Soil and Douglas-fir (*Pseudotsuga menziesii*) foliar nitrogen responses to variable logging-debris retention and competing vegetation control in the Pacific Northwest

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Abstract: Experimental treatments of logging-debris retention (0%, 40%, or 80% surface coverage) and competing vegetation control (initial or annual applications) were installed at two sites in the Pacific Northwest following clearcutting Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) stands to assess short-term effects on tree N acquisition, soil N supply, and total soil N. Vegetation control treatments began in the first year after harvest, and logging-debris manipulations were installed 2 years after harvest. Annual vegetation control increased foliar N concentration and content in most years at both sites, which was associated with higher available soil N and increased soil water content. Logging-debris retention treatments had no detectable effect on any of the foliar variables or soil available N at either site. There were no treatment effects on total soil N at the site with relatively high soil N, but total soil N increased with logging-debris retention when annual vegetation control was applied at the site with a low initial soil N pool. Competing vegetation control is an effective means to increase tree N acquisition in the initial years after planting while maintaining soil N pools critical to soil quality. The effect of logging-debris retention on tree N acquisition appears to be limited during early years of stand development, but increased soil N with heavy debris retention at certain sites may be beneficial to tree growth in later years.

Résumé : Des traitements expérimentaux de rétention des déchets de coupe (couverture de 0 %, 40 % ou 80 % de la surface) et de maîtrise de la végétation compétitrice (application initiale ou annuelle) ont été mis en place dans deux stations du Pacific Northwest à la suite de la coupe à blanc de peuplements de douglas vert typique (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) pour évaluer les effets à court terme sur le prélèvement de N par les arbres, la disponibilité de N dans le sol et la quantité totale de N dans le sol. Les traitements de maîtrise de la végétation ont débuté au cours de la première année après la récolte et les traitements de rétention des déchets de coupe ont été effectués 2 ans après la récolte. La maîtrise annuelle de la végétation a augmenté la teneur et la concentration de N foliaire la plupart des années dans les deux stations. Cette augmentation était associée à une plus grande disponibilité de N dans le sol et à un contenu en eau du sol plus élevé. Les traitements de rétention des déchets de coupe n'ont eu aucun effet manifeste sur aucune des variables foliaires ou sur la disponibilité de N dans le sol dans aucune des stations. Les traitements n'ont eu aucun effet sur la quantité totale de N dans le sol dans la station où la quantité totale de N dans le sol était relativement élevée. Cependant, la quantité totale de N dans le sol a augmenté avec la rétention des déchets de coupe lorsque la maîtrise annuelle de la végétation était appliquée dans la station où les réserves initiales de N dans le sol étaient faibles. La maîtrise de la végétation compétitrices est un moyen efficace pour augmenter le prélèvement de N par les arbres durant les premières années après la plantation tout en maintenant les réserves de N dans le sol qui sont cruciales pour la qualité du sol. L'effet de la rétention des déchets de coupe sur le prélèvement de N par les arbres semble limité aux premières années du développement du peuplement mais, dans certaines stations, l'augmentation de la quantité de N dans le sol due à la rétention des gros déchets de coupe pourrait être bénéfique pour la croissance des arbres des années plus tard.

[Traduit par la Rédaction]

Introduction

Increasing demand for wood products in conjunction with a shrinking land base available for production (FAO 2006) creates expanding challenges for sustainable use of the forest resource for wood fiber and bioenergy. Intensively managed plantations have been suggested as a potential solution to this conundrum (Nambiar 1996; Fox 2000), but success of such an approach is dependent on maintaining soil functions critical to forest productivity and other ecosystem services.

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There is concern about the potential for intensive management to degrade soil (Powers et al. 1990; Jurgensen et al. 1997; Johnson et al. 2002), especially certain practices implemented at time of harvest and stand regeneration. However, results from both short- and long-term studies are equivocal, inhibiting development of effective policies and practices designed to maintain long-term soil productivity. Because of this, there is a need for improved understanding of site-specific response to management practices, as it is likely that effects on soil functions will vary with site factors (e.g., climate, plant community and crop species, soil physical and chemical properties, etc.) (Nambiar 1996; Fox 2000).

Harvest-related effects (i.e., during timber extraction and site preparation) on total soil N and supply of available N have the potential to alter short- and long-term site productivity given the well-documented N limitation to tree growth in many regions (Keeney 1980; Johnson 1992). Past studies have focused on removal of logging debris as a likely practice that would alter N cycling and availability to crop trees following harvest (Powers et al. 2005). Whole-tree harvesting removes between two and three times more N than bole-only harvests, which could reduce N availability for acquisition by succeeding crop trees. However, N mineralization generally increases following harvesting (Vitousek et al. 1992; Prescott 1997), and changes in N supply following logging-debris retention may be inconsequential to early tree growth (Smethurst and Nambiar 1990).

Logging debris can act as a source of N to soil via mobilization (e.g., simple dissolution, microbial degradation) and leaching of preexisting N compounds within debris or following colonization by N-fixing bacteria (Jurgensen et al. 1987). More common is for N to become immobilized during decomposition of logging debris characterized by a high C:N ratio (Carlyle et al. 1998; Laiho and Prescott 1999). Logging debris also modifies the soil environment, generally reducing soil temperature and either reducing or increasing soil moisture (McInnis and Roberts 1995; Devine and Harrington 2007). Soil temperature and moisture have large influences on N mineralization rates (Zak et al. 1999; Knoepp and Swank 2002), and changes in the soil environment following logging-debris retention could either stimulate or impede net N mineralization. Considering the multiple modes and potential interactions among them, it is not surprising that effects on total soil N and net N mineralization from logging-debris retention have been shown to be positive (Piatek and Allen 1999; Chen and Xu 2005), negative (Smethurst and Nambiar 1990; Blumfield and Xu 2003), or neutral (Carter et al. 2002; Li et al. 2003; Mendham et al. 2003). It is unclear what effect these changes may have on tree N acquisition, as total soil N and net N mineralization are at best indices of N availability to plants (Schimel and Bennett 2004), and only rarely have studies examined N supply and foliar N response concurrently (e.g., Smethurst and Nambiar 1990).

