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Soil carbon and nutrient pools in Douglas-fir plantations 5 years after manipulating biomass and competing vegetation in the Pacific Northwest

Robert A. Slesak[a,*], Stephen H. Schoenholtz[b], Timothy B. Harrington[c]

[a] Minnesota Forest Resources Council, 2003 Upper Buford Circle, St. Paul, MN 55108, United States
[b] Virginia Tech, Virginia Water Resources Research Center, 210 Cheatham Hall, Blacksburg, VA 24061, United States
[c] USDA Forest Service, Pacific Northwest Research Station, 3625 93rd Ave., SW, Olympia, WA 98512, United States

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ABSTRACT

We assessed changes in mineral soil total carbon (C) and nutrient (exchangeable Ca, K, Mg, and total N) pools to 60 cm depth 5 years after manipulating biomass and competing vegetation at two contrasting Douglas-fir plantations (Matlock, WA, and Molalla, OR). Biomass treatments included whole-tree (WT) and bole-only (BO) harvest, and competing vegetation control (VC) treatments were applied as either initial or annual herbicide applications. There were main effects of biomass removal and VC on the absolute change in soil pools of some elements at both sites, but significant effects were more prevalent at the lower soil quality Matlock site than the Molalla site, and were generally confined to the top 15 cm of soil. In all cases, treatment effects were associated with increases in C and nutrients following BO and initial VC treatments combined with little change in soil pools following WT and annual VC treatments. At the Matlock site, total soil pools (0–60 cm) of C, N, and Ca significantly increased in the BO and initial VC treatments, and Mg increased and K decreased regardless of treatment. At the Molalla site, soil C and nutrient pools did not change in response to treatments, but total soil Mg increased in all treatments during the study period. Correlation analyses indicated little influence of soil nutrient pools on early growth at Matlock likely because soil water is more limiting than nutrient availability at that site, but vegetation growth was correlated to nutrient pools at Molalla indicating changes in pools associated with harvesting and treatment could influence crop development in the future. These early results indicate low potential for intensive management practices to reduce mineral soil pools of C and nutrients, but there is uncertainty on the long-term growth response because treatments may have influenced nutrient storage in pools other than mineral soil.

1. Introduction

Concern over the potential for intensive forest management to degrade soil properties critical to productivity has existed for decades (e.g., Boyle and Ek, 1972), and widespread interest in the use of biomass for energy production has resurrected and broadened this concern (MFRC, 2007; Janowiak and Webster, 2010). Intensive forest management has many forms, but generally involves greater biomass removals over shorter rotations coupled with increased cultural inputs such as genetically improved planting stock, fertilization, irrigation, or herbicide application. These practices can influence both total nutrient pools available for growth, and the mechanisms controlling nutrient retention and loss following harvest (e.g., vegetative demand, water balance, microbial activity) (Powers et al., 2005; Nambiar, 1990; Vitousek and Matson, 1985). Conceptually, potential risks to productivity span a spectrum from low to high cultural input that vary with level of utilization and site conditions (Grigal, 2000), making identification of broadly applicable sustainability guidelines challenging.

Despite initiation and reporting of several long-term experiments, use of mass balance approaches, and predictive models, uncertainty exists on the potential for the above concerns to be realized. Much of this uncertainty can be attributed to a number of causes including recognition of the difficulties in assessing change in soil properties following experimental manipulation (Homann et al., 2008; Shaw et al., 2008), untested assumptions inherent to mass balance approaches (Grigal, 2004, Ranger and Turpault, 1999), and uncertainty in modeling ecological processes such as the weathering of primary minerals (Klamindera et al., 2010). Despite their drawbacks, long-term manipulative studies, such as the Long Term Soil Productivity study (Powers et al., 2005), offer the greatest potential to elucidate the influence of intensive management on soil properties (Richter et al., 2007). Given the risk spectrum described above, there is a need for such studies across a wide range of site conditions and climate if useful sustainability criteria are to be developed (Nambiar, 1996).

* Corresponding author. Tel.: +1 651 603 6756; fax: +1 651 603 0110.
E-mail address: raslesak@umn.edu (R.A. Slesak).

