Initial Response of Soil Carbon and Nitrogen to Harvest Intensity and Competing Vegetation Control in Douglas-Fir (*Pseudotsuga menziesii*) Plantations of the Pacific Northwest

Robert A. Slesak, Stephen H. Schoenholtz, Timothy B. Harrington, and Nathan A. Meehan

Abstract: We assessed the effect of harvest type (bole-only or whole-tree) and vegetation control treatments (initial or annual application of herbicide) on soil C and N at two contrasting sites in the Pacific Northwest. Pretreatment (2003) and posttreatment (2005) soil samples were collected by depth to 60 cm, and a stratified sampling approach based on four surface conditions was used for posttreatment sampling in surface soils. Surface condition had a significant effect on soil C and N concentrations, generally decreasing with decreasing amounts of logging debris and increasing soil disturbance. There was no difference between harvest treatments in the change in soil C and N content despite differences in surface condition coverage between harvest types, indicating estimates of C and N change determined from the stratification approach were imprecise. Soil C and N content tended to increase regardless of treatment, but increases were significant only in the bole-only harvest at one site and in the whole-tree harvest at the other site. Initial vegetation control caused significantly greater positive change in soil C and N than the annual vegetation control treatment, with effects limited to surface soil at one site and all sample depths at the other site. Much of these increases occurred in deeper (>20 cm) parts of the soil profile, indicating that deep soil sampling is necessary for assessment of harvest-related change in soil C and N. FOR. SCI. 57(1):26–35.

Keywords: biomass, stratified sampling, soil depth, intensive forest management

INTENSIVELY MANAGED FOREST PLANTATIONS are becoming increasingly common as the result of greater demand for wood products in combination with a shrinking land base available for production (Food and Agriculture Organization 2006). Intensive forest management is characterized by shorter rotation lengths and greater biomass removal at harvest, leading to a greater net removal of site C and N at shorter time periods. Some researchers have voiced concern for potential reductions in soil productivity if greater removals of site C and N cause declines in soil pools of these elements (Powers et al. 1990, Jurgensen et al. 1997, Johnson et al. 2002).

Logging debris retention is one management practice likely to maintain or enhance C and N pools (Figure 1), but experimental results are somewhat conflicting. A meta-analysis performed by Johnson and Curtis (2001) indicated an increase in soil C and N when logging debris was retained, with the effect largely restricted to coniferous forests. In contrast, the 10-year summary results from 27 installations of the Long Term Soil Productivity (LTSP) network presented by Powers et al. (2005) suggest no effect of logging debris on soil C when the forest floor is retained. Site-specific factors may have contributed to the contrasting results because both of these studies acknowledged exceptions to their respective conclusions, and each covered a wide range of climate conditions.

Given the complex interactions among climate, vegetation, and soil characteristics that control soil C stocks, it is probably most useful to develop local or regional response functions as suggested by Nambiar (1996). However, apparent response to logging debris retention at the local level may be variable, given the large spatial heterogeneity of soil chemical properties (Homann et al. 2001) and the discontinuous nature of logging debris coverage after harvesting (Eisenbies et al. 2005). These sources of variability may inhibit identification of significant changes in soil C and N and obscure any pattern of response at sites with similar characteristics. Transformations of C and N are biologically mediated, and it is likely that microsite (<1 m^2) conditions will have strong control on the C and N pools after harvesting. Stratified sampling by surface condition (e.g., heavy versus light debris) may reduce sampling variability (Shaw et al. 2008), possibly improving our ability to detect change in soil C and N after harvesting if such an effect occurs.

Vegetation control with herbicide application is a common silvicultural practice after harvesting to increase crop tree survival and growth in the initial years after planting (Harrington et al. 1995, Rosner and Rose 2006), but the practice may also cause concurrent reductions in soil C and N pools (Shan et al. 2001). Vegetation is an important factor controlling N retention (Marks and Bormann 1972, Vitousek et al. 1979), and several studies have documented elevated nitrate leaching after vegetation control (Vitousek and Matson 1985, Smethurst and Nambiar 1995, Briggs et

Robert A. Slesak, Minnesota Forest Resources Council, 2003 Upper Buford Circle, St. Paul, MN 55108—Phone: (651) 603-6756; raslesak@umn.edu. Stephen H. Schoenholtz, Virginia Water Resources Research Center, Virginia Tech. Timothy B. Harrington, Pacific Northwest Research Station, US Forest Service. Nathan A. Meehan, Western Timberlands Division, Weyerhaeuser Company.