Competing vegetation control is a common site preparation practice following harvesting to increase crop tree survival and growth in the initial years after planting. Short-term effects of vegetation control on crop tree growth are generally positive and have been attributed to increased water availability (Morris et al. 1993; Roberts et al. 2005) or increased N availability (Smethurst and Nambiar 1989; Imo and Timmer 1999). However, effects of vegetation control on soil N pools and tree acquisition of N are not as well understood. Competing vegetation control has been shown to be an important factor controlling N loss following harvesting (Marks and Bormann 1972; Vitousek et al. 1979), which may cause a reduction in soil N if inputs (e.g., atmospheric deposition, N fixation) do not equal or exceed losses from leaching or if initial site N is low (Miller et al. 2006). Any reduction in soil N or potential N supply following vegetation control could limit future productivity of the stand when tree N demand increases.

Conifer forests of the Pacific Northwest are considered some of the most productive in the world due largely to a favorable climate. Many of these forests respond positively to N fertilization (Hermann and Lavender 1999), indicating limitations to growth associated with N availability. Forest management, if oriented towards maximizing crop tree productivity, is expected to become progressively more intensive in this region (Adams et al. 2005; Moores et al. 2007), potentially increasing the magnitude of logging-debris removal and the intensity and duration of vegetation control following harvest.

Our objectives were to determine the effect of logging-debris retention and competing vegetation control on (*i*) foliar N status in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) seedlings for 3 years following planting, (*ii*) soil available N (KCl extractable), potential net N mineralization, and volumetric soil water content to determine if these variables were related to Douglas-fir foliar response, and (*iii*) total soil N to assess the potential for longer-term effects on N supply. Two sites that differ in soil characteristics and annual precipitation were utilized to examine if the response to harvest practices varied with these factors.

Methods

Site characteristics

This study is part of a larger research project 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. Potential productivity as indicated with 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 Washington, approximately 45 km northwest of Olympia near the town of Matlock. The soil at Matlock is classified as a sandy-skeletal, mixed, mesic, Dystric Xerorthents formed in glacial outwash with slopes ranging from 0% to 3% (Grove series; Soil Survey Staff, Natural Resources Conservation Service, US Department of Agriculture, Lincoln, Nebraska (available from http://soils.usda.gov/technical/classification/osd/index.html [accessed 16 September 2005]). The Molalla site is located approximately 24 km northeast of the town of Molalla, Oregon, in the foothills of the western Cascades. The soil at Molalla is classified as fine-loamy, isotic, mesic Andic Dystrudepts formed in basic agglomerate residuum with slopes ranging from 2% to 40% (Kinney series; Soil Survey Staff). The regional climate is Mediterranean with mild, wet winters and warm, dry

Table 1. Site characteristics and selected pretreatment soil properties to a depth of 30 cm for study sites near Matlock, Washington, and Molalla, Oregon.

Characteristic or property	Matlock	Molalla
Location	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
50-year site index (m)	35.9	36.2
Soil texture (% sand, silt, clay)	65, 14, 21	37, 34, 29
Bulk density ($Mg{\cdot}m^{-3}$) (SE)[b]	1.45 (0.05)	0.98 (0.02)
Coarse fragments by mass (%) (SE)	65.8 (1.3)	32.2 (2.2)
Total soil N ($kg\ N{\cdot}ha^{-1}$) (SE)	2246 (88)	4338 (173)
Total soil C ($Mg\ C{\cdot}ha^{-1}$) (SE)	66.5 (3.6)	102.2 (4.7)

[a]Calculated from the PRISM model for period 1950–2005 (http://prism.oregonstate.edu).
[b]n = 8 for bulk density at Matlock, n = 24 for all others.

summers with periods of prolonged drought (>2 months) being common.

Experimental design and treatments

Sites were initially clearcut in March (Molalla) and April (Matlock) of 2003. Trees were hand-felled and removed with ground-based mechanized equipment. Following harvest, a 2 × 2 randomized complete block factorial design was installed at each site. The factors were harvest type (two levels: bole only or whole tree) and vegetation control (two levels: 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 (50 m × 60 m). 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 during September of 2003. Following this initial application, only those treatments assigned annual vegetation control were treated with herbicide in the spring of each year. Both sites were planted with plug+1, bare-root Douglas-fir seedlings in February (Molalla) and March (Matlock) of 2004 at a 3 m × 3 m spacing (1111 $trees{\cdot}ha^{-1}$). Each site was enclosed with a 2.5 m high fence to prevent browse damage to seedlings.

In March of 2005, three subplots within each of the eight whole-tree harvest treatment plots were identified for application of a subplot logging-debris retention treatment. Subplots encompassed a 2 m × 2 m area centered on a single planted Douglas-fir seedling. This design modification was chosen to reduce experimental error associated with treatment application (i.e., nonuniform logging-debris coverage at the whole-plot level; Meehan 2006) and spatial variability of soil properties. Use of only whole-tree treatment plots was arbitrary (i.e., compared with use of the bole-only plots), as we only had sufficient resources for 24 subplots at each site and could not address potential interaction between the whole-plot harvest factor and the subplot logging-debris factor given the level of replication. Woody logging debris was randomly applied at a visually estimated surface coverage of 0%, 40%, or 80% (±10%) to one of the subplots in each whole plot. For each assigned treatment application, logging debris 5.0–12.5 cm in diameter (mostly small branches without needles) located adjacent to the associated whole plot was added to preexisting logging debris until the assigned coverage was attained. In the case of the 0% treatment, all logging debris was removed from the subplot, but no attempt was made to remove legacy wood if present. Distribution of needles was relatively uniform across the whole plots (Meehan 2006), making it likely that similar amounts were present at each subplot. The overall modified design used in this study is a randomized complete block split-plot with one whole-plot factor (vegetation control treatment) and one subplot factor (logging-debris coverage).

