This file was created by scanning the printed publication. Text errors identified by the software have been corrected: however some errors may remain.

Dissolved carbon and nitrogen leaching following variable logging-debris retention and competing-vegetation control in Douglas-fir plantations of western Oregon and Washington

Robert A. Siesak, Stephen H. Schoenholtz, Timothy B. Harrington, and Brian D. Strahm

Abstract: We examined the effect of logging-debris retention and competing-vegetation control (CCC, initial or annual applications) on dissolved organic carbon (DOC), dissolved organic nitrogen, and nitrate-N leaching to determine the relative potential of these practices to contribute to soil C and N loss at two contrasting sites. Annual CVC resulted in higher soil water nitrate-N concentration and flux, with the magnitude and duration of the effect greatest at the high-N site. Most of the increase in nitrate-N at the low-N site occurred in treatments where logging debris was retained. Dissolved organic nitrogen increased at the high-N site in March of each year following annual CVC; but the contribution of this increase to total N concentration was small (2% - 4% of total N flux). There was no effect of logging debris retention or CVC treatment on soil water DOC concentrations, indicating that DOC inputs from logging debris and competing vegetation were either retained or consumed in the mineral soil. The estimated increase in leaching flux of dissolved C and N associated with the treatments was low relative to total soil pools, making it unlikely that loss of these elements via leaching will negatively affect future soil productivity at these sites.

Resume: Nous avons etudie l'effet de la retention des dechets de coupe et de la maitrise de la vegetation cornpetitrice (applications initiale ou annuelles) sur Ie carbone organique dissous (COD), l'azote organique dissous et le lessivage de N sous forme de nitrate p.our determiner la contribution relative de ces pratiques à la perte de C et N dans le sol de deux: stations contrastees, La maitrise annuelle de la vegetation a entraine une concentration et un flux accrus de nitrate dans le sol dont l' ampleur et la duree etaient les plus elevees dans la station riche en N. La majeure partie de I' augmentation du nitrate dans la station pauvre en N est survenue dans les traitements oii les dechets de coupe avaient ete conserves. L'azote organique dissous a augmente dans la station riche en N au mois de mars de chaque annee à la suite de la maitrise annuelle de la vegetation mais la contribution de cette augmentation à la concentration totale de N etait faible (2 % - 4 % du flux total de N). La retention des dechets de coupe et la maitrise de la vegetation n'ont pas eu d'effet sur la concentration de COD dans l'eau du sol, indiquant que les apports de COD provenant des dechets de coupe et de la vegetation competitrice ont ete fixes ou utilises dans Ie sol mineral. L'augmentation estimee du lessivage de C et N dissous associee aux traitements etait faible relativement aux pools totaux dans le sol, de telle sorte qu'il soit peu probable que la perte de ces elements par lessivage ail un impact negatif sur la productivite future du sol dans ces stations.

[Traduit par la Redaction]

Introduction

Intensive forest management has posed unanswered questions for maintenance of soil quality and long-term productivity for decades (e.g., Boyle and Ek 1972; Weetman and Webber 1972; Wells and Jorgensen 1979). Increasing demands for biomass and wood products coupled with a reduction in land available for production (FAO 2006) have accelerated the debate on the potential for a reduction in soil productivity and subsequent declines in forest productivity over the long-term (Nambiar 1996; Fox 2000). Past research has focused on retention of soil carbon (C) (as a surrogate for soil organic matter, OM) and nitrogen (N) to maintain soil productivity given the critical role of soil OM for nutrient supply, gas exchange, and water-holding capacity (Powers et al. 1990) and the common N limitation of tree growth in many areas of North America (Keeney 1980; Johnson 1992). Logging debris contains significant amounts of C and N, and there is concern that increased biomass removal (e.g., utilization of all logging-debris residue) could

Received 12 September 2008. Accepted 3 May 2009. Published on the NRC Research Press Web site at cjfr.nrc.ca on 12 August 2009.

R.A. Slesak.[1] Oregon State University, College of Forestry, 204 Peavy Hall, Corvallis, OR 97331, USA.
S.H. Schoenholtz. Virginia Polytechnic Institute and State University, Virginia Water Resources Research Center, 210 Cheatham Hall, Blacksburg, VA 24061, USA.
T.B.Harrington. USDA Forest Service, Pacific Northwest Research Station, 3625 93rdAvenue SW, Olympia, WA 98512, USA.
B.D. Strahm. Cornell University, Department of Ecology and Evolutionary Biology, E343 Corson Hall, Ithaca, NY 14853, USA.

[1]Corresponding author (e-mail: slesa003@umn.edu).

result in reduced pools of soil C and N. Several long-term studies (>10 years) have found no lasting effect of logging-debris retention on total pools of soil C and N following harvest (Olsson et a1. 1996; Johnson et a1. 2002), including summary findings from 26 installations in the Long Term Soil Productivity (LTSP) network that covered a wide range of site and climate conditions (Powers et al. 2005).

The above results contrast with those from several studies that measured large inputs of dissolved organic C (DOC) and dissolved organic N (DON) to mineral soil from logging debris following harvesting (Mattson et al. 1987; Qualls et a1. 2000; Robertson et al. 2000), which presumably have the potential to increase C and N in the mineral soil. However, there is also potential for the inputs to be offset by increased outputs via microbial respiration, denitrification, or leaching of DOC and dissolved forms (inorganic and organic) of N. Total soil pools of C and N are often large relative to flux changes associated with harvesting, making detection of any change in soil pools difficult (Homann et a1. 2001). Assessment of C and N fluxes following logging-debris retention may help to clarify the net effect of logging-debris retention on pools of C and N and provide an indication of the potential for long-term impacts following multiple harvests.