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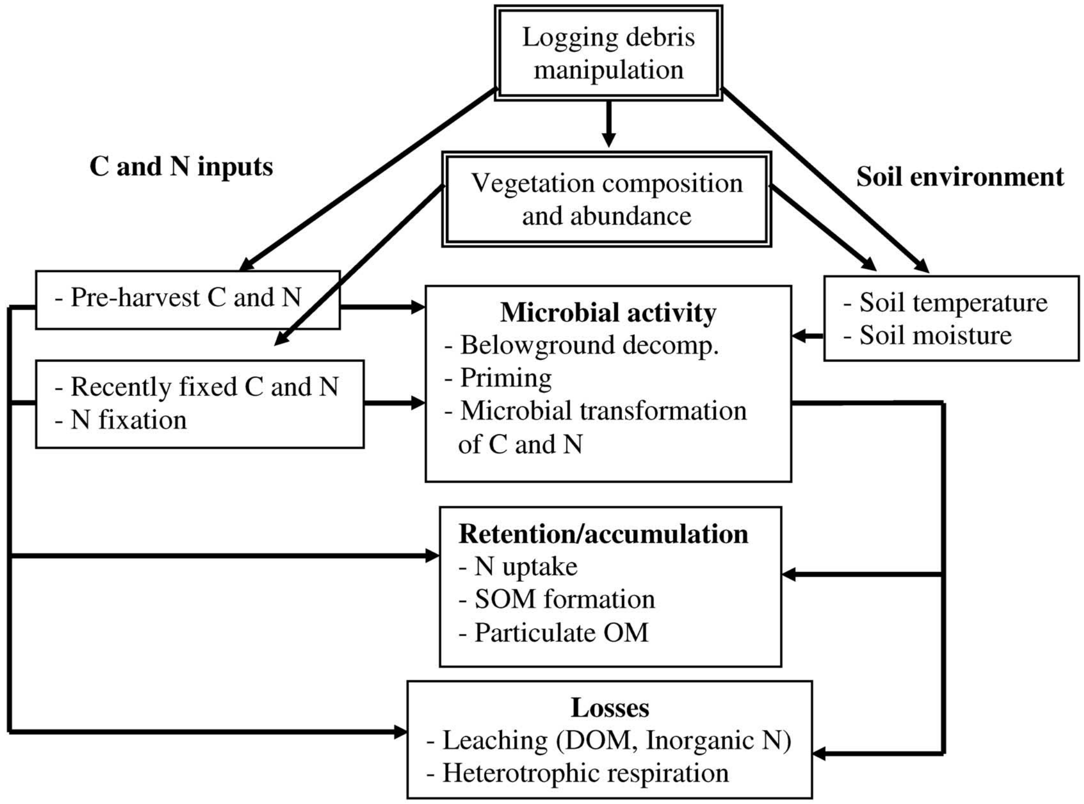

Figure 1. Flow diagram showing the potential processes contributing to soil C and N change in response to logging debris manipulation and competing vegetation control. Note that vegetation can be influenced directly via herbicide application or indirectly in response to various levels of logging debris retention. SOM, soil organic matter; DOM, dissolved organic matter.

al. 2000), which could reduce soil N pools. Soil C may also be reduced if heterotrophic organisms consume more pre-existing soil organic matter when availability of recently fixed organic matter (OM) is low after vegetation control. Several studies from the southeastern United States have shown reductions in soil C after annual vegetation control (Echeverria et al. 2004, Miller et al. 2006), but at least one study in northern California found no effect (McFarlane et al. 2009). It is unclear what factors control the soil response to vegetation control, but it is likely that regional differences in soil and climate will influence the response.

Most studies that measured change in soil C and N after harvesting focused on surface soils (A horizon or top 30 cm), assuming either directly or implicitly that change at greater depth is small or inconsequential. Powers et al. (2005) highlighted the contribution of root decomposition after harvesting to increases in soil C, and there is no reason to suspect that such a process would be limited to surface soil. Fontaine et al. (2007) demonstrated that the stability of deep soil carbon is dependent on inputs of fresh C at depth, which could be altered by management practices such as vegetation control after harvesting. These findings suggest that that there is potential for logging debris and vegetation control to alter pools of C and N at deep portions of the soil profile, but few studies have assessed such a possibility.

We assessed total soil C and N response to different levels of logging debris with either initial or annual competing vegetation control using herbicides for a period of 2 years at two sites in the Pacific Northwest. Although numerous studies have examined the effect of logging debris on soil C and N, relatively few have been performed in the Pacific Northwest, and it is unclear if the results of Johnson and Curtis (2001) and Powers et al. (2005) are applicable to site conditions in this region. Our specific objectives were to determine the effect of surface condition on total soil C and N to assess the feasibility of a stratified sampling scheme, the short-term effect of two levels of logging debris retention and competing vegetation control on total soil C and N pools, and possible variation of the response with depth.

Methods

Site Descriptions

This study was initiated in 2003 at two sites in the Pacific Northwest that are affiliates of the LTSP network (Powers et al. 1990). Potential productivity as indicated with the site index is similar between sites, but large differences exist in precipitation and soil properties (Table 1). The Matlock site is located on the Olympic Peninsula, approximately 8 km Northwest of Matlock, Washington. Soil at Matlock is classified as a sandy-skeletal, mixed, mesic, Dystric Xerorthent, formed in glacial outwash with slopes ranging from 0 to 3% (Soil Survey Staff, Natural Resources Conservation Service, US Department of Agriculture 2005). The Molalla site is located approximately 24 km northeast of the town of Molalla, Oregon, in the foothills of the Western Cascades. Soil at Molalla is classified as a fine-loamy, isotic, mesic Andic Dystrudept, formed in basic agglomerate residuum

Table 1. Site characteristics and select pretreatment soil properties to a depth of 30 cm for the Matlock and Molalla study sites

Characteristic or property	Matlock	Molalla
Location (latitude, longitude)	47.206°N, 123.442°W	45.196°N, 122.285°W
Elevation (m)	35	549
Mean annual temperature (°C)	10.7	11.2
Mean annual precipitation (mm)	2,400	1,600
Site $index_{50\ yr}$ (m)	35.9	36.2
Soil texture (% sand/silt/clay)	65/14/21	37/34/29
Bulk density (Mg ha^{-1})	1.45 (0.05)[1]	0.98 (0.02)
Coarse fragments by mass (%)	67.6 (1.3)	37.7 (2.2)
Total soil N (kg ha^{-1})	2,246 (88)	4,338 (173)
Total soil C (Mg ha^{-1})	66.5 (3.6)	102.2 (4.7)

SE in parentheses, $n = 8$ for bulk density at Matlock, $n = 24$ for all others.

with slopes ranging from 2 to 40% (Soil Survey Staff, Natural Resources Conservation Service, US Department of Agriculture 2005).

