegetation growth.

By employing this dual meta-analytic approach, we evaluated the long-term impacts of harvesting forest residues as a cellulosic biofuel feedstock on soil C and N. In particular, our goals were to answer the following research questions:

- What effect do different methods of biomass removal in addition to conventional harvest have on soil C and N stocks?
- How does this effect differ with soil depth?
- Are the effects on soil C and N persistent or are they reversible with time?
- What effects do LTSP experimental treatments, including whole tree harvest, forest floor removal, and herbicide application, have on soil C and N stocks?
- Are there differences in LTSP treatment effects with depth or time?
- Are the results of the literature synthesis and LTSP analyses comparable and consistent?

2. Methods

2.1. Literature search

Meta-analysis is a cumulative activity which builds upon previous studies with similar research questions and previous meta-analyses about forest harvesting effects on soil C have been conducted (James and Harrison, 2016; Nave et al., 2010). In particular, we revisited the database of James and Harrison (2016), which included 112 literature publications between 1979 and 2016, recreated it, and added sampling variance information (standard deviation (SD), standard error (SE), and sample number) and soil N data (when available) from each study. More importantly, we expanded the database with studies published between 2016 and 2020 by performing the new literature search on the PROQUEST Dialog Databases, which include AGRICOLA, AGRIS, BIOSIS Previews®, CAB ABSTRACTS, Ecology Abstracts, and Environment Abstracts, among others, using a set of search terms (Table 1).

A total of 1067 published papers since 2016 were screened, which were further reviewed by checking abstracts to see if the study included treatments of interest and soil C and/or N data. A paper was deemed acceptable for inclusion in the analysis if a) a relevant forest treatment (such as thinning or clearcutting) was implemented, b) unharvested control was reported, c) soil C and/or N stocks were reported, or could be calculated from concentration and bulk density measurements, and d) both average and variance were reported for each treatment and control (either SE or SD and sample number). After checking the full

Table 1
Search terms used to survey peer reviewed literature for relevant studies.

Category	Search terms
Media	Soil carbon, SOC, soil C, soil organic matter, SOM, soil nitrogen, soil N
Ecosystem	Forest, hardwood, softwood, timber
Treatment	Thinning, clear cut*, whole tree harvest, forest residue removal, forest floor removal, stand management, logging, forest harvest*
Publication Year	> January 1st 2016

Note: the * search character was included after some search terms to capture multiple word endings (e.g. cut, cuts, cutting) texts of 41 papers identified as relevant, 30 papers were added into the database of James and Harrison (2016) for a total of 142 papers used in the meta-analysis described below.

2.2. Data retrieval and effect size calculation

We gathered soil C and N data (including average, SD, sample counts, and SE) from each study identified in the literature search and categorized them into every combination of soil depths and treatments we considered in this study. Soil depths were separated into five groups – O horizon, top soil (0–15 cm), mid soil (15–30 cm), deep soil (30–60 cm), and very deep soil (60–100+ cm). We also estimated the combined soil C or N stock from the five soil depth groups for each treatment were calculated by summing the means of each sampled depth .Standard deviation for the combined soil estimate was calculated as the square root of the sum of variances from each depth. Combined soil C or N stock was calculated only for treatments with greater than 30 cm maximum sample depth. For example, a study with two treatments and a control which measured the O horizon and two mineral soil depths would generate 2 treatments × 4 depths (3 measured+combined soil) = 8 observations of treatment effect.

Due to the variety of harvest intensities and strategies in the published literature, we categorized forest harvesting and biomass removal into i) bole-only (BO, partial or clearcut) harvests, ii) BO with partial (20–80%) removal of logging slash and/or O horizon (BO+Removal), iii) whole tree harvests (WTH), and iv) WTH with partial or complete removal of logging slash and/or O horizon (WTH+Removal). Thinning and clearcut treatments were lumped together within each of these categories. Treatments that included fire, broadcast burning, prescribed fire for fuel management, or tilling/scarification were excluded from the analysis, as these treatments have distinct and sometimes severe effects on soil C (James and Harrison, 2016; Nave et al., 2011) that are outside the scope of this manuscript.

To combine data across studies, effect size was calculated as the log response ratio (*RR*) for each treatment from each study (Hedges et al., 1999; Lajeunesse, 2011). Effect size (*RR*) was calculated as:

$$RR = \ln\left(\frac{\overline{X_1}}{\overline{X_2}}\right) \tag{1}$$

where $\overline{X_1}$ is the mean C or N stock in a specific depth for an individual treatment, and $\overline{X_2}$ is the mean C or N stock at the corresponding depth in the control (unharvested treatment). The SE of *RR* was calculated as:

$$SE[RR] = \sqrt{\frac{SE[\overline{X_1}]^2}{\overline{X_1}^2} + \frac{SE[\overline{X_2}]^2}{\overline{X_2}^2}} \tag{2}$$

Studies that did not report measures of variance were not included in the meta-analysis. The response ratio (and variance) can be back-transformed to be expressed as % change relative to control via equation (3):

$$\%Change = \left(\frac{\overline{X}_t - \overline{X}_c}{\overline{X}_c}\right) \times 100 = \left(\frac{\overline{X}_t}{\overline{X}_c} - 1\right) \times 100 = \left(e^{(RR)} - 1\right) \times 100 \tag{3}$$

2.3. Long-Term soil productivity (LTSP) data

A largely independent dataset from the LTSP network was used to evaluate the effect of various biomass removal treatments on soil C and N during the harvesting of original natural stands. The LTSP network is a set of research sites across the major timber regions in North America installed to address the impact of organic matter removal and compaction on forest productivity of following rotations. Each study contained three levels of organic matter removal (BO, WTH, and WTH+FF) combined with three levels of compaction (background, moderate, severe) in a completely randomized or randomized block design. Unlike the studies from other published literature, LTSP adopted consistent percentage of residue removals for WTH and WTH+FF, which were approximately 80 and 100% of surface organics, among installations. At many of these sites, plots were split and competing vegetation was controlled with either herbicide application or hand removal until crown closure of regenerated forest. However, because 18 combinations of three levels of organic matter removal, three levels of compaction, and with and without (two levels) vegetation control were not replicated at each location, treatment effects (and standard errors) at each site were averaged across levels of compaction and compaction effects were not evaluated. The treatments included in this analysis were:

- BO: bole-only harvest, where tree limbs and tops were left on site
- BO+VC: bole-only harvest with complete vegetation control (planted trees only)
- WTH: whole tree harvest where whole trees are removed from the study plot
- WTH+VC: whole tree harvest with complete vegetation control.
- WTH+FF: whole tree harvest with forest floor (O horizon) removal by hand or mechanical scraping
- WTH+FF+VC: whole tree harvest with forest floor removal and complete vegetation control.

Twenty-two LTSP sites located in California (CA), Idaho (ID), Michigan (MI), Minnesota (MN), North Carolina (NC), Texas (TX), Oregon (OR), and Washington (WA) were included (Table 2). Three studies from the literature database include data from LTSP sites - Mushinski et al. (2017) for Davy Crockett; Kurth et al. (2014) for Chippewa, Huron, and Ottawa; Laiho et al. (2003) for Croatan. Combined soil C and N stocks were calculated for each treatment at each site in the same manner as the literature *meta*-analysis.

Effect size for each depth and treatment at LTSP sites was calculated with the log response ratio (*RR*)–equations (1) and (2), above–except $\overline{X_2}$ was the mean C or N in the BO treatment rather than no-harvest treatment as a control, which was used for the literature meta-analysis. Consequently, the results of the literature synthesis and LTSP studies are not directly comparable because they are compared against different controls.

2.4. Data analysis

The literature and LTSP soil C and N databases were analyzed with multi-level, mixed-effect, meta-regression models. Separate models were fit to examine the treatment effects at different soil depths and the treatment effects over time. In the meta-regression models, nested grouping levels are used to express a hierarchical structure of random effects (Sera et al., 2019; Viechtbauer, 2010). For the model of treatment effects (T_i) at different soil depths (D_j), random effects for each depth group (b_{ij}) and time since harvest (b_{ik}) were nested within the reference-specific random effect (b_i), for a linear model written as:

$$RR_{ijr} = \beta_0 + \beta_1 T_i + \beta_2 D_j + \beta_3 T_i D_j + b_i + b_{ij} + b_{ik} + \varepsilon_{ijkr} \tag{4}$$

β_0 is the model intercept .
β_1 accounts for Treatment effect
β_2 accounts for Depth effect
β_3 accounts for Treatment by Depth interaction
b_i accounts for study (for literature dataset) or location (for LTSP dataset) variability
b_{ij} accounts for depth variability within study i
b_{ik} accounts for temporal correlation within study i
ε_{ijkr} is residual variability
$i = 1, 2, \cdots, m$ studies and $j = 1, 2, \cdots, m_i$ depth groups in study i, and $k = 1, 2, \cdots, n_{ij}$ time points at depth j in study i

with $b_i \sim N(0, \tau_1^2)$ and $b_{ij} \sim N(0, \tau_2^2)$ and $b_{ik} \sim N(0, \gamma_2^2)$ and $\varepsilon_{ijkr} \sim N(0, s_{ijkr}^2)$

Table 2
Site and pre-treatment stand characteristics of LTSP installations.