Debris volume was estimated with the line-transect method (Brown 1974) and converted to a mass estimate (assumed wood density of 0.48 $Mg{\cdot}m^{-3}$). The corresponding mass of logging debris in the 40% and 80% coverages was 13 (SD = 5.2) and 30 (SD = 8.5) $Mg{\cdot}ha^{-1}$, respectively, at Matlock and 14 (SD = 5.2) and 29 (SD = 10.7) $Mg{\cdot}ha^{-1}$, respectively, at Molalla. Assuming a N concentration of 2.5 $g{\cdot}kg^{-1}$ in logging debris (Ares et al. 2007), N applied in the 40% and 80% coverages was 33 and 75 $kg{\cdot}ha^{-1}$, respectively, at Matlock and 35 and 73 $kg{\cdot}ha^{-1}$, respectively, at Molalla.

Soil sampling and analysis

Soil samples were collected at intervals over the 2005–2007 study period to assess treatment effects on available N, potential net N mineralization, and total soil N. Sampling for available N occurred in July of each year, for potential net N mineralization in April, July, and September of 2006 and in July of 2007, and for total soil N in July and October of 2005 and 2007, respectively. Mineral soil was collected to a depth of 20 cm at three locations in each treatment replication and composited in the field. Prior to sampling, the forest floor was removed from the soil surface to ensure that only mineral soil was collected for analysis. Soil morphology was relatively uniform within the 20 cm sample depth, which corresponded to the A horizon of the soil profile at each site. For periods when available N was assessed, samples were stored (<1 week) at 4 °C until processing; otherwise, samples were immediately air-dried, sieved to pass a 2 mm mesh, and then stored at 4 °C until analysis.

Available N (nitrate-N and ammonium-N) was measured on sieved (2 mm) soil samples that were extracted with 2 $mol{\cdot}L^{-1}$ KCl and then analyzed for ammonium-N and nitrate-N concentrations on a Lachat Quick Chem 4200 analyzer (Hach

Co., Loveland, Colorado). Potential N mineralization (sum of ammonification and nitrification) was assessed with an aerobic incubation approach. Initial inorganic N was extracted from air-dried soil with 2 mol·L^{-1} KCl as described above. Approximately 50 g of air-dried sieved soil was then incubated for 17 days at 25 °C and at a soil water potential of –22 kPa. Soil was initially leached with 100 mL of ultrapure water and again after 17 days. At the end of each incubation, inorganic N was extracted with 2 mol·L^{-1} KCl as described above for a final measurement. Salt and water solutions were analyzed for ammonium-N and nitrate-N concentration on a Lachat Quick Chem 4200 analyzer. Potential net N mineralization was calculated as the difference between the initial inorganic N extraction content and the sum of leachate and extraction contents measured during the incubation. For total soil N determination, approximately 5 g of air-dried soil was separated from the bulk sample and ground with a mortar and pestle to pass a 60 mesh sieve (0.25 mm). Samples were dried at 65 °C for 24 h and then dry combusted on a CNS analyzer (LECO CNS-2000 Macro Analyzer; LECO Corp., St. Joseph, Michigan) to determine total soil N concentration. All estimates of available N, N mineralization, and total N are reported on a dry (105 °C) soil mass basis.

Volumetric soil water content (SWC) was measured in situ at 4 h intervals from a depth spanning 20–40 cm below the soil surface at each replication with an ECH$_2$O sensor (Decagon Devices, Inc., Pullman, Washington). Sensors were installed with a bucket auger approximately 45 cm from each tree. Calibration equations were developed in the laboratory for each of the sites by comparing gravimetrically measured SWC with that measured by the sensor. For interpretation of treatment effects, SWC was averaged first by day and then by month to determine a mean SWC for each replication and treatment.