The regional climate is Mediterranean, with mild, wet winters and dry, warm summers with periods of drought (>2 mo) common. Before harvest, both sites supported second-growth even-aged stands that were primarily (>95% of basal area) composed of Douglas-fir. Stand density was approximately 280 trees ha^{-1} at both sites, and basal area was 35 and 46 $m^2\ ha^{-1}$ at Matlock and Molalla, respectively. At time of harvest, stand age was 45 years at Matlock and 56 years at Molalla. In 1994, Molalla was thinned from below, whereas in 1998 some trees were removed at Matlock after a severe ice storm.

Experimental Design and Treatment Application

Sites were initially clearcut harvested with chainsaws in March (Molalla) and April (Matlock) 2003. Trees were delimbed at the stump, and merchantable portions were removed with ground-based mechanized equipment along marked machine trails that were evenly distributed across plots to minimize soil disturbance. After harvest, a 2 × 2 randomized complete block factorial design was installed at each site. The factors were harvest type (bole-only with logging debris widely dispersed across the treatment area or whole-tree with minimal retention of logging debris in the treatment area) and herbicide for vegetation control (two levels with initial vegetation control or annual vegetation control). The factorial combinations were replicated four times in a randomized complete block design and applied to 0.3-ha plots. The bole-only harvest removed only merchantable portions of the tree, and the whole-tree harvest removed most logging debris in addition to the merchantable portions. After log removal across each site, the whole-tree treatment was simulated by removing logging debris within each designated plot with mechanized equipment confined to the previously described machine trails. A twofold difference in logging debris mass between the bole-only and whole-tree treatments resulted from this approach.

All plots received an initial application of herbicide to reduce competing vegetation; at Molalla glyphosate was aerially applied in August 2003 and triclopyr was applied with backpack sprayers at Matlock in September of 2003. After this initial application, only those treatments assigned annual vegetation control were treated with herbicide in the fall or spring to control competing vegetation. The purpose of the vegetation control treatment was twofold: to compare effects of harvest type at two levels of vegetation control that could be used as part of a silvicultural system and to determine whether effects of harvest type are dependent on abundance of competing vegetation. Both sites were hand-planted with bareroot Douglas-fir seedlings in February (Molalla) and March (Matlock) of 2004 at a 3 × 3 m spacing (1,111 trees ha^{-1}).

Soil Sampling and Analysis

Soils at each site were sampled before harvesting in the winter of 2003 with 10-cm diameter augers. Samples were collected from three depths (0–15, 15–30, and 30–60 cm) at five points within each plot and composited by depth increment. Samples for chemical analysis were returned to the laboratory, air-dried, and sieved to pass a 2-mm mesh. Approximately 5 g of the sieved soil was separated and ground with a mortar and pestle to pass a 0.25-mm mesh, followed by dry combustion using a LECO Dumas combustion technique on a Fisons NA1500 NCS Elemental Analyzer (ThermoQuest Italia, Milan, Italy) for determination of total soil C and N. Bulk density was estimated at the midpoint of each depth increment at three locations for the 0–15 and 15–30 cm depths and at one location for the 30–60 cm depth. The core method was used at Molalla, but the high percentage of coarse fragments at Matlock required use of the sand-funnel method (Blake and Hartge 1986). Bulk density was estimated in all plots at Molalla, but only in eight plots (two per block) at Matlock because of the labor-intensive sand-funnel method. Bulk density samples were sieved to pass a 2-mm mesh after initial determination of the whole-soil (intact core) value, and the sieved fine fraction was used to determine C and N mass in the soil-sized fraction at each depth.

Soils were sampled approximately 2 years after harvest to assess initial treatment effects. We used a stratified sampling scheme by surface condition with the intent of reducing postharvest sampling variability in soil chemical properties. Four surface conditions were identified as follows: (1) light logging debris cover with little or no material overlaying intact forest floor, (2) heavy logging debris cover where the surface is covered with extensive logging debris consisting of coarse woody debris or thick litter and twig layers that physically impede access to the original forest floor, (3) debris-covered machine trails where machine contact with forest floor and mineral soil was minimal because of presence of logging debris, and (4) exposed mineral soil machine trail where the original forest floor was displaced and mineral soil was exposed. Five random samples from each condition and plot were sampled to a depth of 15 cm and composited. The 15–30 and 30–60 cm depths were not sampled with the stratified scheme as we expected the effect of surface condition over a 2-year period to be limited to shallow soil, and accordingly those depths were sampled with the same protocol used for the preharvest collection. Area extent of each surface condition in each plot was estimated with the line transect method (Brown 1974). The same individual performed all surface condition estimates and identification (for soil sampling), limiting any error associated with operator bias in qualitative assessments. Soil processing and total C and N determination were performed as described above.