State	Location	Forest type	Soil sampling interval (yr)	Mean annual precipitation (mm)	Texture[a]	Number of response ratio (C and N)
CA	Aspen	Mixed conifer	0, 5, or 10	226	C	30, 30
	Blodgett		0,10, or 20	1650	F	30, 30
	Brandy		0,10, or 20	1900	F	30, 30
	Central		0,10, or 19	1140	C	30, 30
	Challenge		0,10, or 20	1730	F	30, 30
	Cone		0, 5, or 10	238	C	30, 30
	Lowell Hill		0,10, or 20	1730	F	30, 30
	Owl		0,10, or 19	1140	C	30, 30
	Rogers		0,10, or 20	1700	C	30, 30
	Vista		0,10, or 19	760	C	30, 30
	Wallace		0,10, or 20	1780	C	30, 30
ID	Council	Mixed conifer	0, 5, or 10	772	F	18, 18
	Priest River		0, 5, or 10	873	F	12, 12
MI[b]	Huron	Aspen	0, 5,10, or 15	75	C	32, 32
	Ottawa		0, 5,10, or 15	77	F	32, 32
MN[b]	Chippewa	Aspen	0, 5,10, or 15	64	F	32, 32
NC	Croatan	Pine–hardwoods	0, 5,10, or 20	1360	F	45, 45
OR[b]	Diamond Lake	Douglas-fir	0 or 5	1234	C	4, 4
	Molalla		0 or 10	1600	F	4, 0
TX[b]	Davy Crockett	Loblolly pine	0 or 20	1107	F	4, 4
WA[b]	Fall River	Douglas-fir	15	2260	F	18, 0
	Matlock		0 or 10	2400	C	4, 0

[a] C - coarse (contains gravel or greater than 60% sand); F - fine (no gravel & loam or finer texture)
[b] Use values from published literature

Treatment and depth are of primary interest in this fitted model; therefore, they are fit with fixed effects and for the interaction term. Random effects accounted for differences between studies, and different depth groups within studies. The data for this model utilizes calculated effect sizes, i.e., log response ratios, and the associated uncertainty estimates for each treatment and depth group within each study, rather than raw replicate measurements. Replicate data would allow for a more standard least-squares approach if there were sufficient studies with identical objectives, measurements, and replication. Uncertainty differs for each calculated *RR*, therefore the random effect terms in the fitted model also must account for these differences. In the definition of error structures above, N is the normal distribution. ${\tau_1}^2$ is the variance for the random effects for study differences and ${\tau_2}^2$ is the variance for each depth group within each study. ${\gamma_2}^2$ is the variance for the random effects for each time point within each study. The data indexed by r represent the n_{ijk}reported effect sizes for each time point k measured in depth group j nested within study i, each with known within-study variance ${s_{ijkr}}^2$ (from equation (2), above).

Specification of the linear model for the analysis of treatment effects over time utilized a longitudinal repeated measure *meta*-analysis to evaluate variability in effect sizes by study, accounting for the n_{ij} repeated measurements over time at depth j in study i. The full fitted model can be written as follows:

$$RR_{ijkr} = \beta_0 + \beta_1 T_i + \beta_2 D_j + \beta_3 t_{ijk} + \beta_4 T_i D_j + \beta_5 T_i t_{ijk} + \beta_6 D_j t_{ijk} + \beta_7 T_i D_j t_{ijk} + b_i + b_{ij} + b_{ik} + \varepsilon_{ijkr} \tag{5}$$

β_0 is the model intercept
β_1 accounts for Treatment (T) effect
β_2 accounts for Depth (D) effect
β_3 accounts for temporal (t) trend
β_4 accounts for Treatment | Depth interaction
β_5 accounts for temporal trend within treatment levels
β_6 accounts for temporal trend within depth groups
β_7 accounts for three-way Treatment | Depth | Time interaction
b_i accounts for study (literature) or location (LTSP) variability
b_{ij} accounts for depth variability within study i
b_{ik} accounts for temporal correlation within study i
ε_{ijkr} is residual variability
$i = 1, 2, \cdots, m$ studies and $j = 1, 2, \cdots, m_i$ depth groups in study i, and $k = 1, 2, \cdots, n_{ij}$ time points at depth j in study i

with $b_i \sim \mathrm{N}(0, {\tau_1}^2)$ and $b_{ij} \sim \mathrm{N}(0, {\tau_2}^2)$ and $b_{ik} \sim \mathrm{N}(0, {\gamma_2}^2)$ and $\varepsilon_{ijkr} \sim \mathrm{N}(0, {s_{ijkr}}^2)$

The temporal trend for each treatment effect at each depth is of primary interest in this fitted model. Thus, they are fit with fixed effects and two- and three-way interaction terms to allow the intercept and slope to differ for each depth measured in each treatment. Random effects accounted for differences between studies (b_i), different depth groups within studies (b_{ij}), and the correlation between repeated measurements of the same treatments and depths over time (b_{ik}). The structure of the temporal correlation was specified as heteroscedastic autoregressive of first order, which allows the correlation between measurements in a study to decrease the farther apart they are in time. ${\tau_1}^2$ is the variance of the random effects for study differences, ${\tau_2}^2$ is the variance for each depth group within each study, and ${\gamma_2}^2$ is the variance for the random effects for each time point within each study. The data indexed by r represent the n_{ijk}reported effect sizes for each time point k measured in depth group j nested within study i, each with known within-study variance ${s_{ijkr}}^2$ (from equation (2), above).

For the LTSP data, location was included as a random effect in place of reference, since multiple treatments were compared against a single bole-only treatment within each forest. Depth was included as a random effect nested within forest installation name to account for correlation in measurements of different soil depths within each site. Because the LTSP data is structured with resampling of the same treatment plots in each forest over 20 years, time since treatment was added as a second random effect nested within forest installation name. Separate models evaluated the effect of treatments at different soil depths and over time.

Tukey post-hoc comparisons between harvest treatments at each depth were evaluated for both the literature and LTSP databases (Hothorn et al., 2008). The Benjamini and Hochberg (1995) correction for the false discovery rate was used to adjust the significance level for multiple comparisons. For all statistical tests in this analysis, alpha was 0.05. All statistical analyses were completed in the R statistical computing language (R Core Team, 2019). Meta-analytic models to evaluate the effect of treatments with soil depth and over time were fit using the rma.mv function in the metafor package (Viechtbauer, 2010). Multiple comparisons were computed with the glht function in the multcomp package (Hothorn et al., 2008).

3. Results

3.1. Effect of harvesting and biomass removal treatments on soil C in the literature meta-analysis

The combined soil C was significantly reduced compared to no-harvest control for the treatments of BO+Removal (-19.2% [95% CI −29.7 to −7.2%]), WTH (-15.4% [-24.6 to −5.1%]), and WTH+Removal (-24.9% [–32.2 to −16.7%; Fig. 1, Supplementary Table 1). The difference was not significant between BO harvest and no-harvest control. The WTH+Removal treatment also had significantly reduced soil C compared to BO harvest. However, the sample size for the more intensive treatments was very small and thus may not be representative of broader-scale trends. Furthermore, the maximum sampling depths for studies examining the three treatments were typically only 30 cm, which was shallower than BO treatments (Fig. 2). Consequently, the relatively large effects seen in the combined soil are more highly influenced by reductions in the O horizon and surface mineral soil.

Treatment effects varied with soil depth in the literature meta-analysis (Fig. 1). Soil C in all three intensive treatments was significantly reduced in the O horizon compared to no-harvest control, which is in line with direct manipulation and removal of O horizon material by these treatments. In the mineral soil, the WTH+Removal treatment was significantly different from no-harvest control in all depths but had very few or just a single effect size estimate below the topsoil. WTH in itself was not significantly different from the control in the mineral soil. The BO+Removal treatment was significantly different from no-harvest in the mid soil depth group (approximately 15–30 cm), although the 95%