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Many long-term soil studies focus on changes in soil organic matter (SOM), because it is a critical soil property that influences a host of processes controlling resource supply to plants (e.g., aeration, water holding capacity, nutrient cycling). It has been hypothesized that a reduction in SOM (or soil C as a surrogate) has high potential to reduce soil productivity across a wide range of site conditions in the long term (Jurgensen et al., 1997; Powers et al., 1990). However, specific nutrient limitations, such as the well-known N limitation in the Pacific Northwest (e.g., Chappell et al., 1991) or dual limitation by N and P (Blevins et al., 2006), may have greater potential to reduce long-term productivity than a reduction in SOM *per se*. Other limitations to forest productivity such as available soil water are also likely in the Pacific Northwest (Waring et al., 2008). Identification of site-specific factors most likely to limit growth would clarify the potential for intensive management to negatively impact soil resources, and facilitate development of guidelines to maintain soil productivity and mitigate such impacts.

We assessed soil C and nutrient response to two levels of biomass removal with either initial or annual competing vegetation control 5 years after forest harvesting at two contrasting sites in the Pacific Northwest. Our objectives were to (1) determine 5-year treatment effects on mineral soil C and macronutrients in the root-exploitable zone (0–60 cm depth), and (2) assess selected soil chemical properties to determine which nutrients are most likely to limit growth of planted Douglas-fir at these sites.

2. Methods

2.1. Site descriptions

The research project was initiated at two sites in 2003 to assess long-term effects of logging-debris retention and vegetation control treatments on soil properties, nutrient cycling, and Douglas-fir growth. The sites are affiliates of the Long Term Soil Productivity (LTSP) study (Powers et al., 2005). Potential productivity as indicated by Douglas-fir 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 in WA, approximately 4 km SW of the town of Matlock. Soil at Matlock is classified as a sandy-skeletal, mixed, mesic, Dystric Xerorthents formed in glacial outwash with slopes ranging from 0% to 3% (Soil Survey Staff, USDA-NRCS). The Molalla site is located approximately 24 km NE of the town of Molalla, OR in the foothills of the western Cascades. Soil at Molalla is classified as fine-loamy, isotic, mesic Andic Dystrudepts formed in basic agglomerate residuum with slopes ranging from 2% to 40% (Soil Survey Staff, USDA-NRCS). The regional climate is Mediterranean, characterized by mild, wet winters and dry, warm summers with periods of drought (>2 mo) common.

Table 1
Site characteristics and selected pre-treatment soil properties from samples collected to a depth of 60 cm for study sites near Matlock, WA, and Molalla, OR.

Characteristic or property	Matlock	Molalla
Location (latitude, longitude)	47.206° N, 123.442° W	45.196° N, 122.285° W
Elevation (m)	118	449
Mean annual temperature (°C)	10.7	11.2
Mean annual precipitation (cm)[a]	240	160
Site index$_{50\ year}$ (m)[c]	36	36
Stand age at harvest (year)	45	56
Basal area at harvest ($m^2\ ha^{-1}$)	35	46
Particle size distribution (% sand/silt/clay)[c]	65/14/21	37/34/29
Bulk density ($Mg\ m^{-3}$)	1.45 (0.05)[b]	0.98 (0.02)
Coarse fragments by mass (%)	67.6 (1.3)	37.7 (2.2)
Water holding capacity (mm)[d]	170	297
Total soil C ($Mg\ ha^{-1}$)	92.4 (5.8)	169.5 (12.0)
Total soil N ($kg\ ha^{-1}$)	3300 (150)	7220 (410)
Exchangeable Ca ($kg\ ha^{-1}$)	420 (43)	5050 (683)
Exchangeable Mg ($kg\ ha^{-1}$)	35 (2)	604 (97)
Exchangeable K ($kg\ ha^{-1}$)	124 (5)	1430 (152)

[a] Precipitation was estimated from the PRISM model for period 1950–2005 (PRISM, 2008).
[b] Standard error in parentheses, $n = 8$ for bulk density at Matlock, $n = 16$ for all others.
[c] From Harrington and Schoenholtz, 2010.
[d] Determined with the hydrometer method.
[e] Estimated for a 1.25 m profile based on pressure plate analyses by the Central Analytical Laboratory, Oregon State University, Corvallis, OR.