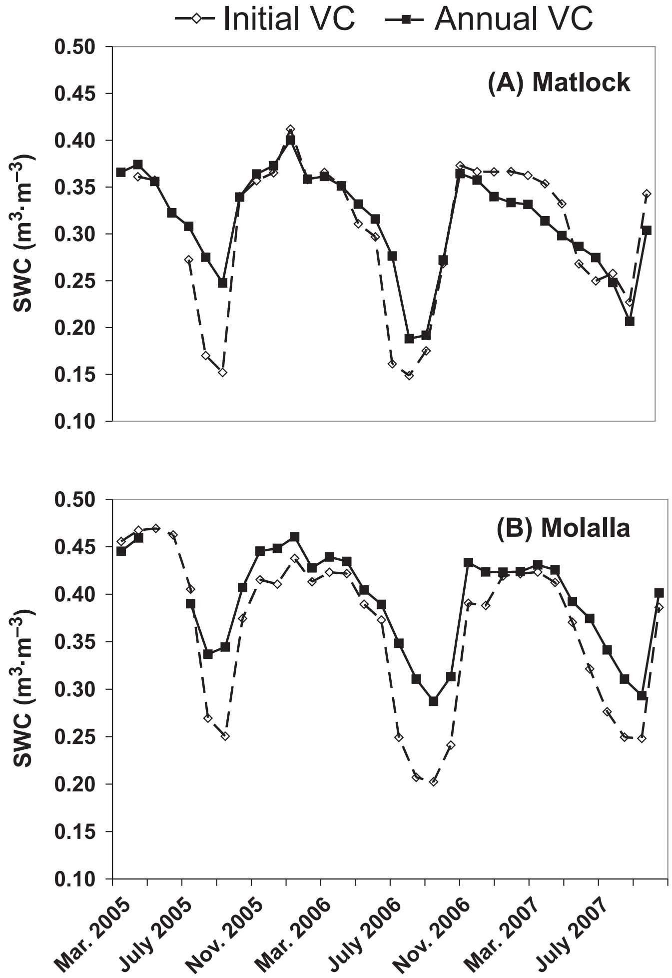
Foliar sampling and analysis

Foliage samples were collected in the fall of each year from three randomly chosen current-year shoots from the second whorl of each tree to determine treatment effects on foliar N concentration, N content, and needle mass. Samples were placed in paper bags, dried at 65 °C to a constant weight, and needles stripped from each shoot. A subset of 100 intact needles was separated from the bulk sample and weighed to determine oven-dry mass of 100 needles. The remaining sample was ground in a Wiley mill to pass a 1 mm sieve, dried at 65 °C until constant mass was attained, and then analyzed on a LECO CNS-2000 Macro Analyzer for N concentrations. Nitrogen content was calculated as the product of needle mass and N concentration.

Statistical analysis

A mixed model with repeated measures was used to assess treatment effects on SWC, net ammonification, net nitrification, net N mineralization, available N, and foliar variables. Block, whole-plot within block, and subplot nested within whole plot were modeled as random effects and the whole-plot factor, subplot factor, time variable (either year or sample period), and their interactions were modeled as fixed effects. Soil N concentrations in 2005 and 2007 were analyzed separately with a mixed model where block, whole-plot within block, and subplot nested within whole plot were modeled as random effects and both the whole-plot and subplot factors were modeled as fixed effects. Examination of the residuals for each variable indicated that assumptions of homogenous variance and normality were valid.

Fig. 1. Volumetric soil water content (SWC) as influenced by vegetation control (VC) treatments at (A) Matlock, Washington, and (B) Molalla, Oregon.



A priori orthogonal contrasts were performed to test for significant differences between (*i*) the absence and presence of debris (0% coverage versus the mean of the 40% and 80% coverages) and (*ii*) 40% and 80% logging-debris coverages. When significant interaction was observed for the time × whole-plot × subplot term, treatment effects were initially assessed by slicing with time and the whole-plot factor held constant followed by slicing with time and the subplot factor held constant. Tukey's honestly significant difference test was used to determine significant differences among means for the soil N data. An alpha level of 0.05 was used to assess statistical significance in all evaluations. All statistical analyses were performed with SAS version 9.1 (SAS Institute Inc., Cary, North Carolina).

Results

Volumetric SWC

At both sites and in each year, initial vegetation control treatments had lower volumetric SWC than the annual vege-

Table 2. Mean total soil N concentration (g N·kg soil^{-1}) to a depth of 20 cm by treatment and sample year at the Matlock, Washington, and Molalla, Oregon, sites.

	Logging-debris coverage (%)			Vegetation control	
Year	0	40	80	Initial	Annual
Matlock					
2005	2.05a (0.14)	2.44ab (0.14)	2.63b (0.14)	2.25 (0.11)	2.50 (0.11)
2007[a] initial vegetation control	3.02a (0.03)	2.13b (0.03)	3.34a (0.03)		
2007 annual vegetation control	2.48a (0.03)	2.93ab (0.03)	3.32b (0.03)		
Molalla					
2005	3.14 (0.37)	2.98 (0.37)	3.12 (0.37)	2.77 (0.46)	3.41 (0.46)
2007	4.02 (0.42)	3.53 (0.42)	4.01 (0.42)	3.54 (0.52)	4.17 (0.52)

Note: Means within a row followed by different letters are significantly different at $\alpha = 0.05$. SE of the mean in parenthesis; $n = 8$ for logging-debris treatments, $n = 12$ for competing vegetation control treatments.

[a]Significant logging-debris × vegetation control interaction ($p = 0.039$).

tation control during some summer months (from June to September) (Fig. 1). At Matlock during months where differences existed, mean SWC in the initial vegetation control treatment was 0.08, 0.05, and 0.02 m^3·m^{-3} lower than in the annual vegetation control treatment in 2005, 2006, and 2007, respectively. At Molalla, mean SWC in the initial vegetation control treatment was approximately 0.08, 0.09, and 0.06 m^3·m^{-3} lower than in the annual vegetation control treatment in 2005, 2006, and 2007, respectively.

Effects of logging debris on SWC were generally less pronounced than those for vegetation control treatments at both sites (data not shown). In many instances, a priori contrasts were not significant when ANOVA results indicated significant two- or three-way interaction among fixed variables. However, there was a main effect ($p = 0.027$) of logging-debris coverage on SWC at Molalla in 2006 where mean annual SWC content decreased in the order 0% (mean 0.40 m^3·m^{-3}, SE = 0.02), 80% (mean = 0.36 m^3·m^{-3}, SE = 0.02), and 40% coverage (mean = 0.33 m^3·m^{-3}, SE = 0.02). A similar nonsignificant pattern was observed in 2005 and 2007 ($p = 0.083$ and 0.303 for 2005 and 2007, respectively). Lower SWC in the 40% coverage was likely a result of greater rain interception relative to the 0% coverage combined with greater evaporation relative to the 80% coverage (i.e., mulch effect). At Matlock, there was no consistent effect of logging-debris retention on SWC in any year (data not shown).