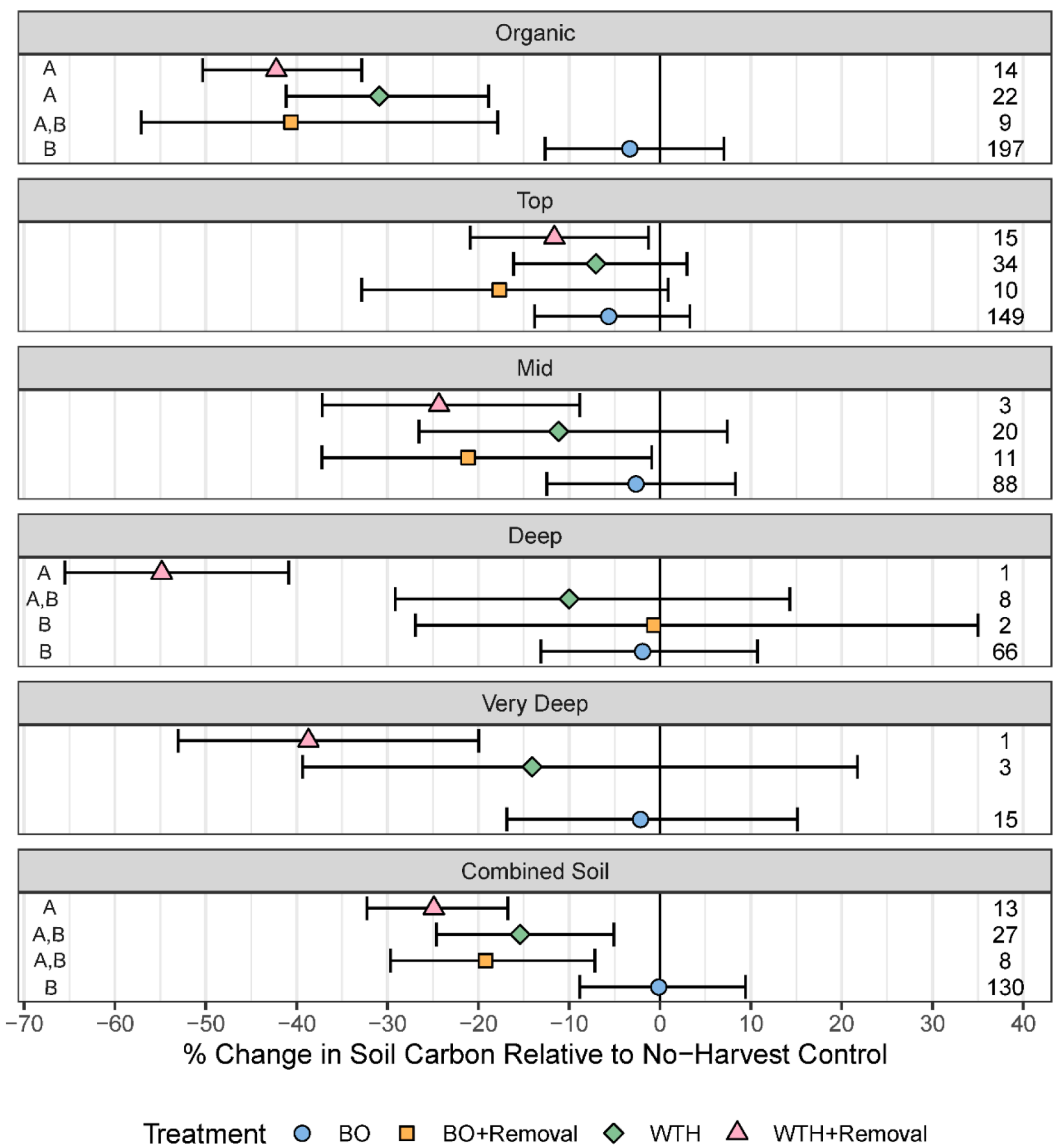

Fig. 1. The effect of bole-only harvest (BO), whole tree harvest (WTH), and biomass removal (+Removal) on soil C in the organic horizon and different mineral soil depths in the literature meta-analysis. Each estimate is shown with a 95% confidence interval. Within each facet, treatments with different capital letters are statistically significantly different from each other ($p < 0.05$); facets without letters were not significantly different. The number of observations from literature included in each estimate is listed on the right. Depth, time since harvest and reference were included as random effects in the model with depth and time nested within the levels of reference. This accounted for correlation in the effects observed at different depths and times in the same study, as well as for correlation in effects of different treatments within individual studies that utilize a single control treatment. The test of moderators was $Q_M = 263$ (df = 22), $p < 0.0001$, and test of residual heterogeneity was $Q_E = 7571$ (df = 816), $p < 0.0001$, and $I^2 = 80.7\%$.

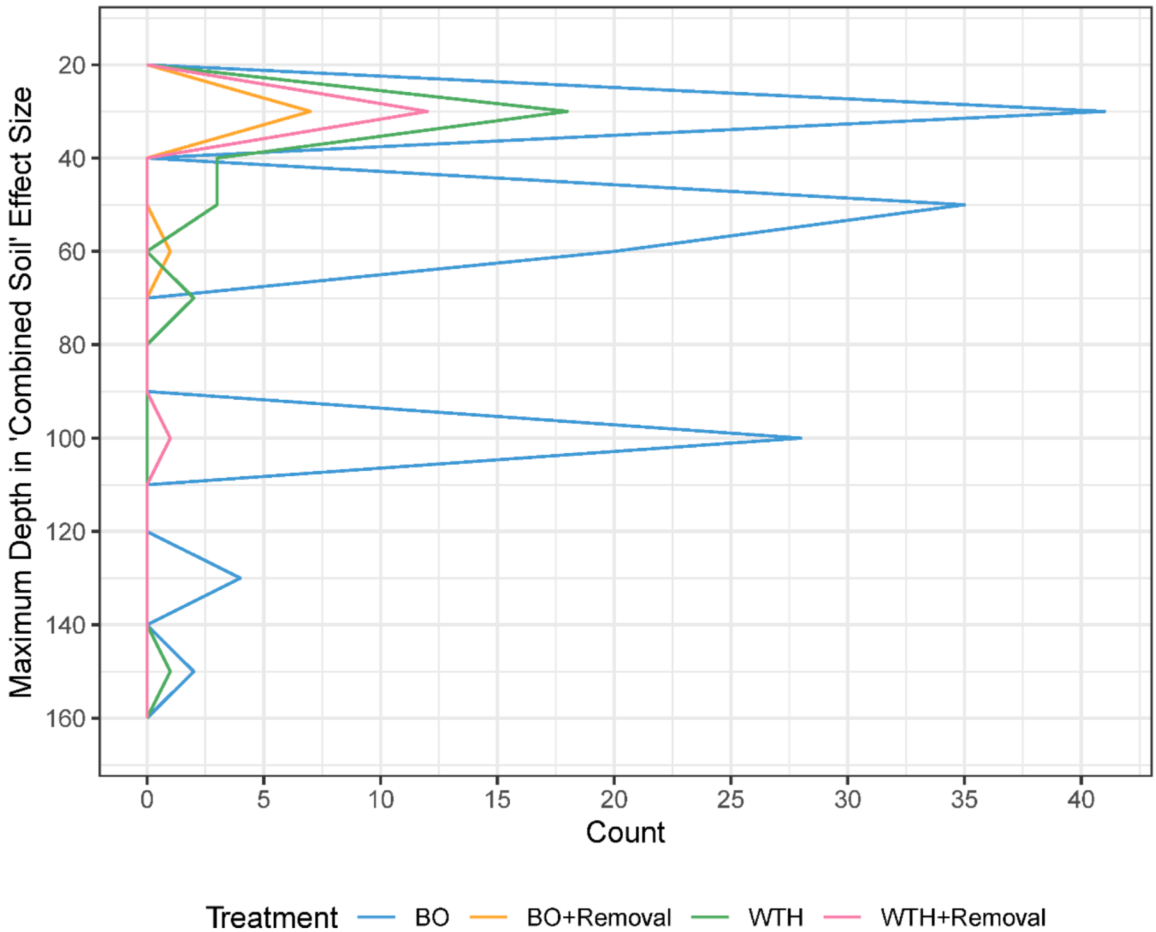

Fig. 2. Frequency of maximum sampling depths for soil C effect sizes included in 'combined soil', split between treatments.

CI was wide due to the small number of effect sizes (11). No effect size estimates were available for the BO+Removal treatment deeper than 60 cm.

I^2 for the overall literature soil C model was 80.7%, which indicates how much of the unaccounted variance in the observed effects (which is composed of unaccounted variance in the true effects plus sampling variance) can be attributed to residual heterogeneity (Viechtbauer, 2010). The high level of residual heterogeneity indicates that site- and study-specific variability and environmental factors play a considerable role in moderating the effects of harvest treatments on soil C (Thiffault et al., 2011).

The trend in treatment effects over time was fit with a second-degree polynomial within the *meta*-regression model to account for the initial loss in soil C followed by a slow recovery over decades (Fig. 3). Studies on regular BO harvesting practices extend much longer after treatment than for BO+Removal, WTH, or WTH+Removal treatments (~110 years vs ~ 40 years for BO+Removal and ~ 20 years for WTH and WTH+Removal). For BO harvest, combined soil C declined slightly over the first 50 years and recovered around 100 years after treatment. While declines in the O horizon were not consistently evident for the BO treatment, slightly temporal trends were evident in top (~0–15 cm) and mid (15–30 cm) soil depths with more consistent decline in deep soil (~30–60 cm). However this trend was driven by a relatively small number of studies with lower variance, and a number of other studies show little difference or an increase relative to no-harvest control. Temporal trends for BO+Removal treatments were imprecise due to the gap in sampling timeframes between 5 and 35 years after treatment. 35–40 years after BO+Removal treatments, O horizon C had not yet recovered, but top (~0–15 cm) and mid (~15–30 cm) mineral soil C were estimated to be close to no different from no-harvest control. The WTH treatments in the combined soil showed little temporal trend, which had a slight decline over the first decade and recovery toward no change relative to no-harvest control largely driven by the O horizon. No trend was evident in top mineral soil and only a small number of effect sizes estimates were available in deeper mineral soil layers. It should be noted that for WTH+Removal treatments, a decline over the first 20 years in combined soil C appears to be strongly influenced by a single study (Mushinski et al. 2017) where deep (~30–60 cm) and very deep (~60–100 + cm) soil were examined. I^2 for the model was 81.3%, which indicates a high degree of residual variability was due to heterogeneity in treatment responses among different papers. This heterogeneity reflects both variance due to sampling and analytical error as well as site- and study-specific response to treatments. Differences in treatment implementation and study design among studies in the literature also contributes to high residual heterogeneity. Fixed effect parameter estimates and statistical tests for temporal models may be found in Table S2.

3.2. *Whole tree harvest (WTH), forest floor removal (+FF), and vegetation control (+VC) effects on soil C in LTSP installations*

The LTSP study provided an complementary dataset to indirectly compare with the results of the literature meta-analysis. One notable difference in study design is the lack of a no-harvest control at most LTSP sites. By using the least intensive treatment – BO harvest - as the denominator when computing effect sizes, the LTSP results are qualitatively comparable to the pairwise comparison of WTH and WTH+Removal treatments vs BO treatment in the literature meta-analysis (Fig. 1). There is greater variability in the study design,