2.2. Experimental design and treatment application

Sites were initially clear-cut harvested with chainsaws in March (Molalla) and April (Matlock) of 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. Following 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. Logging debris mass (estimated with the line transect method, Brown, 1974) was 22.5 (se = 3.0) and 13.5 $Mg\ ha^{-1}$ (se = 3.0) in the bole-only and whole-tree harvests, respectively, at Matlock, and 24.0 (se = 2.8) and 13.9 $Mg\ ha^{-1}$ (se = 2.8) in the bole-only and whole-tree harvests, respectively, at Molalla (Harrington and Schoenholtz, 2010). All plots received an initial application of herbicide to reduce competing vegetation, and then only those treatments assigned annual vegetation control were treated with herbicide in the fall or spring of each year to control competing vegetation (Harrington and Schoenholtz, 2010). Both sites were hand planted with bare-root Douglas-fir seedlings in February (Molalla) and March (Matlock) of 2004 at a 3×3 m spacing (1111 trees ha^{-1}). At the end of the study period, total aboveground biomass of competing vegetation averaged 2278 and 3131 $kg\ ha^{-1}$ at Matlock and Molalla, respectively, while that for Douglas-fir averaged 1415 and 2196 $kg\ ha^{-1}$, respectively (Devine et al., accepted for preparation).

2.3. Sampling and analytical methods

Soils at each site were sampled prior to harvesting in the winter of 2003 and again in the summer of 2008 with 10 cm-diameter augers. Samples were collected from three depths of the mineral soil (0–15, 15–30, and 30–60 cm) at 5 points within each plot, and composited by depth increment. Bulk density was estimated at the midpoint of each depth increment at three locations per sampled plot 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 following initial determination of the whole-soil (intact core) value, and the mass of the sieved fine-fraction was determined.

Table 2
F-statistic probabilities from ANOVA of effects of biomass removal and vegetation control (VC) by site and soil depth for each of the dependent variables. Values in bold are significant.

Effect	Total C	Total N	C:N	Exchangeable cations			pH
				Ca	K	Mg	
Matlock							
0–15 cm							
Biomass	0.230	**0.052**	**0.029**	**0.018**	0.408	**0.067**	0.128
VC	**0.027**	**0.043**	0.272	0.159	0.934	0.123	0.835
Biomass*VC	0.128	0.224	0.258	0.999	0.743	0.719	0.678
15–30 cm							
Biomass	0.613	0.181	0.126	0.218	0.319	0.157	0.873
VC	0.110	0.127	0.168	0.446	0.943	0.369	0.357
Biomass*VC	0.885	0.694	0.784	0.709	0.544	0.674	0.527
30–60 cm							
Biomass	0.668	0.528	0.865	0.229	0.999	0.532	0.948
VC	0.505	0.560	0.583	0.511	0.612	0.656	0.857
Biomass*VC	0.336	0.486	0.202	0.558	0.986	0.596	0.427
Total (0–60 cm)							
Biomass	0.464	0.123	NA	**0.072**	0.275	**0.030**	NA
VC	**0.099**	**0.098**	NA	0.214	0.847	**0.046**	NA
Biomass*VC	0.347	0.352	NA	0.649	0.949	0.458	NA
Molalla							
0–15 cm							
Biomass	0.984	**0.052**	**0.085**	0.197	**0.049**	0.122	0.116
VC	0.920	0.982	0.678	0.645	0.802	0.136	0.912
Biomass*VC	0.724	0.837	0.368	0.912	0.479	0.757	0.608
15–30 cm							
Biomass	0.513	0.785	**0.091**	0.918	0.794	0.827	0.110
VC	0.399	0.721	0.441	0.923	0.790	0.705	**0.012**
Biomass*VC	0.117	0.078	0.417	0.417	0.189	0.325	0.494
30–60 cm							
Biomass	0.274	0.257	0.678	0.787	0.614	0.443	0.408
VC	0.417	0.559	0.496	0.459	**0.095**	0.283	0.971
Biomass*VC	0.820	0.797	0.210	0.605	0.734	0.828	0.444
Total (0–60 cm)							
Biomass	0.344	0.627	NA	0.700	0.493	0.417	NA
VC	0.706	0.906	NA	0.752	0.419	0.535	NA
Biomass*VC	0.702	0.593	NA	0.898	0.504	0.949	NA

Samples for chemical analysis were returned to the laboratory, air-dried, and sieved to pass a 2-mm mesh. Total soil C and N was measured on a subsample that was 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). Exchangeable Ca, Mg, and K were extracted with ammonium acetate and extract concentrations were measured with inductively coupled plasma spectroscopy (Varian Vista MPX, Varian, Palo Alto, CA, USA). Soil pH was measured with a glass electrode in a 2:1 water to soil solution following 30 min of reaction time. All estimates of soil C and nutrient content are reported on an oven-dry (105 °C) basis. Sample collection, processing, and analytical procedures for the 5-year post harvest sampling were conducted as described above for pre-treatment samples.