No concerted effort was made to assess posttreatment bulk density because of resource limitation, and we assume that changes in bulk density fine soil fraction (used for mass estimates of C and N) were small during the study period. S. Gall (Oregon State University, unpublished data, 2005) independently assessed differences in bulk density among surface conditions at Molalla and found significantly higher fine fraction bulk density (approximate difference of 0.1 Mg m^{-3}) in machine trails with exposed soil at 0–5 cm depth, but no difference at 10 cm depth or among the other surface conditions. There was also no distinguishable difference between pre- and posttreatment estimates, and no differences among the harvest or vegetation control treatments in fine fraction bulk density (S. Gall, unpublished data). No information is available for Matlock, but the likelihood for altered bulk density after treatment is lower than that at Molalla, given the coarse texture and high rock content of soils at Matlock.

Data Analysis

Pretreatment bulk density was used to convert soil C and N concentrations to a mass estimate by depth for both pretreatment and posttreatment data. At Matlock, the two bulk density estimates per block were averaged to determine mean values per block, which were then used for mass calculations for plots within each block. Posttreatment estimates of total C and N content in the 0–15 cm depth increment were calculated by weighting C and N concentrations in each surface condition by the percent area extent of that surface condition for each plot. The weighted mean concentration per plot was then multiplied by the bulk density in the 0–15 cm depth for the associated plot to determine a weighted C and N content. Change in total soil C and N content was calculated as the mass difference between pretreatment and posttreatment samples, with negative values indicating absolute loss and positive values indicating gains.

Effect of treatment on the change in total soil C and N content was analyzed by depth increment and the total sum for all depths using a mixed model (Proc Mixed in SAS; SAS Institute, Cary NC) with block modeled as a random effect, and pretreatment values were used as covariates. The covariate with equal slopes was significant in all model runs at Matlock but in none at Molalla. *t* tests were used to develop confidence intervals for the mean change in total soil C and N content within a treatment and depth to independently assess whether differences were significantly different from zero. Effect of surface condition on total soil C and N concentration was assessed by treating surface condition as a split-plot within the whole plot to account for spatial correlation among surface conditions within a given plot. For the split-plot analysis, block and the interaction between block and the whole-plot factors were modeled as random effects, and surface condition and whole-plot treatments were modeled as fixed effects. Examination of the residuals indicated that assumptions of normality and homogeneity were valid. When F tests indicated significant treatment effects, Tukey's honestly significant difference test was used to determine significant differences among means. For all analyses, each site was analyzed independently. An α level of 0.10 was used in all statistical tests.

Results

Surface Condition

Surface condition coverage differed between harvest treatments (Figure 2). Patterns were similar between sites and generally reflected differences in logging debris retention between harvest types, with the heavy logging debris condition being more prevalent in the bole-only harvest and the light logging debris condition being more prevalent in the whole-tree harvest. There was no difference between harvest treatments in the area coverage of machine trail conditions at either Molalla or Matlock. Surface condition had significant effects on total soil C and N concentrations at both sites (Table 2). Total soil C and N concentrations decreased in the order heavy logging debris > light logging debris ≈ machine trails with logging debris > machine trails with exposed soil at both sites, but the significance and magnitude of difference varied (Figure 3). Differences between heavy logging debris and light logging debris conditions were estimated to be 0.3 (SE = 0.01) and 0.3 (SE = 0.01) g kg^{-1} for N and 8.8 (SE = 2.9) and 6.3 (SE = 2.3) g kg^{-1} for C at the Matlock and Molalla sites, respectively. There was little difference between the light logging debris and machine trails with logging debris for either C or N, but total C concentration was significantly lower in the machine trails with exposed soil compared with those for the other conditions (Figure 3). Differences in total soil C concentration between machine trails with logging debris and those with exposed soil were estimated to be 6.3 (SE = 2.5) and 6.7 (SE = 3.0) g kg^{-1} at Matlock and Molalla, respectively.

Change in Soil C and N Content

Despite the higher total C and N concentrations in the heavy logging debris condition and the greater coverage of heavy logging debris in the bole-only treatment, there was

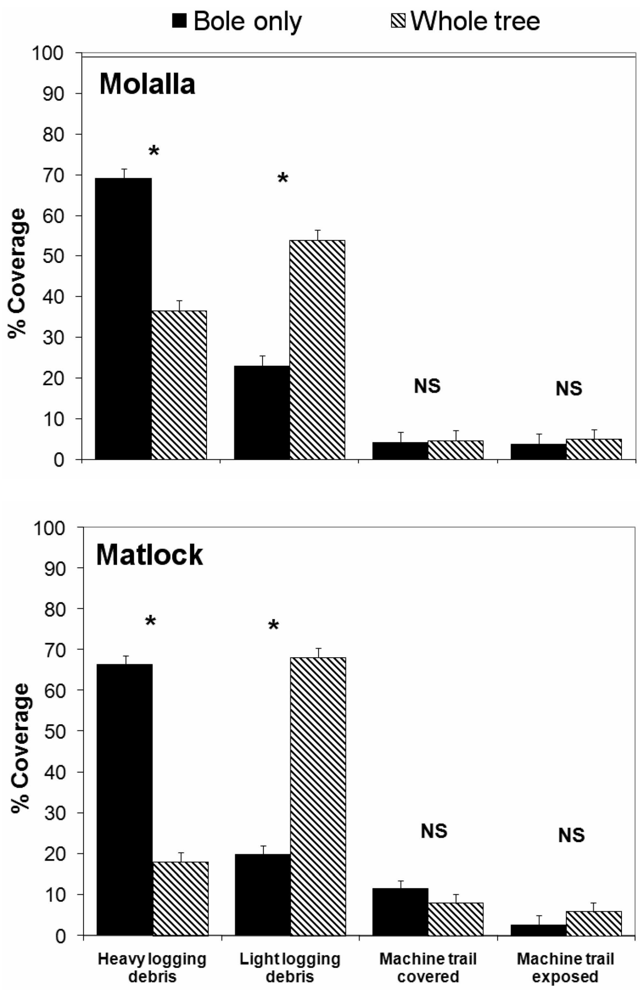

Figure 2. Effect of harvest treatment on estimated coverage by surface condition used for stratified soil sampling in the 0–15 cm depth at Molalla (top) and Matlock (bottom) sites. *Significant difference between harvest treatments at $\alpha = 0.1$, NS, nonsignificant. Error bars are SEM.