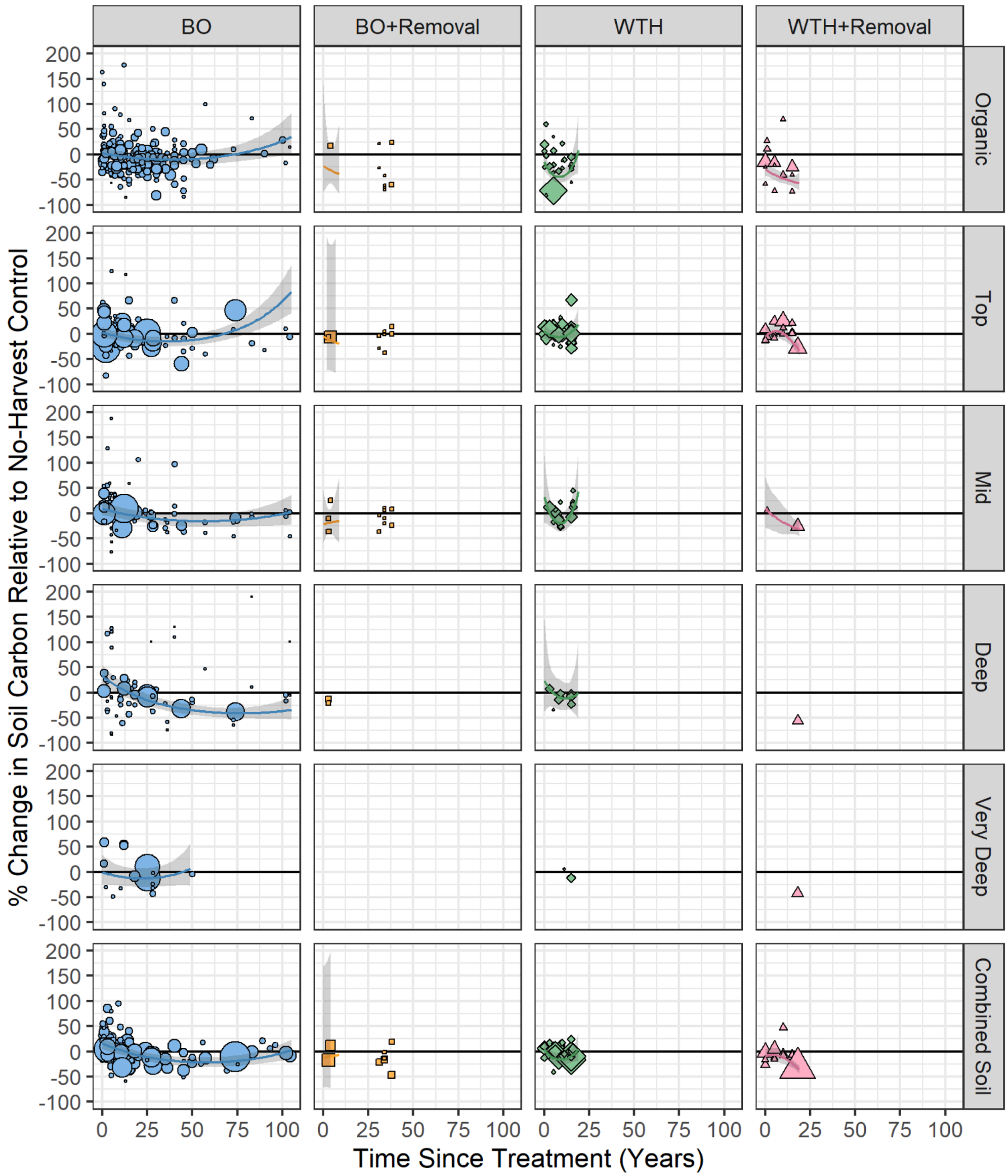

Fig. 3. The effect of intensive removal and regular harvest on soil C in O horizon and different mineral soil depths over time in the literature meta-analysis. Within the meta-analytic model, the effect over time was fit with a second-degree polynomial. The meta-regression model fit was weighted by the inverse of the variance of each effect size, which is visualized by the size of each point where larger points correspond with smaller variance. Grey areas represent 95% confidence intervals for each temporal trend line. Time since treatment was also included in the model as a random effect nested within each reference; the random effects utilized a heterogeneous autoregressive (co)variance structure to account for temporal correlation. The interclass correlation coefficient for time since treatment as a random effect was 0.28. The test of moderators was $Q_M = 599$ (df = 60), $p < 0.0001$, and the test of residual heterogeneity was $Q_E = 6527$ (df = 778), $p < 0.0001$, with $I^2 = 88.7\%$.

sampling depth, and treatment implementation/intensity in literature studies than in the LTSP meta-analysis.

Across the combined soil profile (O horizon + 0–30 cm mineral soil), there was significantly less soil C relative to bole only harvest following BO+VC (-3.6% [95% CI −6.3 to −0.8%], $p = 0.01$), WTH+FF (-8.5% [-10.7 to −6.3%], $p < 0.0001$), and WTH+FF+VC (-15.3% [-18.0 to −12.5%], $p < 0.0001$) treatments (Fig. 4). While BO+VC was significantly different from BO harvest in combined soil, there was no significant difference in any of the individual soil depths and the size of the effect was small. Soil C in WTH and WTH+VC treatments was similar to BO harvest within each soil depth group (except WTH in the O horizon) as well as combined soil C, and the treatments were significantly different from WTH+FF and WTH+FF+VC. In addition to the large difference between WTH+FF and BO treatments in the O horizon, significant soil C losses were observed in the 0–10 cm and 10–20 cm soil depths for WTH+FF relative to BO harvest. Soil C in WTF+FF+VC treatments was significantly lower than BO harvest in all measured mineral soil depths with the largest decline occurring in the 20–30 cm

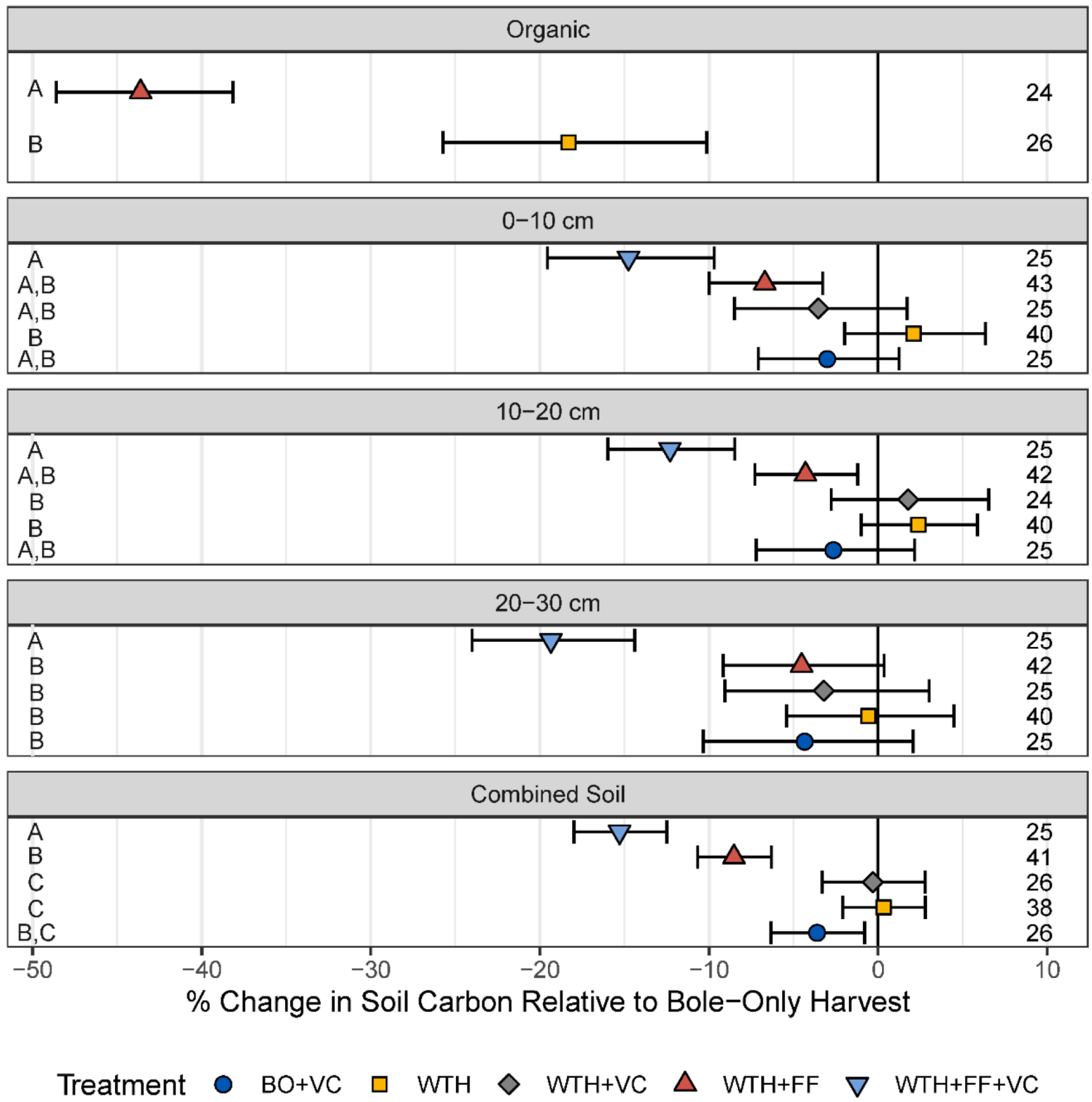

Fig. 4. The effect of whole tree harvest (WTH), forest floor removal (+FF), and herbicide application (+VC) on soil C relative to bole-only harvest (BO) at the LTSP sites. Each estimate is shown with a 95% confidence interval. Within each facet, treatments with different capital letters are statistically significantly different from each other ($p < 0.05$). The number of observations included in each estimate is listed on the right. Both time since treatment and depth were included as random effects nested within individual LTSP sites. The random effects utilized a heterogeneous autoregressive (co)variance structure to account for temporal and spatial correlation. The test of moderators was $Q_M = 420$ (df = 21), $p < 0.0001$, and test of residual heterogeneity was $Q_E = 1173$ (df = 655), $p < 0.0001$, and $I^2 = 59.1\%$.

depth interval. This was also the only treatment that was significantly different from other treatments in mineral soil. WTH+FF+VC was significantly different than WTH alone in all mineral soil depths and in the combined soil. This most intensive treatment was also significantly different than WTH+VC and BO+VC treatments in the 10–20 cm and 20–30 cm depth increments. This suggests a compounding effect of vegetation control and O horizon/harvest residue removal treatments.