2.4. Data analysis

Fine-fraction (<2 mm) bulk density values were used to convert soil C and nutrient concentrations to mass estimates by depth. 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 the associated block. Change in total soil C and nutrient content was calculated as the mass difference between pre- and 5-year post-treatment samples, with negative values indicating absolute loss and positive values indicating gains.

Effect of treatment on the change in total soil C and nutrient content was analyzed by depth increment and the total sum for all depths using mixed model analysis of variance (Proc Mixed in SAS; SAS Institute, Cary NC) with block modeled as a random effect, and pre-treatment values used as covariates when significant ($\alpha = 0.10$). Confidence intervals were developed for the mean change in total soil C and N content within a treatment and depth to independently assess if differences were significantly different from zero. Examination of the residuals indicated assumptions of normality and homogeneity were valid. When F tests indicated significant treatment effects, linear contrasts were used to estimate differences between treatment means. For all analyses, each site was analyzed independently.

We used 5-year post-treatment tree growth and understory abundance data (Harrington and Schoenholtz, 2010) to determine if relationships existed between vegetation growth and selected pre-treatment soil nutrient pools. Our purpose in conducting this analysis was to determine which, if any, nutrients influence growth in early years of stand establishment, thereby providing indication of potential nutrient limitation at later stages of stand development. Pearson correlation coefficients were calculated between growth variables (Douglas-fir height and stem diameter at 15 cm, and sum of Douglas-fir and understory biomass) and each soil property by depth increment. Aboveground biomass of Douglas-fir was predicted from stem diameter and that of understory vegetation was derived from unit-area estimates (Devine et al., accepted for publication). An alpha level of 0.10 was used in all statistical tests. All analyses were performed in SAS V9.1 (SAS Institute, Cary NC).

3. Results

3.1. Soil chemical properties

There were significant main effects of the biomass and vegetation control treatments at both sites for some of the response variables, and no significant interaction between the two factors. Treatment effects were more prevalent at the Matlock site than at the Molalla site, and generally confined to the 0–15 cm depth increment (Table 2, Figs. 1 and 2). In all instances where treatment effects were observed, differences were caused by increases in C and nutrients following bole-only harvest versus whole tree harvest and following initial vegetation control versus annual vegetation control.

At Matlock, effects at the 0–15 cm depth in combination with similar non-significant patterns at greater depths resulted in significant differences in total 0–60 cm pools between harvest treatments for Ca and Mg, and between vegetation control treatments for C, N, and Mg. The magnitude of these differences was such that total pools to a depth of 60 cm of C, N, Ca, and Mg were increased above pre-harvest levels in the bole only harvest and initial vegetation control treatments (Figs. 1 and 2). In contrast, treatment effects at the Molalla site on soil N (biomass treatment only) and K did not cause comparable effects in the total 60 cm pool, because patterns between treatments were not consistent across depth increments. Regardless of treatments, soil Mg pools increased during the 5-year period following harvesting at both sites, while soil K decreased at the Matlock site only (Fig. 2). Change in carbon and nutrient content was a function of increased fine fraction bulk density and concurrent changes in nutrient concentration at Molalla, but almost entirely due to change in nutrient concentration alone at Matlock (data not shown).