Total soil N

There was a main effect of logging debris on total soil N at Matlock for both 2005 and 2007 ($p = 0.032$ in 2005 and $p = 0.013$ in 2007). In 2005, mean total soil N increased with logging-debris coverage, with N concentration in the 80% coverage being 0.6 g N·kg soil^{-1} (SE = 0.2) greater than the 0% coverage (Table 2). Interaction between logging debris and vegetation control was significant in 2007 ($p = 0.039$), mostly due to the 40% coverage being lower than the 0% and 80% coverages when initial vegetation control was applied. When annual vegetation control was applied, the 2007 pattern was the same as that observed in 2005. In contrast with Matlock, there was no effect of logging debris or vegetation control on total soil N for either sample period at Molalla ($p > 0.40$) and no apparent trend among means (Table 2).

Potential N supply and available N

There was significant interaction between incubation period and each of the treatments on net ammonification, net nitrification, and total net N mineralization at both sites (Table 3). Total net N mineralization (sum of net ammonification and nitrification) was lower in the annual vegetation control compared with the initial vegetation control at both sites during the July 2006 incubation, with an estimated reduction of 0.91 mg N·kg soil^{-1}·day^{-1} (SE = 0.42) at Matlock (Fig. 2*a*) and 1.60 mg N·kg soil^{-1}·day^{-1} (SE = 0.48) at Molalla (Fig. 2*b*). Two- and three-way interactions among logging-debris treatment and the remaining fixed treatment effects were associated with lower potential N supply in the 40% logging-debris coverage relative to the other coverages. For example, in the April 2006 period, net nitrification was lower in the 40% logging-debris coverage relative to the other coverages at Molalla, and net ammonification was significantly lower in the 40% coverage relative to the other logging-debris treatments at Matlock when initial vegetation control was applied (data not shown). These effects largely mirror those observed for total soil N pools during the 2007 sample period (Table 2).

Available nitrate-N and total available N were significantly higher when annual vegetation control was applied compared with the initial vegetation control during the July sampling period of each year (Table 4; Fig. 3). For all sample periods at Molalla, nitrate-N contributed more to total available inorganic N than ammonium-N when annual vegetation control was applied, but the same effect was only observed at Matlock in 2007. In contrast, ammonium-N dominated available total inorganic N when initial vegetation control was applied in most years. There was no effect of logging-debris retention on available N at either site or in any sample year (Table 4).

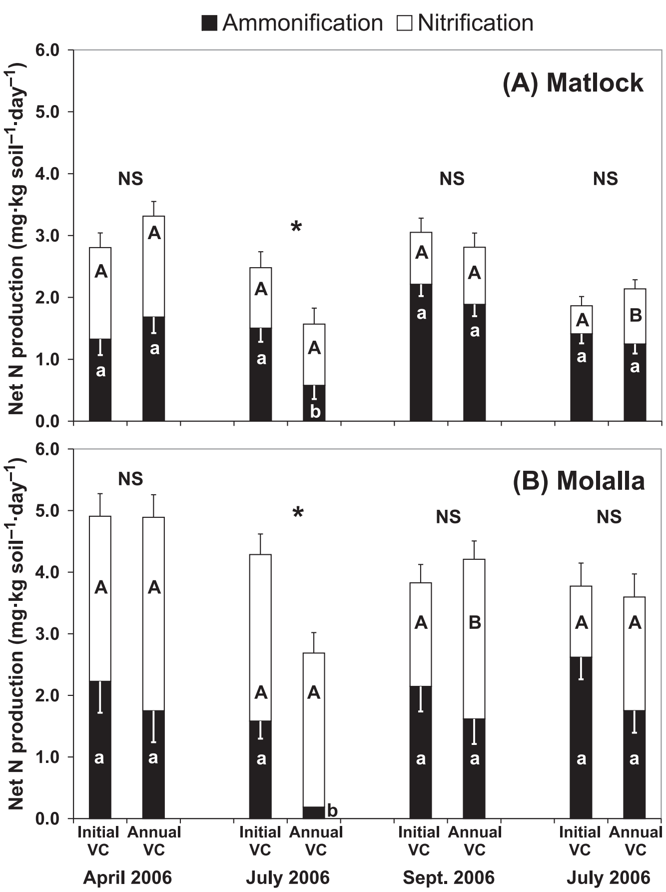
Foliar analysis

Needle N concentration and N content increased following annual vegetation control at both sites (Table 5). At Matlock, annual vegetation control increased needle N concentration by 5.5 and 3.4 mg N·g^{-1} in 2005 and 2007, respectively, in comparison with the initial vegetation control (Table 6). Increased concentration caused an increase in N content, which was 4.3 and 1.8 mg N higher with annual vegetation control in 2005 and 2007, respectively. At Mo-

Table 3. ANOVA *F* statistic probabilities for fixed treatment effects on net ammonification, net nitrification, and potential net N mineralization at the Matlock, Washington, and Molalla, Oregon, sites.