I^2 for the model was 59.1%, which indicates a moderate amount of residual heterogeneity related to sampling and measurement error, site-specific response, and other environmental factors. Adding other environmental covariates to the model such as soil order and forest type did not improve model fit and were not statistically significant. Complete meta-analytic model results for depth comparisons can be found in Table S3.

There were statistically significant trends for the effect on soil C relative to BO harvest in almost all LTSP treatments. In the O horizon, the initial effect of WTH+FF is nearly −50%, while it is closer to −10% when the forest floor is left in place (WTH; Fig. 5, Table S4). However, the C in the O horizon trended upwards over 20 years after WTH+FF treatment, while such trended downwards after WTH (Fig. 5); after 20 years, O horizon C for both WTH+FF and WTH was approximately −25% compared to BO harvest. Over two decades, all of the LTSP treatment effects trend downward in all three mineral soil sampling depths and in the combined soil (O horizon + 0–30 cm). The BO+VC treatment trends downward in the combined soil, which corresponds with declining trends in 10–20 cm and 20–30 cm depth intervals. The WTH treatment has higher soil C than BO harvest control over the first 10–15 years after treatment but trends towards no change at 20 years after harvest in all mineral soil depths and the combined soil. The WTH+VC treatment had small temporal trends, declining slightly from 5 to 20 years after treatment in all mineral soil increments and the combined soil. The WTH+FF treatment trended downward most steeply in the surface 0–10 cm with small or negligible trends in 10–20 cm and 20–30 cm depths. Combined soil for WTH+FF trended downward over 20 years. The steepest declines over time were visible in the WTH+FF+VC treatment. No effect size estimates at 18–20 years after WTH+FF+VC treatment were larger than bole-only harvest. I^2 for the model including time as a fixed effect (not just as a random effect nested

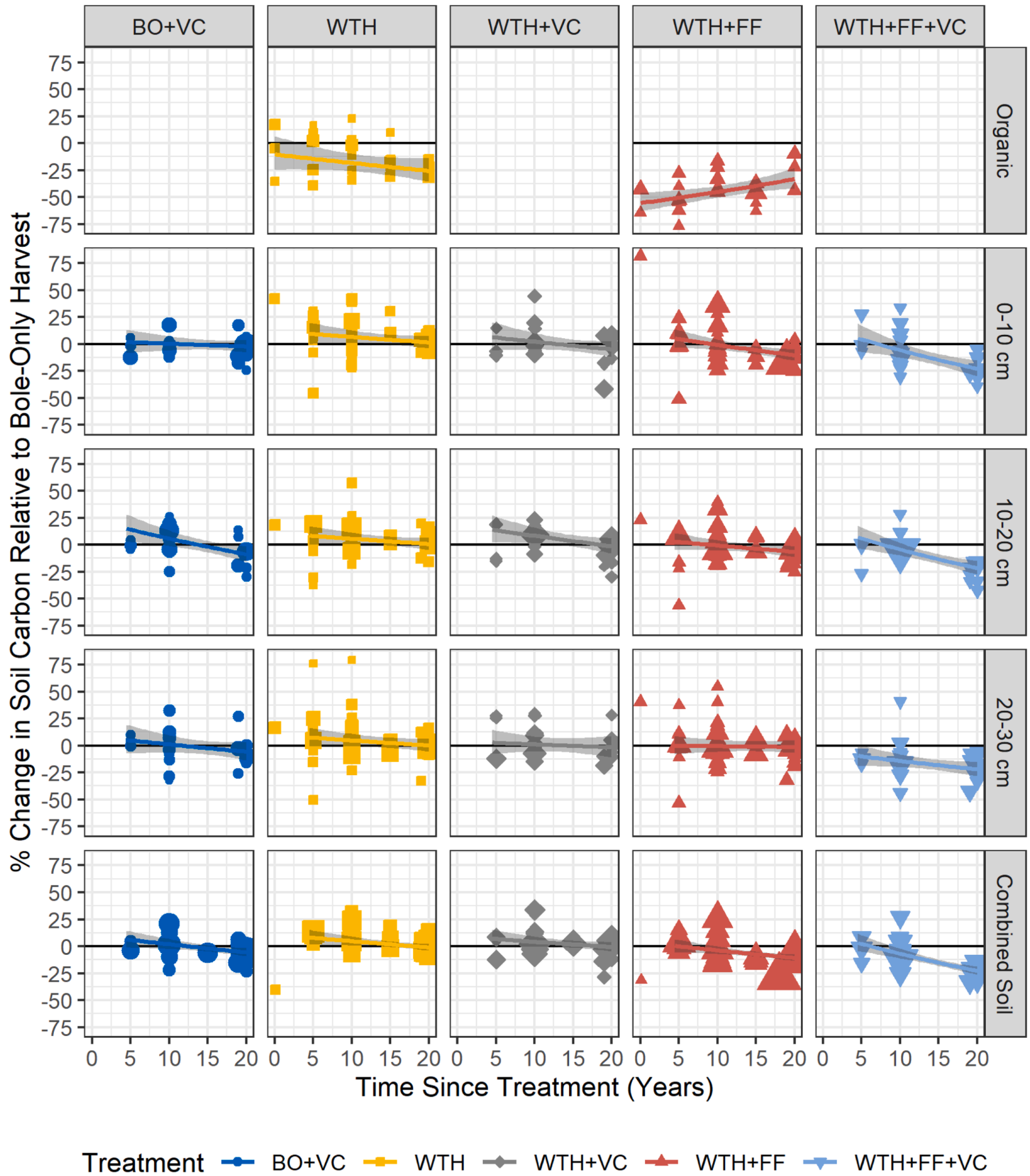

Fig. 5. The effect of whole tree harvest (WTH), forest floor removal (+FF), and vegetation control (+VC) on soil C over time since treatment relative to bole-only harvest at the LTSP sites. The meta-regression model fit was weighted by the inverse of the variance of each effect size, which is visualized by the size of each point where larger points correspond with smaller variance. Grey areas represent 95% confidence intervals for each temporal trend line. Time since treatment was also included in the model as a random effect nested within each LTSP site. The random effects utilized a heterogeneous autoregressive (co)variance structure to account for temporal correlation. The interclass correlation coefficient for time since treatment as a random effect was −0.15. The test of moderators was $Q_M = 466$ (df = 43), $p < 0.0001$, and test of residual heterogeneity was $Q_E = 954$ (df = 633), $p < 0.0001$, and $I^2 = 42.7\%$.

within each experimental forest) was 42.7%, which indicates that most of the remaining variation was due to chance rather than site-specific responses (heterogeneity). The lower I^2 compared to the model excluding time as a fixed effect (59.1%, above) illustrates that temporal trends were a substantial proportion of the remaining variation after accounting for treatment effects. Coefficients for the trend lines in each LTSP treatment can be found in Table S4.

3.3. Effect of harvesting and biomass removal treatments on soil N in the literature meta-analysis

Compared to soil C in the literature meta-analysis, treatment effects on soil N were more muted and the number of studies reporting soil N stocks is smaller . Across the combined soil (O horizon plus 30 + cm of mineral soil), only the WTH+Removal treatment was significantly different from no harvest (−27.3% (95% CI −35.0 to −18.8%; Fig. 6). In the O horizon, there were significant effects for both +Removal treatments, which is axiomatic since the treatments fully or partially removed the O horizon. Unlike soil C, there was no significant effect of