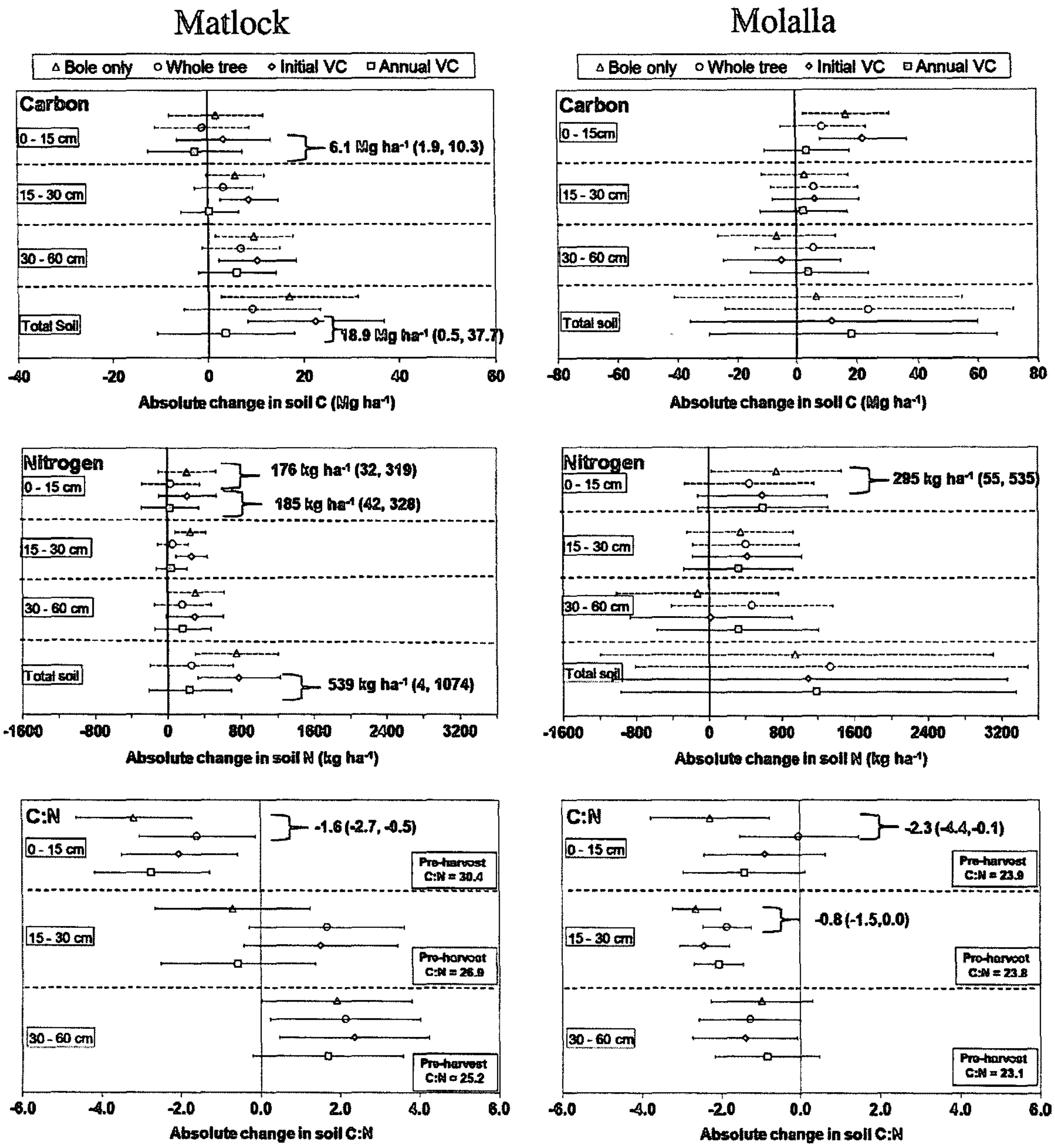

Fig. 1. Absolute change in soil C and N mass, and C:N by treatment, soil depth, and site 5 years after forest harvest as affected by biomass removal and vegetation control. Error bars are the 90% confidence interval for each mean. Value next to a bracket when present is the estimated difference between treatments when significant effects occurred (associated 90% CI in parenthesis). Note difference in scale among panels.

3.2. Soil-growth relationships

There was no correlation between any of the 5-year growth measures and soil chemical properties at any soil depth at the Matlock site (data not shown). At Molalla, N was most commonly positively correlated with 5-year growth measures across all treatments, and was the only soil chemical property related to Douglas-fir height and diameter growth in the initial vegetation control treatment (Table 3). In addition to soil N, exchangeable soil K in 0–15 and 15–30 cm depth increments was positively correlated with Douglas-fir height and diameter in the annual vegetation control treatment. Across all treatments, total aboveground biomass (Douglas-fir + understory vegetation) was also positively correlated with exchangeable Ca in the 0–15 cm and 15–30 cm depth increments, and with Mg in the 15–30 cm depth increment.