no difference in C and N content change between harvest treatments at any depth for each site (Table 3; Figures 4 and 5). Coefficients of variation at 0–15 cm by harvest treatment ranged from 475 to 737% at Matlock and from 252 to 707% at Molalla. At Molalla, *t* tests indicated that total soil C and N content increased during the study period in the whole-tree harvest treatment at 30–60 cm depth, leading to a significant increase from zero for the total depth of soil sampled in that treatment (Figures 4 and 5). At Matlock, total soil C and N increased during the 2-year period at a depth of 15–30 cm in both harvest treatments, and soil C increased in the bole-only harvest at 30–60 cm. Total soil C content increased for the whole soil to 60 cm in both harvest treatments at Matlock.

There was a significant effect of vegetation control treatment on change in total soil C and N content at both sites, but the depth of the effect varied by site (Table 3). At Molalla, change in total soil C and N content was greater after initial vegetation control at 0–15 cm depth, with the effect attributable to slight increases in the initial vegetation control treatment coupled with decreases in the annual vegetation control treatment over the 2-year period (Figures 4 and 5). However, at deeper depths, mean change in total soil N tended to be lower in the initial vegetation control treatment, such that there was no identifiable difference between treatments in total soil N content for the total 60 cm depth. In contrast, at Matlock the change in total soil C and N content was significantly greater after initial vegetation control at all depths of the profile, but the effect on soil C content at 30–60 cm depth and the total 0–60 cm depth only occurred in combination with the bole-only treatment (i.e., significant interaction) (Table 3). Magnitude of change was greater than zero when initial vegetation control was applied at both sites for C content and for N content at the Matlock site.

Discussion

Effects of Surface Condition on Soil C and N

The significant effect of surface condition on total soil C and N concentrations indicates that localized accumulations of logging debris influenced these pools in the initial years after harvesting treatments. Most C in logging debris is respired directly to the atmosphere (Mattson et al. 1987, Palviainen et al. 2004), but at least a portion enters the mineral soil as dissolved organic carbon (Qualls et al. 2000, Robertson et al. 2000, Piirainen et al. 2002). Logging debris also reduces soil temperature (Roberts et al. 2005, Devine and Harrington 2007), probably reducing microbial decomposition of C, given the well-known influence of temperature on microbial activity (e.g., Lloyd and Taylor 1994). The lowest concentrations of C and N occurred where mineral soil was exposed on skid trails, which could have been caused by loss of the forest floor or mixing of mineral soil horizons during harvesting operations. Posttreatment bulk density samples collected at Molalla (S. Gall, unpublished data) showed higher fine fraction (<2 mm) soil density in the exposed mineral soil condition at 0–5 cm depth compared with the remaining conditions, which could account for some of the change in soil C and N concentration observed at the 0–15 cm depth. Regardless of the cause, it appears that there is little potential for additional reductions in C and N at machine trails when logging debris is present to buffer any change in those pools (Figure 3).

The difference in soil C and N concentration among surface conditions, combined with the difference in condition coverage between harvest treatments, suggests that posttreatment stratified sampling by surface condition may be a useful approach to detect treatment effects. However, the large coefficients of variation associated with estimates of the change in soil C and N content at 0–15 cm indicates that this is not the case. Variation in surface condition coverage, pretreatment soil C and N concentrations, and posttreatment soil C and N concentrations was probably compounded such that estimates of the change in soil C and N became less precise. Homann et al. (2008) found that pre- and posttreatment comparisons greatly reduced minimum detectable change in experimental manipulations, especially when measurements were paired within small subplots. Such an approach is not possible when sample stratification

Table 2. Test statistics for fixed treatment effects on soil total C and N concentrations at a depth of 0–15 cm at the Matlock and Molalla sites

Effect	Carbon		Nitrogen	
	F statistic	P	F statistic	P
Matlock				
Harvest (df = 2, 15)[1]	0.69	0.519	0.35	0.709
VC (df = 1, 15)	0.27	0.608	0.15	0.700
Harvest · VC (df = 2, 15)	1.66	0.224	0.89	0.429
Surface condition (df = 3, 52)	12.38	<0.001	14.10	<0.001
Harvest · surface (df = 6, 52)	0.35	0.907	0.76	0.604
VC · surface (df = 3, 52)	1.36	0.265	1.11	0.353
VC · harvest · surface (df = 6, 52)	0.26	0.951	0.20	0.976
Molalla				
Harvest (df = 2, 15)	2.18	0.147	1.92	0.181
VC (df = 1, 15)	0.04	0.835	0.11	0.746
Harvest · VC (df = 2, 15)	2.76	0.096[2]	2.46	0.119
Surface condition (df = 3, 50)	15.27	<0.001	22.38	<0.001
Harvest · surface (df = 6, 50)	0.41	0.867	0.70	0.654
VC · surface (df = 3, 50)	0.57	0.640	1.21	0.318
VC · harvest · surface (df = 6, 50)	2.11	0.070[2]	1.99	0.087[2]

VC, competing vegetation control.
[1] df for the critical F statistic in parentheses.
[2] No significant pairwise comparisons were found for any of the interactions indicated with F tests at Molalla.