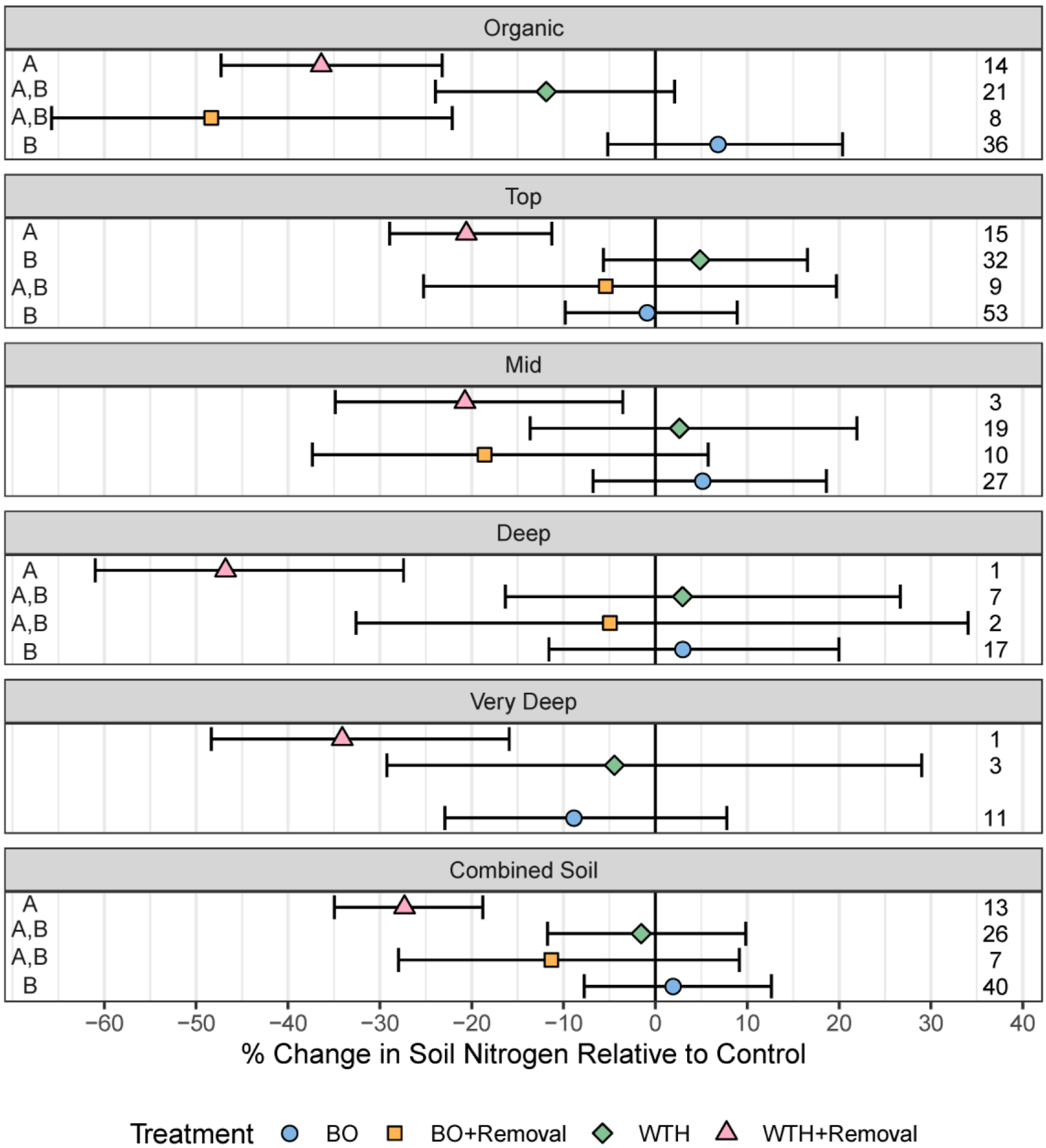

Fig. 6. The effect of intensive removal (whole tree harvest with or without forest floor removal) and regular harvest (all other types, including bole-only, clear-cut, thinning, etc.) on soil N at different soil depths in the literature meta-analysis. Each estimate is shown with a 95% confidence interval. Within each facet, treatments with different capital letters indicate significant difference from each other ($p < 0.05$); facets without letters were not significantly different.. The number of observations from literature included in each estimate is listed on the right. Depth, time since harvest and reference were included as random effects in the model with depth and time nested within the levels of reference. This accounted for correlation in the effects observed at different depths and times in the same study, as well as for correlation in effects of different treatments within individual studies that utilize a single control treatment. The test of moderators was $Q_M = 268$ (df = 22), $p < 0.0001$, and test of residual heterogeneity was $Q_E = 6439$ (df = 347), $p < 0.0001$, with $I^2 = 93.7\%$.

WTH on O horizon N. In the mineral soil, only WTH+Removal was significantly different from no-harvest control. The WTH+Removal treatment was also statistically significantly different from BO harvest in topsoil (~0–15 cm), deep soil (~30–60 cm), and combined soil. However, in deep soil only one study estimated the effect of WTH+Removal in the deep or very deep soil (~60–100 + cm) intervals. I^2 for the meta-analytic model was 93.7%, which indicates that a high degree of remaining variance is associated with heterogeneity in study- and site-specific response to treatment.

There were no statistically significant temporal trends for soil N in the literature meta-analysis, with the lone exception of an increasing trend in very deep soil (60–100 + cm) after BO harvest (Table S.6 and Figure S.1). Across combined soil, no temporal trends in soil N were evident. I^2 for the model was 89.6%, which is only slightly lower than the model excluding time as a fixed effect and suggests that heterogeneity in soil N responses among different studies is not related to temporal differences.

3.4. Whole tree harvest (WTH), forest floor removal (+FF), and vegetation control (+VC) effects on soil N at the LTSP sites

Across the combined soil (O horizon + 0–30 cm mineral soil), there were significant reductions in soil N relative to bole only harvest following BO+VC (-4.4% [95% CI −7.6 to −1.0%], $p = 0.01$), WTH+FF (-3.5% [-6.1 to −0.7%], $p = 0.01$), and WTH+FF+VC (-13.3% [-16.2 to −10.2%], $p < 0.0001$) treatments (Fig. 7). The WTH+FF+VC treatment contained significantly less soil N than all other treatments in the combined soil. There were substantial differences in treatment effects at

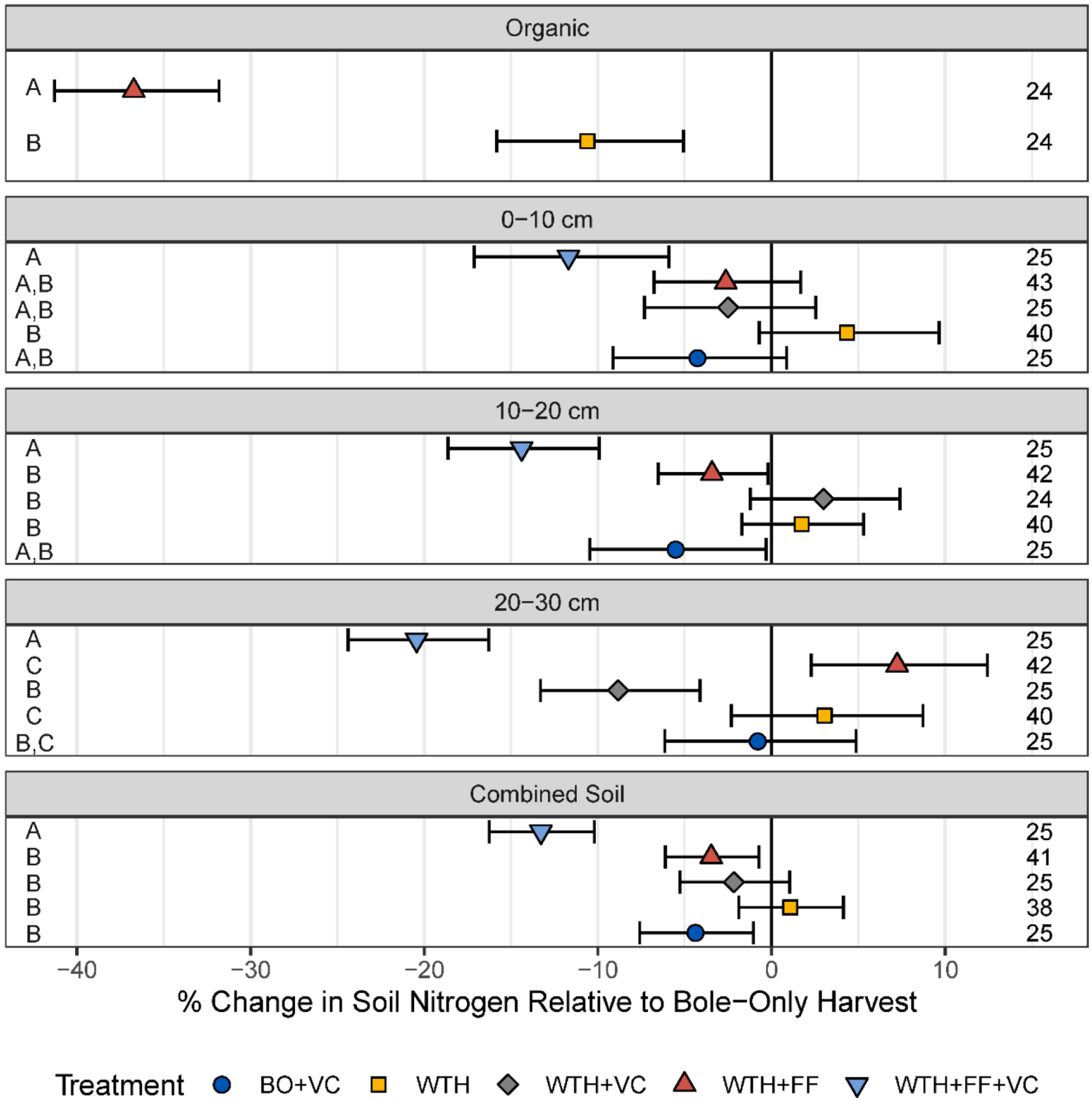

Fig. 7. The effect of whole tree harvest (WTH), forest floor removal (+FF), and vegetation control (+VC) on soil N relative to bole-only harvest at the LTSP sits. Each estimate is shown with a 95% confidence interval. Within each facet, treatments with different capital letters indicate significant difference from each other ($p < 0.05$). The number of observations included in each estimate is listed on the right. Both time since treatment and depth were included as random effects nested within individual LTSP sites. The random effects utilized a heterogeneous autoregressive (co)variance structure to account for temporal correlation. The test of moderators was $Q_M = 497$ (df = 21), $p < 0.0001$, and test of residual heterogeneity was $Q_E = 1850$ (df = 651), $p < 0.0001$, with $I^2 = 49.9\%$.

different soil depths. The effects of WTH and WTH+FF were significantly different from BO harvest in O horizons (Fig. 7, Table S7). Additional removal of the forest floor resulted in 29% more N loss compared to whole tree harvest alone. In mineral soil, the most notable effect was the significant loss of N in all three depth intervals after the most severe treatment, WTH+FF+VC. Soil N in this treatment was also significantly lower than WTH in all mineral soil intervals. No other treatments were significantly different from BO harvest in 0–10 cm mineral soil. In the 10–20 cm interval, both BO+VC and WTH+FF treatments contained significantly less soil N than BO, although both effects were small (-5.5% and −3.4%, respectively). In the 20–30 cm interval, WTH+VC contained significantly less soil N than BO harvest and was also significantly less than WTH and WTH+FF treatments. The WTH+FF treatment in the 20–30 cm interval was the only treatment with significantly more soil N than BO harvest, suggesting that N leaching out of O horizon and surface mineral soil is being retained in the subsoil.

There were significant trends in soil N effects over time for a limited number of treatments & depths in the LTSP meta-analysis (Table S8). Soil N trended lower over time since treatment in the 10–20 cm depth increment and combined soil (O horizon + 0–30 cm mineral soil) for all treatments (Figure S2). Significant downward trends were evident in all depth increments for the WTH treatment, which declined from slightly greater soil N than BO harvest in the first 5–10 years to no difference at 20 years after treatment. In general, temporal trends were less steep in soil N than soil C at equivalent depths. The I^2 for the model including time as a fixed effect was 46.9%, which was a very small decline from the model excluding time (49.9%), which suggests that site-specific response to treatment was a much larger factor for soil N than temporal trends within treatments.