	Matlock			Molalla		
Effect	Ammonification	Nitrification	Net N mineralization	Ammonification	Nitrification	Net N mineralization
Vegetation control (df = 1,3)	0.278	0.503	0.809	0.147	0.320	0.430
Debris (df = 2,12)	0.394	0.219	0.320	0.237	0.182	0.085
Vegetation control × debris (df = 2,12)	0.179	0.512	0.330	0.595	0.067	0.540
Period (df = 3,53)	<0.001	<0.001	<0.001	<0.001	<0.001	0.016
Vegetation control × period (df = 3,53)	0.027	0.388	0.023	0.150	0.043	0.004
Debris × period (df = 6,53)	0.273	0.200	0.820	0.628	0.045	0.531
Vegetation control × debris × period (df = 6,53)	0.010	0.032	0.803	0.298	0.069	0.178

Fig. 2. Effect of vegetation control (VC) treatments on net ammonification, nitrification, and total N mineralization by incubation period at (A) Matlock, Washington, and (B) Molalla, Oregon. Means within a date with different letters are significantly different at $\alpha = 0.05$. Lowercase letters are for net ammonification and uppercase letters are for net nitrification. An asterisk and NS indicate a significant or nonsignificant difference, respectively, between total N mineralization for each date. Error bars are 1 SE of the mean.



lalla, needle N concentration was significantly higher following annual vegetation control in all years, with mean increases of 2.9, 5.0, and 3.5 mg $N{\cdot}g^{-1}$ in 2005, 2006, and 2007, respectively, when compared with the initial vegetation control (Table 7). For these same periods, annual vegetation control increased total needle N content at Molalla by 2.5, 1.0, and 1.7 mg N in 2005, 2006, and 2007, respectively. Needle mass was lower in the annual vegetation control treatment relative to the initial vegetation control treatment at Molalla in 2006, but the opposite response was observed at Matlock in 2005.There was no effect of logging-debris retention on any of the foliar variables at either site (Table 5). Needle N concentration and content tended to increase with logging-debris coverage at both sites in 2005 and 2006 but not in 2007 (Tables 6 and 7).

Discussion

Competing vegetation control

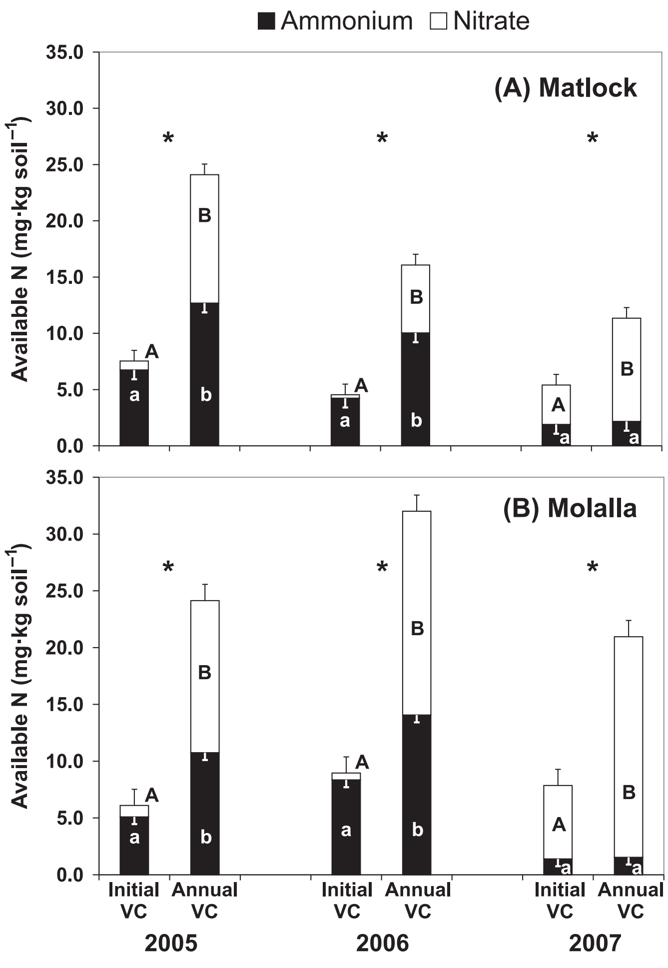
The benefits of vegetation control to crop tree growth can be generally attributed to decreased competition for available resources required for growth including light, water, and nutrients, but light is generally not limiting to growth immediately following harvesting (Harrington 2006). Application of annual vegetation control increased needle N status (concentration and content) at both sites in most years after planting. Such an effect has been noted in previous studies (Woods et al. 1992; Perie and Munson 2000; Harrington 2006), demonstrating the broad effectiveness of annual vegetation control to increase N acquisition in crop trees. Volume growth of trees receiving annual vegetation control at these sites was two to four times greater than that in initial vegetation control treatments (T.B. Harrington, unpublished data), indicating that the increase in N status was biologically significant.

Increased foliar N status could be a result of increased N available for uptake, increased N assimilation associated with increased available water, or a combination of both, as they generally occur in concert following vegetation control (Ludovici and Morris 1997; Powers and Reynolds 1999). Both SWC and available N were significantly affected by vegetation control at each site and in all years, thereby limiting evaluation of the causal factor contributing to the increase in foliar N status. For example, at both sites, the greatest difference in foliar N concentration (Tables 6 and 7) between the two treatments occurred in years with the greatest difference in SWC and available N (Figs. 1 and 3). The relative importance of each factor probably varies temporally, where available N is more important when soil water availability is sufficient and available soil water is

Table 4. ANOVA *F* statistic probabilities for fixed treatment effects on available ammonium-N, available nitrate-N, and total available N at the Matlock, Washington, and Molalla, Oregon, sites.