4. Discussion

Greater biomass removal and annual vegetation control have potential to degrade soil properties critical to long-term productivity because they result in greater removal and loss (i.e., leaching, heterotrophic respiration) of C and nutrients following harvesting (Likens et al., 1970; Vitousek and Matson, 1985; Powers et al., 2005; Slesak et al., 2010b). However, with the exception of K, our results indicate that mineral soil C and exchangeable nutrient pools tended to increase or not change with little evidence of reductions even when whole tree harvesting and annual vegetation control were applied in concert. Less intensive practices resulted in greater total pools than their counterparts, but differences were largely associated with post-treatment increases when bole only harvesting and initial vegetation control treatments were applied. The results indicate low potential for detrimental effects

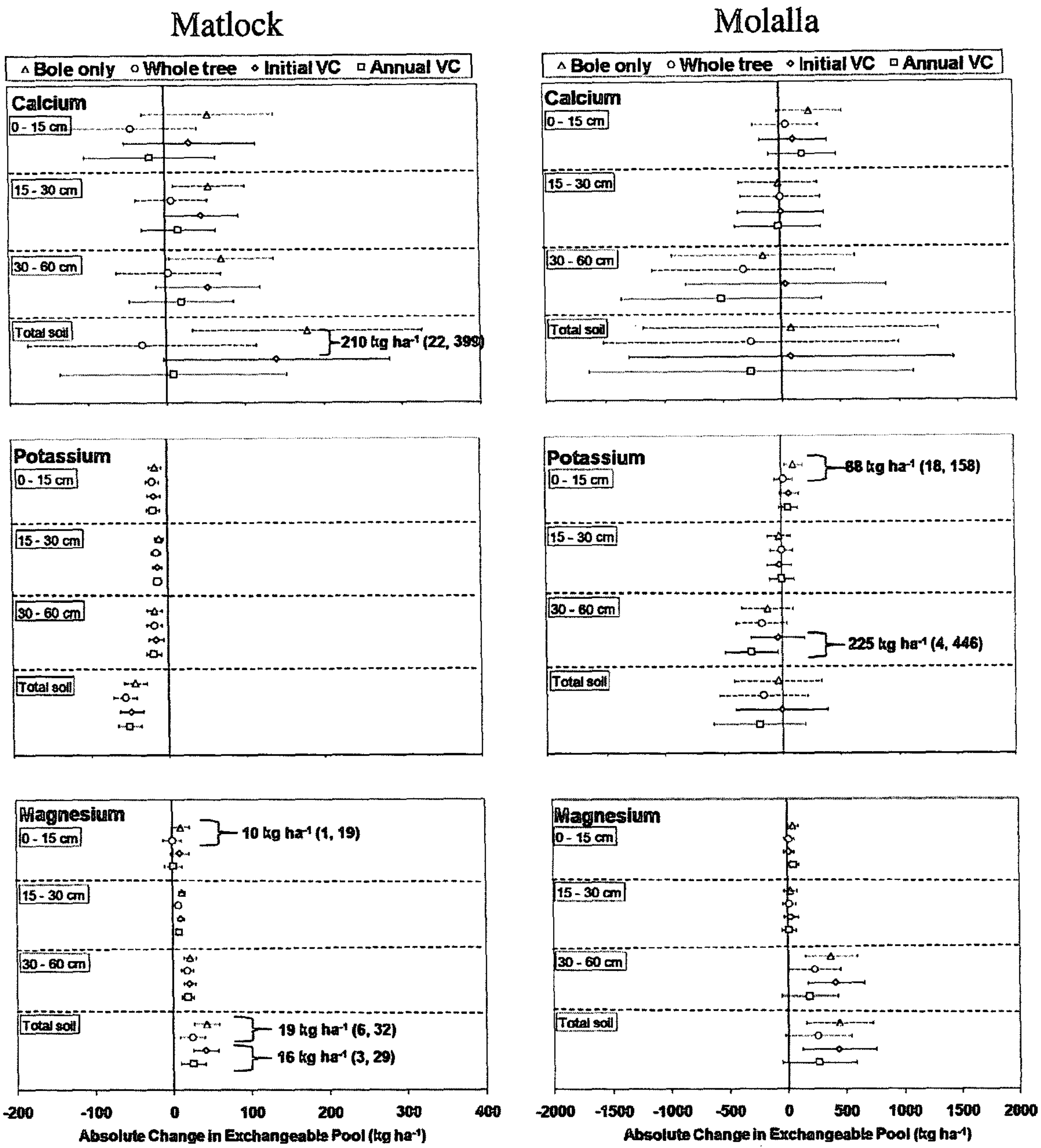

Fig. 2. Absolute change in exchangeable cations by treatment, depth, and site 5 years after forest harvest as affected by biomass removal and vegetation control. Error bars are the 90% confidence interval for each mean. Value next to a bracket when present is the estimated difference between treatments when significant effects occurred (90% CI in parenthesis).

on mineral soil when intensive management practices are utilized at these sites, but moderate potential for enhancement of mineral soil C and nutrient pools with use of less intensive management practices.

Differences between sites in the significance and magnitude of response are likely caused in part by differences in the size of pre-harvest pools between sites. Larger pools are generally more buffered to change, and small changes may be undetectable because of high variability (Homann et al., 2008). Differences in the vegetative community composition between sites, including presence of N-fixing Scotch broom (*Cytisus scoparius* (L.) Link) at the Matlock site (Harrington and Schoenholtz, 2010), likely contributed to the differing response as well. However, the results for N observed here are consistent with those observed 2 years post-harvest