4. Discussion

4.1. What effects do different methods of biomass removal in addition to conventional harvest have on soil C stocks?

Both the literature and LTSP meta-analyses show that whole tree harvest (WTH) with additional harvest residue (+Removal) or forest floor removal (+FF) results in significant additional soil C loss compared to bole-only (BO) harvest (-24.8 and –8.5%) in the combined soil for the literature and LTSP meta-analyses, respectively. There are several possible explanations for the differences in these estimates. First, there is a much greater variety in removal intensity, experimental designs, and sampling depth in the literature meta-analysis than in the LTSP sites. Second, pairwise comparisons between WTH+Removal and BO harvest in the literature meta-analysis are highly unequal in sample size (13 vs 130 effect sizes for combined soil) and therefore also have unequal coverage of soil types and environmental conditions. Third, there are considerable differences in the maximum sampling depth included in the combined soil between treatments (Fig. 2), where BO treatments have many more observations in deep and very deep soil (greater than30 cm depth). The disparity in sampling depths and dearth of studies examining deeper soil C in WTH and other intensive biomass removal treatments are clear research gaps that have been highlighted in several recent reviews (Harrison et al., 2011; James et al., 2014; Gross and Harrison, 2019; Mayer et al., 2020). The small sample size for the WTH+Removal treatment can lead to skewed results that overstate the effect of the treatment across forest stands, particularly given the high degree of residual heterogeneity in the response to treatment (I^2 = 80.7%). Heterogeneity in treatment responses at LTSP sites was a much smaller proportion of residual variability (I^2 = 59.1%), which implies that more consistent treatment effects were captured by this model. Finally, the BO treatment spans a much greater period after treatment than WTH+Removal (approximately 100 years vs. 20 years), which means that WTH+Removal treatments are only capturing the period of initial decline while BO treatments also capture the recovery period (Fig. 3).

Within individual depth increments, the effect of WTH+Removal (in the literature meta-analysis) and WTH+FF (in the LTSP meta-analysis) on O horizon C were almost identical (-40.3% and −43.6%, respectively). This effect is not surprising due to the direct manipulation of the O horizon in the implementation of these treatments. The LTSP showed a higher loss (-43.6%) because the forest floor was uniformly and delicately removed when the treatments were applied (Busse et al., 2021). In the mineral soil, the literature *meta*-analysis only differentiated the WTH+Removal and BO treatments in deep soil (~30–60 cm) where only a single study was available for WTH+Removal (Mushinski et al. 2017). While this study showed a considerable treatment effect, it is insufficient to make any generalizable statements about effect outside of the environmental context in which the study was conducted. In contrast, the LTSP meta-analysis found significantly less soil C in the 0–10 cm and 10–20 cm increments following WTH+FF (-6.7% and −4.3%, respectively). Overall, much greater confidence (narrower 95% confidence intervals in Fig. 4) in the size and direction of LTSP results may be recognized due to the larger sample size, common study design, standard sampling depth & frequency, and variety of forest & soil types represented by the LTSP sites.

The WTH+Removal and WTH+FF treatments are frequently intended to represent an intensive endmember along the spectrum of real-world soil disturbance and biomass removal impacts. In contrast, the WTH treatment on its own is a common forestry practice and much more representative of realistic bioenergy harvests. In both the literature and LTSP meta-analyses, WTH does not result in additional soil C losses compared to BO harvest (Fig. 1 pairwise comparisons, Fig. 4). WTH treatments contained significantly less soil C than no-harvest controls in the literature (-15.4%), although no significant loss was evident in any individual depth increment except for the O horizon. The significant soil C decline for the BO+Removal treatment in the literature meta-analysis (-19.2% in combined soil relative to no harvest), while subject to the same caveats as WTH+Removal, suggests that additional residue and O horizon removal has a more substantial effect on soil C than WTH alone. There was a large degree of site-specific response to WTH in the literature meta-analysis with most studies measuring only O horizon and topsoil (~0–15 cm). In actively managed forest stands, the results suggest that WTH could be used to extract additional biomass for bioenergy production without widespread reductions in soil C.

The results discussed above are largely consistent with prior meta-analyses and reviews. Thiffault et al. (2011) noted no clear or consistent effect of WTH relative to stem-only (BO) harvest with only four of 14 studies reporting significant differences between WTH and BO treatments. Likewise, Achat et al. (2015) observed no significant difference between WTH and BO treatments within individual soil intervals and a marginally significant decline ($0.05 < p < 0.1$) when combining mineral soil layers. James and Harrison (2016) found no overall difference between WTH and BO treatments, although they observed a significant increase in mineral soil C in WTH relative to BO harvest. James and Harrison (2016) also found no significant effect of residue removal treatments in addition to harvest, whereas our analysis shows a consistent and clear effect of WTH+Removal (in the literature meta-analysis) and WTH+FF (in the LTSP meta-analysis) on soil C. There are several methodological differences between our analysis and both Achat et al. (2015) and James and Harrison (2016). To increase sample size, both prior meta-analyses combined all WTH variations as a single treatment (e.g. WTH, WTH+Removal, WTH+Till were combined). Consequently, our results are a step forward by more finely differentiating between treatments as well as simultaneously controlling for temporal and spatial correlation within each study, which is not possible with the bootstrapping methods used by Achat et al. (2015) and James and Harrison (2016). The LTSP meta-analysis results also confirm the lesser effect of WTH compared to WTH+FF (or WTH+FF+VC) treatments utilizing more consistent study design and more robust sample size.

4.2. What effects do different methods of biomass removal in addition to conventional harvest have on soil N stocks?

As with soil C, soil N declined following WTH+Removal treatments in the combined soil of the literature meta-analysis but there was no significant decline for WTH or BO+Removal. No other treatment significantly differed from no-harvest controls. In the mineral soil, modeled treatment effects for soil N were mostly smaller than for C in the same depths and treatments for both datasets with the exception of WTH+FF+VC treatment in the LTSP study, where the effect on soil N and C was similar (Figs. 4 and 7). The significant loss of soil N in the O horizon and 10–20 cm soil intervals following WTH+FF treatments coupled with the significant increase in the 20–30 cm interval suggests that some mineralization and leaching of N from surface soil may be occurring at some sites (in addition to organic matter loss which contains both C and N). As with soil C, there was no effect of WTH treatment on soil N in the combined soil or in mineral soil layers in either the literature or LTSP meta analyses. Despite returning less organic material to the site compared to standard BO harvest, WTH does not appear to substantially effect N. Overall, results suggest that WTH may provide a means to extract additional residues for bioenergy production without major losses of soil C or N.

4.3. Feedback between changes in soil C and N following residue removal & vegetation control

Nitrogen is the most common limiting nutrient for plant productivity (LeBauer and Treseder, 2008), and the removal of nitrogen contained within forest residues by bioenergy harvest may induce or deepen N limitation. By far the most impactful treatment on both soil C and N in the LTSP meta-analysis was WTH+FF+VC. Both C and N declined in all mineral soil depths by more than 10% in response to this treatment and continued to trend downward over 20 years. This suggests a multiplicative effect of vegetation control and forest floor removal at LTSP sites. Neither BO+VC nor WTH+VC treatments were significantly different from BO harvest for soil C in any mineral soil interval, and the treatment effect of WTH+FF+VC on soil C was more than double the WTH+FF treatment effect in all mineral soil layers (Fig. 4). For soil N, BO+VC was significantly lower than BO harvest in combined soil as well as in the 10–20 cm interval (Fig. 7). These losses are directionally consistent with mineralization and leaching loss of NO_3-N and dissolved organic N observed at the Matlock, Molalla, and Fall River LTSP sites following annual vegetation control treatments (Devine et al., 2011; Slesak et al., 2009).

Increased solar heating after harvesting can stimulate microbial decomposition, particularly when mineral soil is exposed, thereby mineralizing organic-bound N into plant available, mobile forms such as nitrate. Early seral vegetation maintains that portion of the total N stock on site by uptake and growth. Powers et al. (2013) showed that competing vegetation represents the majority of aboveground biomass 10 years after tree planting in harvested stands. After crown closure, the competing vegetation begin to decline and return their biomass C and N to the soil, thereby providing a long-term reservoir of organic matter and nutrients for tree growth (Bormann et al., 2015; Jurgensen et al., 1997). By coupling forest floor removal with herbicide and almost complete exclusion of early seral vegetation, mineralized N is lost to the ecosystem through leaching, denitrification and/or volatilization (Strahm et al., 2005; Strahm and Harrison, 2007). Herbicide may also exclude nitrogen-fixing species that would be able to offset some loss of mineralized nitrogen, and which are particularly important for sustained productivity of the subsequent forest stand on nitrogen limited sites (Cole, 1995; Cromack et al., 1999; Van Miegroet and Cole, 1985). Indeed, VC may be as important as intensive residue removal in post-harvest N loss given the significantly lower N observed in the BO+VC treatment.

4.4. Implication of forest soil C changes on biofuel life cycle assessment (LCA)

Currently, biofuel LCAs adopted by regulatory agencies do not account for changes in soil C stocks associated with various land management practices in feedstock production, partly because such occur too slowly to be quantified or verified within a short time. Instead, most LCAs assume that soil C stocks remain in steady state during the years of feedstock production, even though this simplification is likely untrue in situations with extreme biomass removal and intensive management (Buchholz et al. 2014).