	Matlock			Molalla		
Effect	Ammonium-N	Nitrate-N	Total N	Ammonium-N	Nitrate-N	Total N
Vegetation control (df = 1,3)	0.012	0.006	0.008	0.010	0.002	0.001
Debris (df = 2,12)	0.205	0.071	0.261	0.260	0.758	0.408
Vegetation control × debris (df = 2,12)	0.872	0.156	0.283	0.413	0.342	0.230
Year (df = 2,36)	<0.001	0.001	<0.001	<0.001	0.001	<0.001
Vegetation control × year (df = 2,36)	<0.001	0.001	<0.001	<0.001	0.168	0.006
Debris × year (df = 4,36)	0.139	0.729	0.425	0.182	0.308	0.098
Vegetation control × debris × year (df = 4,36)	0.563	0.628	0.904	0.126	0.542	0.321

Fig. 3. Effects of vegetation control (VC) treatments on soil available N concentrations at time of sample collection in July of each year at (A) Matlock, Washington, and (B) Molalla, Oregon. Means within a year with different letters are significantly different at α = 0.05. Lowercase letters are for ammonium-N and uppercase letters are for nitrate-N. An asterisk indicates a significant difference in total available N for each year. Error bars are 1 SE of the mean.



more important during severe drought (Roberts et al. 2005). Nevertheless, variation in foliar N response among years at both sites indicates a complex interaction between soil water and available N on needle N status.

Relative differences between vegetation control treatments for SWC and N availability were similar between sites, but the absolute changes were greater at Molalla than at Matlock. These differences are not surprising given the much higher total pore space and total soil N present at Molalla compared with Matlock (Table 1). At Molalla, increased SWC and available N were observed in all years following annual vegetation control, but at Matlock, the magnitude of the effect decreased with each successive year (Figs. 1*a* and 3*a*). Volume growth data (T.B. Harrington, unpublished data) indicate that tree growth during the study period was greater at Matlock than at Molalla when annual vegetation control was applied, suggesting that the apparent decrease in resource availability at Matlock with time is accounted for by increased acquisition by crop trees. If true, this implies greater efficacy of annual vegetation control at Matlock than at Molalla, with increased resource availability being more fully utilized to maximize growth at Matlock. Such an effect may be associated with greater fine root production at Matlock in response to the generally lower resource availability inherent to soil at that site (Vogt et al. 1983; Lee et al. 2007).

Contrary to several studies that documented reductions in surface soil N following vegetation control (e.g., Busse et al. 1996; Miller et al. 2006), we found no evidence for a decrease in soil N when annual vegetation control was applied at these sites. The reduction in potential N mineralization following annual vegetation control during the April 2006 incubation could indicate detrimental effects on N supply, but there was no evidence of any decrease in any of the other incubation periods (Fig. 3). The lower N supply in the April 2006 incubation could be associated with a number of factors including temporal variation in the microbial community structure (Rogers and Tate 2001) or variation in organic matter quality (ease of mineralization) and quantity (Whalen et al. 2000). Whatever the cause, it appears that the potential for chronic reductions in soil N supply following annual vegetation control is low at these sites.

Logging-debris retention

Logging-debris from traditional harvests is composed of unmerchantable material including foliage, tops, and branches. Here, we experimentally manipulated the woody portion of logging debris in the whole-tree harvest treatment 1 year after planting to examine the effects on foliar N and soil N supply. Therefore, levels of needle debris were relatively low but uniform across all of the treatments. Following harvesting, N within logging-debris needles is likely available for tree uptake prior to that from woody material given the more rapid decomposition and higher N content

Table 5. ANOVA *F* statistic probabilities for fixed treatment effects on the dependent variables needle N concentration, needle N content, and mass of 100 needles at the Matlock, Washington, and Molalla, Oregon, sites.

	Matlock			Molalla		
Effect	Needle N concentration	Needle N content	Mass of 100 needles	Needle N concentration	Needle N content	Mass of 100 needles
Vegetation control (df = 1,3)	0.006	0.021	0.311	0.008	0.021	0.975
Debris (df = 2,12)	0.346	0.595	0.967	0.629	0.546	0.692
Vegetation control × debris (df = 2,12)	0.186	0.304	0.132	0.275	0.367	0.507
Year (df = 2,36)	<0.001	0.063	0.218	<0.001	<0.001	0.001
Vegetation control × year (df = 2,36)	<0.001	<0.001	0.051	0.036	0.186	0.005
Debris × year (df = 4,36)	0.747	0.568	0.634	0.578	0.154	0.076
Vegetation control × debris × year (df = 4,36)	0.363	0.725	0.906	0.158	0.097	0.527

Table 6. Mean needle N concentration, needle mass, and needle N content as affected by year, logging-debris coverage, and vegetation control treatment at the Matlock, Washington, site.

		Logging-debris coverage (%)			Vegetation control		
Foliar property	Year	0	40	80	Initial		Annual
N concentration (mg·g^{-1})	2005	13.5 (0.4)	14.2 (0.4)	14.1 (0.4)	11.2 (0.3)	*	16.7 (0.3)
	2006	13.3 (0.8)	14.2 (0.8)	13.7 (0.7)	13.5 (0.7)		13.9 (0.6)
	2007	12.0 (0.60)	12.8 (0.6)	11.5 (0.6)	10.4 (0.5)	*	13.8 (0.5)
Needle mass (g)	2005	0.50 (0.03)	0.48 (0.03)	0.50 (0.03)	0.44 (0.03)	*	0.55 (0.03)
	2006	0.40 (0.06)	0.44 (0.06)	0.48 (0.06)	0.45 (0.05)		0.43 (0.05)
	2007	0.51 (0.05)	0.52 (0.05)	0.47 (0.04)	0.49 (0.04)		0.51 (0.04)
N content (mg)	2005	6.9 (0.5)	7.0 (0.5)	7.2 (0.5)	4.9 (0.5)	*	9.2 (0.5)
	2006	5.5 (0.9)	6.4 (0.9)	6.6 (0.8)	6.4 (0.8)		5.9 (0.7)
	2007	6.2 (0.8)	6.8 (0.8)	5.5 (0.8)	5.3 (0.7)	*	7.1 (0.7)

Note: SE of the mean in parenthesis; *n* = 12 for vegetation control, *n* = 8 for logging debris. Needle mass based on 100 needles.An asterisk indicates a significant difference between vegetation control treatments within a year.