when Scotch broom coverage was low (Slesak et al., 2011), indicating other N sources contributed to the increase. Presence of allophane and imogolite minerals at Matlock (Strahm and Harrison, 2007) could have also contributed to the response, as these minerals are capable of absorbing large quantities of dissolved organic matter (Harsh et al., 2002).

The increase in exchangeable Mg that occurred at both sites is probably associated with greater net production, either from increased decomposition of OM (Fahey et al., 1988) or increased rates of primary weathering (Bormann et al., 1998), combined with a reduction in uptake. The concurrent reduction in exchangeable K at Matlock has been observed in other studies, with the reduction attributed to increased uptake by the succeeding forest (Duchesne and Houle, 2008) or leaching (Olsson, 1999). Displacement of K from the exchange complex by Mg and subsequent leaching is likely at Matlock, especially given that the reduction in soil K was similar between vegetation control treatments even though demand and uptake would have been lower in the annual vegetation control treatment.

The question arises as to what long-term effect these changes in nutrient pools may have on crop tree growth. Based on the correlation analysis, within-site variation in nutrient availability has

Table 3
Pearson correlation coefficients between pre-harvest soil nutrient pools and 5-year Douglas-fir growth variables by competing vegetation control treatment, and total aboveground biomass (Douglas-fir and understory vegetation) at Molalla, Oregon. Only significant correlations are shown.

Soil nutrient	Initial vegetation control[a]		Annual vegetation control		All treatments
	Volume	Height	Volume	Height	Total biomass
			0–15 cm depth		
N	0.77 (p = 0.03)	0.68 (p = 0.06)			0.51(p = 0.04)
Ca					0.43 (p = 0.09)
K			0.74 (p = 0.04)	0.74 (p = 0.03)	
C:N					−0.49 (p = 0.06)
			15–30 cm depth		
N	0.65 (p = 0.08)	0.70 (p = 0.05)	0.80 (p = 0.02)	0.86 (p < 0.01)	0.80 (p < 0.01)
Ca					0.43 (p = 0.09)
K			0.82 (p = 0.01)	0.82 (p = 0.01)	
Mg					0.50 (p = 0.05)

[a] n = 8 for each vegetation control treatment, n = 16 for all treatments combined.