This meta-analysis study confirmed that intensive removal of forest residues could cause persistent loss of soil C and N. Such impacts vary by harvest methods and forest management practices. This study suggests that modest residue removals (<80%) of biomass using whole tree harvest with forest floor retention could provide a sustainable source of biomass for bioenergy production without additional soil C losses compared to bole-only harvesting practices. LCA of sourcing forest residues for bioenergy production should carefully evaluate impacts of harvest and forest management practices that may cause change in soil C.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. . Publications providing response ratios (k) for this analysis

Reference	k for soil C	k for soil N	Experimental period (year)	Max Depth (cm)	Location
(Alban and Perala, 1992)	7		74	50	MN, USA
(Bauhus et al., 2004)	12	12	9	40	Germany
(Bisbing et al., 2010)	6	3	45	100	MT, USA
(Black and Harden, 1995)	13	8	79	20	CA, USA
(Boerner et al., 2006)	4		4	10	SC, USA
(Borchers and Perry, 1992)	4	4	16	15	OR, USA
(Bravo-Oviedo et al., 2015)	8	8	15	30	Spain
(Cade-Menun et al., 2000)	12	12	10	26	BC, Canada
(Carter et al., 2002)	8	8	2	15	LA, TX, USA
(Chatterjee et al., 2009)	15	8	45	54	WY, USA
(Chen et al., 2016)	24		88	100	China
(Chiti et al., 2016)	24		50	100	Ghana, Cameroon, Gabon
(Christophel et al., 2013)	6	6	17	30	Germany
(Christophel et al., 2015)	18	18	34	30	Germany
(Cromack et al., 1999)	1	1	10	100	OR, USA
(Dai et al., 2001)	3	3	14	8	NH, USA
(DeByle, 1979)	10		5	5	WY, USA
(DeLuca and Zouhar, 2000)	6	6	11	8	MT, USA
(Diochon et al., 2009)	28		80	50	NS, Canada
(Edmonds and McColl G, 1989)	4	4	5	20	Australia

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Reference	k for soil C	k for soil N	Experimental period (year)	Max Depth (cm)	Location
(Edwards and Ross-Todd, 1983)	6		1	45	TN, USA
(Elliott and Knoepp, 2005)	12	12	3	15	NC, USA
(Ellis et al., 1982)	5	5	1	10	Tasmania
(Ellis and Graley, 1983)	9	9	2	10	Tasmania
(Esquilin et al., 2008)	2	2	14	10	CO, USA
(Falsone et al., 2012)	4	4	5	30	Russia
(Fraterrigo et al., 2005)	1	1	30	15	NC, USA
(Frazer et al., 1990)	4	4	18	14	CA, USA
(Gartzia-Bengoetxea et al., 2009)	2	2	16	5	Spain
(Gillon et al., 1999)	2	2	1	0	France
(Goh and Phillips, 1991)	4	4	2	60	New Zealand
(Goodale and Aber, 2001)	2	2	85	10	NH, USA
(Gough et al., 2007)	15		68	80	MI, USA
(Grady and Hart, 2006)	2	2	12	15	AZ, USA
(Grand and Lavkulich, 2012)	6	6		80	BC, Canada
(Gresham, 2002)	6		10	30	SC, USA
(Griffiths and Swanson, 2001)	3		40	10	OR, USA
(Gundale et al., 2005)	8	8	3	10	MT, USA
(Das Gupta and DeLuca, 2012)	10	10	8	50	Wales
(Hart et al., 2006)	2	2	1	15	AZ, USA
(Hendrickson and Chatarpaul, 2016)	8	8	3	20	ON, Canada
(Herman et al., 2003)	2	2	9	9	CA, USA
(Hölscher et al., 2001)	2	2	22	20	Germany
(Hwang and Son, 2006)	2	2	2	30	Korea
(Jang et al., 2015)	12	12	38	30	MT, USA
(Johnson, 1991)	3		3	20	NH, USA
(Johnson and Todd, 1998)	6	6	15	45	TN, USA
(Johnson, 1995)	12		8		NH, USA
(Johnson et al., 1997)	14		8	53	NH, USA
(Johnson et al., 2014)	4	4	1	60	CA, USA
(Jones et al., 2011)	12	12	15	30	New Zealand
(Kaye and Hart, 1998)	4	4	1	15	AZ, USA
(Keenan et al., 1994)	1		4	20	BC, Canada
(Kelliher et al., 2004)	4	4	22	50	OR, USA
(Kishchuk et al., 2015)	4	4	11	7	AB, Canada
(Klockow et al., 2013)	9	9	1	20	MN, USA
(Klopatek, 2002)	8	8	40	20	WA, USA
(Knoepp and Swank, 1997)	17	17	17	10	NC, USA
(Korb et al., 2004)	1	1	1	10	AZ, USA
(Kraemer and Hermann, 1979)	2	2	26	10	WA, USA
(Kurth et al., 2014)	72	72	15	30	MI, MN, USA
(Laiho et al., 2003)	5		5	22	NC, LA, USA
(Latty et al., 2004)	2	2	90	15	NY, USA
(Law et al., 2001)	12	3	106	100	OR, USA
(LeDuc and Rothstein, 2007)	1	1	5	10	MI, USA
(Maassen and Wirth, 2004)	2			5	Germany
(Mattson and Smith, 1993)	30		23	10	WV, USA
(Mattson and Swank, 1989)	8		7	60	NC, USA
(May and Attiwill, 2003)	2	2	5	10	Australia
(McKee et al., 2013)	8		24	60	ME, USA
(McLaughlin et al., 1996)	10		5	50	AL, USA
(McLaughlin and Phillips, 2006)	2	2	17	50	MI, USA
(Merino and Edeso, 1999)	6	6	4	15	Spain
(Moreno-Fernández et al., 2015)	54		104	50	Spain
(Mu et al., 2013)	18		5	50	China
(Murphy et al., 2006)	28	28	1	60	CA, USA
(Neher et al., 2003)	3		2	20	NC, USA
(Norris et al., 2009)	15		31	100	SK, Canada
(O'Brien et al., 2003)	6		26	50	Australia
(Powers et al., 2011)	20		29	30	MN, WI, USA
(Prest et al., 2014)	5	5	35	50	NS, Canada
(Prietzel et al., 2004)	4	4	2	0	WA, USA
(Puhlick et al., 2016)	10	8		100	ME, USA
(Rab, 1996)	8		1	10	Australia
(Riley and Jones, 2003)	3		1	10	SC, USA
(Roaldson et al., 2014)	4	4	9	20	CA, USA
(Rothstein and Spaulding, 2010)	6	6	15	30	MI, USA
(Sanchez et al., 2006)	6		3	105	SC, USA
(Sanscrainte et al., 2003)	4	4		70	WA, USA
(Saynes et al., 2012)	8		20	5	Mexico
(Selig et al., 2008)	3		14	30	VA, USA
(Shelburne et al., 2004)	4	4	1	10	SC, USA
(Sheng et al., 2015)	5		8	100	China
(Skovsgaard et al., 2006)	12		0	30	Denmark
(Slesak et al., 2011)	12	12	5	60	OR, WA, USA
(Small and McCarthy, 2005)	4	4	7	10	OH, USA

(continued on next page)

(*continued*)

Reference	k for soil C	k for soil N	Experimental period (year)	Max Depth (cm)	Location
(Stone et al., 1999)	1	1	1	15	AZ, USA
(Stone and Elioff, 1998)	4	4	5	30	MN, USA
(Strong, 1997)	8		40	40	MN, USA
(Strukelj et al., 2015)	12		9	10	QC, Canada
(Tang et al., 2009)	12		74	60	MI, WI, USA
(Trettin et al., 2011)	6	6	11	150	MI, USA
(Ussiri and Johnson, 2007)	15	15	14	60	NH, USA
(Vario et al., 2014)	6		120	60	NH, USA
(Vesterdal et al., 1995)	18	18		0	Denmark
(Waldrop et al., 2003)	3	3	1	0	CA, USA
(Wu et al., 2010)	1	1	10	20	China
(Xiang et al., 2009)	8	8	1	30	China
(Yanai et al., 2000)	35		85	0	NH, USA
(Zabowski et al., 2008)	2	2	25	20	OR, WA, USA
(Zhong and Makeschin, 2003)	4	4	16	10	Germany
(Zummo and Friedland, 2011)	15	15	3	60	NH, USA
(Bai et al., 2016)	10	10		5	Australia
(Bastida et al., 2019)	4	4	9	15	Spain
(Chen et al., 2016)	16	4	7	25	China
(Cheng et al., 2017)	8	8	25	60	
(Dang et al., 2018)	3	3	11	10	China
(Dore et al., 2016)	6		2	15	NV, USA
(Durigan et al., 2017)	2	2		30	Brazil
(Fan et al., 2016)	4		17	50	China
(Gabriel et al., 2018)	4		44	50	NS, Canada
(Ganzlin et al., 2016)	4	4	11	10	MT, USA
(Gross et al., 2018)	12	12	28	150	OR, USA
(Hamburg et al., 2019)	12	12	15	53	NH, USA
(He et al., 2018)	10	10	15	70	China
(Kim et al., 2018)	74	2	7	29	Korea
(Krueger et al., 2016)	6		20	100	Germany
(Lacroix et al., 2016)	8		55	45	NH, USA
(Ma et al., 2018)	18		4	50	China
(Marinsek et al., 2016)	8	8		80	Slovenia
(Mazza et al., 2019)	12	12	1	30	Italy, Greece
(Mushinski et al., 2017)	8	8	18	100	TX, USA
(Ntoko et al., 2018)	6	6		10	AL, USA
(Overby and Gottfried, 2017)	12	12	3	15	CO, USA
(Panichini et al., 2017)	12	12	50	125	Chile
(Ruiz-Peinado et al., 2014)	10		10	30	Burgos, Spain
(Settineri et al., 2018)	6		4	30	Italy
(Simola, 2018)	93		100	2	Finland
(Slesak et al., 2016)	8	0	10	0	WA, OR, USA
(Veloso et al., 2018)	27		17	100	Brazil
(Wen et al., 2015)	2	2	1	10	China
(Zhang et al., 2016)	24	24	16	30	CA, USA

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