Table 7. Mean needle N concentration, needle mass, and needle N content as affected by year, logging-debris coverage, and vegetation control treatment at the Molalla, Oregon, site.

		Logging-debris coverage (%)			Vegetation control		
Foliar property	Year	0	40	80	Initial		Annual
N concentration (mg·g^{-1})	2005	13.2 (0.8)	13.5 (0.8)	13.7 (0.8)	12.0 (0.6)	*	14.9 (0.6)
	2006	11.4 (0.6)	12.5 (0.6)	13.0 (0.6)	9.8 (0.5)	*	14.8 (0.5)
	2007	16.8 (0.7)	16.4 (0.7)	16.8 (0.7)	14.9 (0.6)	*	18.4 (0.6)
Needle mass (g)	2005	0.49 (0.05)	0.58 (0.05)	0.53 (0.05)	0.50 (0.04)		0.57 (0.04)
	2006	0.43 (0.04)	0.46 (0.04)	0.42 (0.04)	0.48 (0.04)	*	0.39 (0.04)
	2007	0.45 (0.03)	0.40 (0.03)	0.42 (0.03)	0.42 (0.03)		0.43 (0.03)
N content (mg)	2005	6.4 (0.7)	7.8 (0.7)	7.5 (0.7)	6.0 (0.6)	*	8.5 (0.6)
	2006	4.7 (0.3)	5.5 (0.3)	5.4 (0.3)	4.7 (0.2)	*	5.7 (0.2)
	2007	7.5 (0.5)	6.6 (0.5)	7.1 (0.5)	6.2 (0.4)	*	7.9 (0.4)

Note: SE of the mean in parenthesis; *n* = 12 for vegetation control, *n* = 8 for logging debris. Needle mass based on 100 needles. An asterisk indicates a significant difference between vegetation control treatments within a year.

of foliage (Ares et al. 2007). Given this, our assessment primarily evaluates indirect effects of logging debris on soil N availability and tree N uptake (e.g., soil mineralization response to modified temperature and moisture and greater uptake with increased SWC) rather than evaluation of logging debris (i.e., needles) as an immediate, direct N source. Meehan (2006) determined that logging-debris needles immobilized N for at least 2 years after harvest at these sites, suggesting that logging debris was a small net direct source of N to trees during the study period.

With few exceptions, the lack of significant effects of logging-debris treatments on foliar N characteristics, available N, and potential net N mineralization indicates that logging-debris retention has little direct influence on tree N nutrition and N supply at these sites in the initial years after planting. These results generally agree with past studies that have found no significant effect of logging-debris retention on either foliar N status (Roberts et al. 2005; Kranabetter et al. 2006; Thiffault et al. 2006) or net N mineralization (Fox et al. 1986; Carter et al. 2002; Li et al. 2003). However, a large amount of logging debris is still present at the sites, making it possible that available N or foliar N status could be modified at longer time periods than assessed here. For example, Piatek and Allen (1999) found significantly lower N mineralization in whole-tree harvests compared with bole-only harvests 15 years after harvest, even though no clear difference was observed 2 years after harvest at the same site (Vitousek and Matson 1985). Similarly, Olsson et al. (2000) found a significant reduction in foliar N concentration following whole-tree harvesting compared with bole-only harvesting at sites in Sweden 8–10 years after harvest but not at later sample periods (up to 24 years). Logging debris could influence N availability in the future, but the likelihood of such a possibility is probably low given the large amount of N present in the mineral soil at these sites (Table 1).

In a summary of 5-year findings from 19 Long-Term Soil Productivity network sites across five regions in the United States, Sanchez et al. (2006) found no effect of logging-debris removal on total soil N, but there were significant increases in total soil N following harvesting that were attributed to root decomposition and (or) adsorption of dissolved organic matter to mineral surfaces. Our results support those of Sanchez et al. (2006), as we observed a general increase in total soil N concentration during the 3-year study period, and the initial measures in 2005 were also higher than preharvest levels in 2003 (increases of 1.9 and 2.4 g N·kg $soil^{-1}$ for Matlock and Molalla, respectively; Meehan 2006). The additional increase in total soil N when logging debris was retained at Matlock may be due to soil mineralogy at that site. Strahm and Harrison (2007) found high quantities of allophone and imogolite in the soil at Matlock, which have been shown to adsorb large amounts of dissolved organic matter (Parfitt 1980; Harsh et al. 2002). Given the magnitude of the increase in total soil N concentration and the relatively small amount of N in logging debris, the source of increased total N is likely from decomposition of roots or the forest floor.

Conclusions

Annual application of competing vegetation control was an effective means to increase availability of soil water and N for crop tree growth at these sites. Greater apparent efficacy of annual vegetation control at the relatively low-N Matlock site indicates that this practice may be especially appropriate at sites with inherently low resource availability. There was no evidence of a decrease in total soil N or chronic reductions in soil N supply, indicating low potential for annual vegetation control to negatively affect N-related aspects of soil quality at these sites.

The lack of any effect of logging-debris manipulations applied 2 years after harvest on foliar N status and available soil N indicated a relatively small influence of logging debris on crop tree N acquisition in the initial years after planting. The increase in total soil N at each site following harvesting and additional increases at Matlock associated with logging-debris retention could result in greater N acquisition by crop trees if maintained over the course of the rotation. However, the stability and availability of increased soil N is unclear given the limited duration of this study, and effort should be made to determine the long-term biological significance of the short-term changes observed here.

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