little influence on measures of growth in the early years of stand establishment at the Matlock site regardless of whether or not competing vegetation was controlled. Given the regional Mediterranean climate where summer drought is common and water availability limits growth (Waring et al., 2008), we suspect that water holding capacity may have stronger influence on tree growth than nutrient availability at that site. In a related study, we observed a strong influence of water availability on root respiration that was more pronounced at the Matlock site than the Molalla site (Slesak et al., 2010b). Available water holding capacity at Matlock is less than 40% of that at Molalla primarily due to large differences in particle size distribution associated with the parent material at each site (Table 1). In individual-tree studies at the same sites, differences in soil water due to absence and presence of competing vegetation were no longer significant in year 3 at Matlock and in year 4 at Molalla, indicating a difference between sites in the timing at which the focal Douglas-fir seedling was able to fully deplete soil water within its rooting zone (T.B. Harrington, unpublished data). If water limitation is more limiting to growth than nutrient availability, then the modest treatment and harvest-related changes in nutrient pools may have little impact on future growth. Alternatively, the increase in soil N at Matlock may become more important to tree growth in later years if N availability is increased following crown closure, resulting in greater uptake and increased productivity (Busse et al., 1996; Zhang et al., 2006).

In contrast, the significant correlation between some nutrients and early plant growth at Molalla suggests that treatment and harvest-related changes in nutrient pools may have a compounding effect on growth that will become more prominent over time compared to Matlock. Most of the significant correlations were between pre-harvest soil N and various measures of growth for each vegetation control treatment, demonstrating the well-known N imitation to tree growth in the Pacific Northwest (Chappell et al., 1991). The positive correlation between exchangeable K and Douglas-fir growth in the annual vegetation control treatment likely indicates the importance of less-commonly limiting nutrients to growth when N availability to crop trees was increased with competing vegetation removal (Slesak et al., 2010a). The importance of nutrients other than N to growth is further demonstrated by the significant correlation between total aboveground biomass and soil Ca and Mg pools (Table 3). Although nutrient supply appears to be more limiting to tree growth at Molalla than Matlock, changes in soil nutrient pools associated with biomass removal manipulation have had a negligible effect on tree growth thus far (Harrington and Schoenholtz, 2010), similar to early findings at other LTSP installations (Fleming et al., 2006). However, longer-term (10–20 years) assessments have shown detrimental effects of biomass removal on tree nutrition and growth, but effects are generally species-specific (Thiffault et al., 2006; Krananbetter et al., 2006), limited to nutrient-poor soils (Egnell and Leijon, 1999, O'Hehir and Nambiar, 2010), or observed following application of more intensive practices (Egnell and Valinger, 2003; Smith et al., 2000).

The above assessment is specific to mineral soil pools of C and selected nutrients, so the results should be considered relative to other pools of potentially plant-available nutrients including those in logging-debris, the forest floor, and belowground structural OM (i.e., roots, stumps). In particular, Powers et al. (2005) highlighted the role of root decomposition to increased soil C and nutrients following harvesting and forest floor removal, and it is likely that this process contributed to the increases in soil C and nutrient pools observed in the present study (Slesak et al., 2011). We are not aware of any assessment of dead belowground OM pools following biomass manipulation treatments, but treatment effects are likely given the influence of slash on soil temperature (Devine and Harrington, 2007; Slesak et al., 2010b) and the strong control of soil temperature on root decomposition (Chen et al., 2000). Sanchez et al. (2006) also identified belowground root decomposition as a primary driver contributing to changes in soil C and N at other installations of the LTSP network, observing a strong control of regional climate and soil texture on the response. Given this, it is possible that these early effects are not indicative of the long-term response, as we did not account for all of the nutrient pools influenced by the experimental treatments and differences in total site pools may influence growth in later years. Continued monitoring and assessment of soil pools and stand growth in response to these and similar treatments in other studies is critical to understanding impacts of intensive forest management and its role in sustainable forestry.

5. Conclusions

Five-year response of mineral soil C and selected nutrient pools to experimental treatments of biomass removal and vegetation control indicate low potential for detrimental effects on mineral soil at these contrasting Douglas-fir sites. Use of less intensive management practices such as slash retention and limited vegetation control can increase pools of C and nutrients at sites where pre-existing pools are relatively low. However, the potential influence of increased pools on tree growth will be dependent on the relative degree to which water and nutrient availabilities limit growth, with the former likely more limiting at the Matlock site and the latter more limiting at the Molalla site. Although there is little indication of reduced productivity associated with use of intensive management practices at these two sites, uncertainty exists regarding long-term growth responses because treatments may have influenced nutrient storage in dead belowground OM pools which were not assessed in the present study. Continued monitoring and assessment of treatment effects at these and other installations of the LTSP network will be critical in determining the sustainability of intensive forest management.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.foreco.2011.07.021.

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