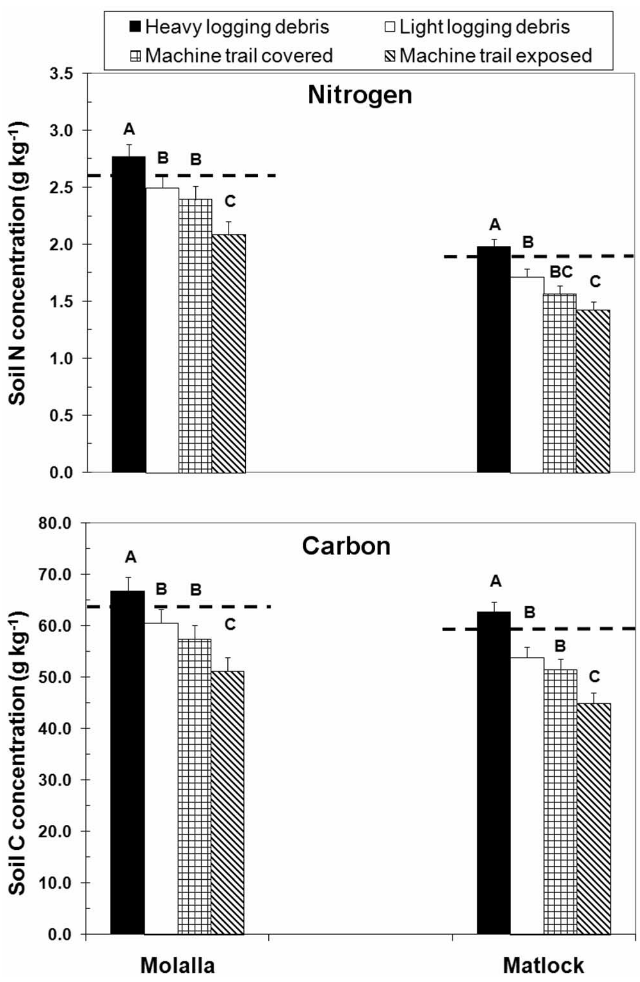

Figure 3. Effect of surface condition used for stratified sampling on soil C and N concentration to a depth of 15 cm at the Matlock and Molalla sites. Mean values were calculated across harvest and vegetation control treatments. For each site, means with different letters are significantly different at α = 0.1. Dashed horizontal lines represent the preharvest soil C and N concentration. Error bars are SEM.

is based on surface condition, because there is no way to predict the posttreatment (i.e., harvest-induced) condition at a discrete point within a plot. Consequently, it is probably more efficient to increase the number of random samples to assess treatment effects, rather than stratify by surface condition.

Effects of Harvest Type on Soil C and N

The absence of any difference in the change in soil C and N content between harvest treatments is in accordance with results from the LTSP network (Powers et al. 2005, Sanchez et al. 2006). Clearly there is some influence of logging debris on soil C and N, given the surface condition results, but the effect appears to be small and undetectable at the plot scale. Powers et al. (2005) noted significant increases in soil C and N content after harvesting regardless of OM removal, which they attributed to decomposition of the residual root systems. We also noted a general tendency for soil C and N content to increase regardless of harvest treatment, with significant increases for the total soil to 60 cm in the bole-only treatment at Matlock and the whole-tree treatment at Molalla. Carbon inputs to the mineral soil from debris only account for a small fraction of the increase given that much of the logging debris was still present at the soil surface. Fine root decomposition could have contributed 5 Mg ha^{-1} C to the increase (assuming relative fine root biomass of 10 Mg ha^{-1} (Vogt et al. 1987) and a C concentration of 500 g kg^{-1}), indicating that some of the increase must have been derived from the forest floor or coarse root biomass, which can be as much as an order of magnitude greater than fine roots (McDowell et al. 2001).

It is unclear why the increase in soil C occurred in different harvest types at each site, but it seems likely that the response is associated with differences between sites in the factors controlling belowground decomposition.

Table 3. Test statistics for fixed treatment effects on the change in soil C and N content by sample depth at the Matlock and Molalla sites

Effect	Carbon F statistic	Carbon *P*	Nitrogen F statistic	Nitrogen *P*
Matlock				
0–15 cm[1]				
Harvest (df = 1, 9)[2]	1.26	0.298	0.04	0.851
VC (df = 1, 9)	7.21	0.031	8.38	0.023
Harvest · VC (df = 1, 9)	2.30	0.173	0.02	0.91
15–30 cm				
Harvest (df = 1, 9)	0.12	0.737	0.42	0.535
VC (df = 1, 9)	6.74	0.032	4.70	0.062
Harvest · VC (df = 1, 9)	0.28	0.613	1.47	0.260
30–60 cm				
Harvest (df = 1, 9)	1.03	0.339	0.44	0.525
VC (df = 1, 9)	5.43	0.048	4.14	0.076
Harvest · VC (df = 1, 9)	5.17	0.053	3.19	0.112
Total (0–60 cm)				
Harvest (df = 1, 9)	0.93	0.363	0.19	0.676
VC (df = 1, 9)	6.79	0.031	5.33	0.050
Harvest · VC (df = 1, 9)	3.96	0.082	1.44	0.265
Molalla				
0–15 cm				
Harvest (df = 1, 9)	0.08	0.791	0.18	0.680
VC (df = 1, 9)	6.03	0.040	3.62	0.090
Harvest · VC (df = 1, 9)	1.70	0.228	2.02	0.189
15–30 cm				
Harvest (df = 1, 9)	0.25	0.634	0.18	0.683
VC (df = 1, 9)	0.66	0.440	0.02	0.885
Harvest · VC (df = 1, 9)	0.00	0.960	0.15	0.708
30–60 cm				
Harvest (df = 1, 9)	1.00	0.357	2.10	0.995
VC (df = 1, 9)	0.13	0.729	0.32	0.921
Harvest · VC (df = 1, 9)	1.38	0.285	1.16	0.323
Total (0–60 cm)				
Harvest (df = 1, 9)	0.98	0.360	1.02	0.351
VC (df = 1, 9)	0.43	0.535	0.08	0.793
Harvest · VC (df = 1, 9)	0.89	0.382	0.32	0.594

[1] 0–15 cm depth calculated from weighted content estimates by surface condition cover.
[2] df for the critical F statistic in parentheses.

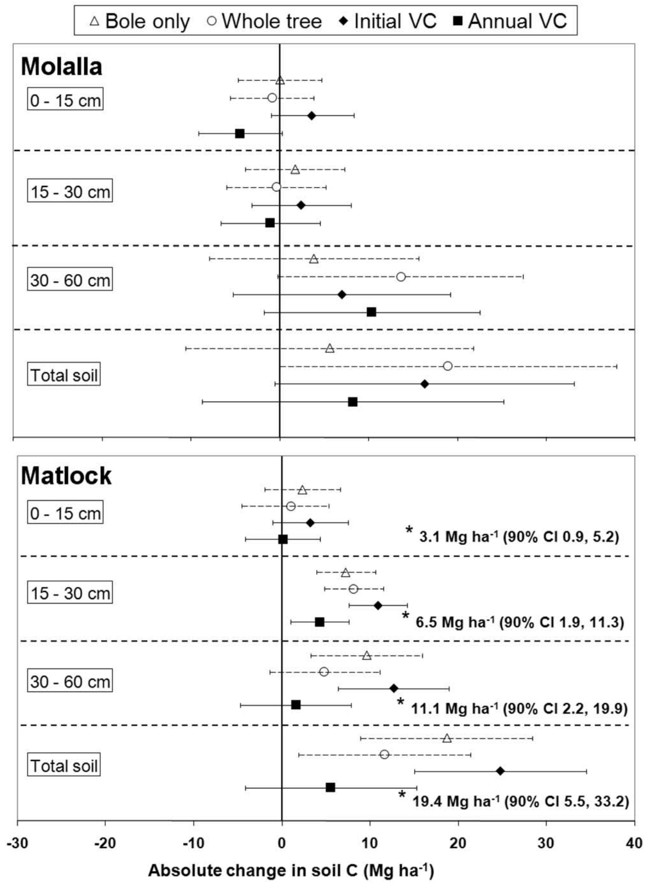

Figure 4. Effect of soil depth, harvest type, and vegetation control (VC) treatment on change in soil C concentration at Molalla (top) and Matlock (bottom) sites. Error bars are 90% confidence limits of the mean; bars that do not overlap the zero line indicate a significant change in mass over the 2-year study period. *Significant treatment effect with the estimated difference between treatments listed. Differences between vegetation control treatments for the 30–60 cm and total depth are for the bole-only treatment only Estimates for the 0–15 cm depth were calculated by weighting concentrations for a respective surface condition by the percentage cover of that condition.

Root decomposition generally increases with soil temperature and may be inhibited at either low or high water content (Chen et al. 2000). Soil temperature is generally higher in whole-tree harvests than in bole-only harvests (Roberts et al. 2005, Devine and Harrington 2007), potentially increasing root decomposition and increasing soil C as was observed at Molalla. The opposite response observed at Matlock may indicate that soil moisture is more limiting to decomposition than temperature at that site, which could arise from the relatively low water-holding capacity of the coarse-textured soil present at Matlock (Table 1). Bole-only harvesting can reduce evaporative water loss through a mulch effect (Devine and Harrington 2007), potentially allowing root decomposition to continue for longer periods in the growing season than in the whole-tree harvest.

Although increased decomposition via a mulch effect seems plausible at Matlock, visual examination of the change in soil C by depth indicates that much of the increase observed in the total soil to 60 cm in the bole-only harvest was associated with increases in the 30–60 cm depth, and the increase at that depth only occurred when initial vegetation control was applied. Harvest treatment had a strong effect on the form and distribution of competing vegetation in the initial vegetation control plots (T. Harrington, Oregon State University, unpublished data, 2005), and it may be that these vegetation differences were more important to the changes in soil C than differences in logging debris retention between harvest types. Regardless of the mechanism, it appears that harvest type can influence the magnitude of initial C increase after harvesting at these sites, with the effect being most pronounced in deeper portions of the soil profile.

Effects of Competing Vegetation Control on Soil C and N

The decrease in soil N content at 0–15 cm depth at Molalla after annual vegetation control was countered by greater N content at deeper depths in the same treatment,

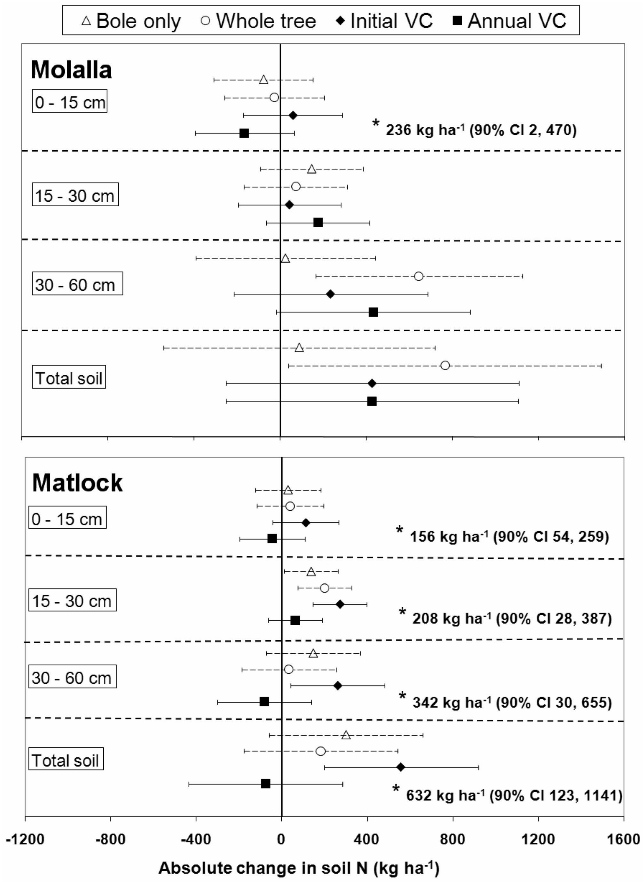

Figure 5. Effect of soil depth, harvest type, and vegetation control (VC) treatments on change in soil N concentration at Molalla (A), and Matlock (B) sites. Error bars are 90% confidence limits of the mean; bars that do not overlap the zero line indicate a significant change in mass over the 2-year study period. *Significant treatment effect, with the estimated difference between treatments listed. Estimates for the 0–15 cm depth were calculated by weighting concentrations for a respective surface condition by the percentage cover of that condition.

such that there was no distinguishable difference in total soil N (0–60 cm) between vegetation control treatments (Figure 5). It is likely that reduced N uptake in the annual vegetation control treatment caused N to be redistributed (i.e., leached) to lower portions of the soil profile at Molalla. In contrast, change in soil N content was significantly greater at all depths after initial vegetation control at Matlock, and mean values in annual vegetation control were close to zero. The increase in N after initial vegetation control may be partly caused by growth of N-fixing Scotch broom (*Cytisus scoparius*) in that treatment at the Matlock site (T. Harrington, unpublished data), but plot coverage of Scotch broom was only 2% in the first 2 years postharvest, and it is unlikely that the contribution from this source was large. A more likely dominant N source was N inputs from the decomposing root system, which would imply that N was lost via leaching in the annual vegetation control treatment because there was no change in soil N content in that treatment. Nitrogen leaching is common after annual vegetation control (Vitousek and Matson 1985, Smethurst and Nambiar 1995, Briggs et al. 2000), and the coarse-textured soil at Matlock may be especially susceptible to N leaching in the initial years after harvest.

Contrary to other studies that have observed decreased soil C when annual vegetation control was applied (Shan et al. 2001, Echeverria et al. 2004, Miller et al. 2006), we found little evidence for a decrease in soil C content to a depth of 60 cm at these sites. The one exception was in surface soils at Molalla, where the difference between treatments was at least partly due to reductions in soil C content after annual vegetation control. However, most of the differences between vegetation control treatments were largely associated with increased C content in the initial vegetation control treatment, indicating that recently fixed C inputs from competing vegetation were retained in soil or increased decomposition of belowground OM (roots) after harvest (i.e., microbial priming). These increases could have important implications for soil productivity and C sequestration (i.e., increase above the pretreatment soil pool) if maintained over the course of a rotation, but the stability of the C fraction contributing to the increase is unknown, and these early changes may be misleading.

Conclusions

We had hypothesized that stratified sampling by surface condition may improve our ability to detect change in soil C and N in response to harvest type, but variation in each component of the calculation was compounded such that plot estimates became less precise, and it is probably more effective to increase sample size to address this variability. The surface condition results indicate that there is an effect of logging debris on soil C and N at these sites, but the effect was undetectable at the plot scale and probably small relative to total soil pools. These initial plot-level results are in accordance with past studies from other regions. Initial vegetation control increased soil C and N at these sites, but there was little evidence for a decrease in these properties when annual vegetation control was applied. Increases in C and N appear to be largely associated with the influence of recently fixed C (retention or priming), a reduction in N leaching, and an increase in N fixation. More studies are needed to clarify the potential for this practice to alter soil properties in this region and the factors that buffer soil change when control of competing vegetation is used.

Treatment effects and the change in soil C and N generally varied widely by soil depth increment. Increases in soil C and N were relatively small in surface horizons, but larger in deeper soil. These differential responses with depth may be unique to the Pacific Northwest, but the potential for similar effects in other regions should be evaluated. In the case of vegetation control treatment effects, examination limited to surface soil would have resulted in the same conclusion for C and N compared with examination of the total soil to 60 cm depth at Matlock. However, a contradictory conclusion would have resulted for N at Molalla in the same comparison. Our results demonstrate the importance of sampling to greater depths for valid assessment of change in soil properties after experimental manipulation.

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