Several studies have shown increased N leaching following harvesting (e.g., Vitousek et al, 1997), but the effect of logging-debris retention on this increase is unclear: it has been shown to increase (Hendrickson et a1. 1989; Strahm et a1. 2005), to decrease (Vitousek and Matson 1985; Carlyle et a1. 1998), or to have no detectable effect (Mann et al. 1988) on N leaching. Variability in response is most likely a function of site-specific factors (Gundersen et al. 2006), underlying a need to evaluate potential effects of logging-debris retention on N leaching at a variety of site conditions. Nitrogen leaching following harvesting is generally dominated by inorganic N forms (primarily nitrate), but there is also potential for N loss as DON (Sollins and McCorison 1981), which may also be modified by logging debris. Carlyle et a1. (1998) found a 25%-30% reduction in DON leaching when logging debris was retained following harvesting in southeastern Australia, but Strahm et al. (2005) observed no effect of logging-debris retention on DON in southwestern Washington. Soil N concentration at the Australia site was low (sandy soil, 1.1 $g\ N \cdot kg^{-1}$ at 0-15 cm depth), but that at the Washington site was high (silt loam soil, 4.6 $g\ N \cdot kg^{-1}$ at 0-12 cm depth), possibly indicating that the response may be a function of preharvest soil N pools. However, the differing response could be caused by any number of factors; because there is generally a poor understanding of processes that govern DON production and loss from soil (Kalbitz et al. 2000; McDowell 2003).

Potential for increased DOC loss following harvesting appears to be lower than for N. Qualls et al (2000) concluded that DOC inputs from logging debris following harvesting of a deciduous forest in the southeastern United States were effectively retained in the mineral soil, and a similar conclusian was reached by Piirainen et al. (2002) following harvest of a coniferous forest in Finland. Others have noted no general effect of harvesting on DOC (McDowell and Likens 1988) or a general decrease in DOC export (Meyer and Tate 1983). These studies generally indicate low potential for DOC leaching following logging-debris retention, but the effect of logging-debris removal is less clear. Removal of logging debris causes an increase in soil temperature and a change in soil moisture (e.g., Roberts et a1. 2005; Devine and Harrington 2007), which are likely to modify rates of microbial activity and DOC production in soil. In the LTSP summary findings, Powers et a1. (2005) and Sanchez et a1. (2006) attributed increased soil C and N following harvesting to rapid decomposition of the root system of the previous stand, with the effect most pronounced when all surface OM was removed, presumably because of increased soil temperature. Greater decomposition when logging debris is removed could result in greater DOC leaching, but this possibility has not been evaluated.

Other management practices at time of harvest and the initial years following planting have potential to influence C and N loss via leaching. Competing-vegetation control (CVC) with herbicide application is commonly used in the initial years after planting to increase crop tree survival and growth (Newton and Preest 1988; Harrington et al. 1995). Vegetation is an important factor controlling N retention following harvesting (Marks and Bormann 1972; Vitousek et al. 1979), and several studies have documented elevated nitrate leaching following CVC (Briggs et al. 2000; Smethurst and Nambiar 1995; Vitousek and Matson 1985). Nitrogen loss via leaching following CVC may cause a reduction in soil N if losses are large, inputs (e.g., atmospheric deposition, N fixation) are low, or initial soil N pools are small (Miller et al. 2006).

Competing-vegetation control also has strong potential to alter production and transport of DOC. Both aboveground and belowground litter contribute to DOC production and flux through mineral soil, but the relative contribution of each to DOC loss at deep soil horizons is poorly understood (Kalbitz et a1. 2000). Several recent studies have highlighted the importance of belowground production (e.g., root turnover or exudation) to DOC in mineral soil (Froberg et al. 2007; Giesler et a1. 2007; Uselman et al. 2007). These studies indicate practices that reduce root inputs to mineral soil, such as CVC, may cause a concurrent reduction in DOC leaching. However, CVC also modifies the soil environment and increases soil water flux via a reduction in evapotranspiration (ET) (Fleming et a1. 1994), so the net effect of CVC on DOC flux could be to increase C loss from soil. There is potential for CVC to modify DOC leaching following harvesting, but no experimental studies have been performed to examine this possibility.

The Douglas-fir *(Pseudotsuga menziesii* (Mirb.) Franco) forests of the Pacific Northwest are some of the most productive in the world, and management intensity is expected to increase in the future, primarily in intensively managed plantations (Adams et a1. 2005; Moores et al. 2007). It is likely that biomass removal will increase (magnitude and frequency), and the use of CVC will probably be more frequent and of longer duration. There is a need to understand the main and interactive effects of these practices on Nand C leaching across a range of site conditions, but only a few experimental studies have been performed in the region (e.g., Strahm et a1. 2005). We focus on leaching recognizing that changes in soil C and N following harvesting are often difficult to detect; estimates of leaching may provide a better indication of long-term effects assuming that leaching losses at future harvests are similar and that inputs remain constant. We hypothesized that there would be greater N loss when competing vegetation was controlled annually, that greater loss would still be detectable 2 years after harvesting, and that logging-debris retention would modify the response. Our objectives were to determine the effect of increasing logging-debris retention in combination with either initial or annual applications of on *(i)* DOC and N (nitrate-N, ammonium-N, and DON) solution concentrations and fluxes below the rooting zone to determine the potential for leaching and *(ii)* production of water-leachable DOC and N under controlled laboratory incubations to infer the causal mechanisms contributing to the results observed in situ. Two sites with contrasting soil properties and annual precipitation were used to determine if observed effects varied between sites.

Methods

Site characteristics

This study is part of a larger research project initiated at two sites in 2003 to assess effects of logging-debris retention and CVC treatments on soil properties, nutrient cycling, and Douglas-fir growth. Both study sites are affiliates of the LTSP network (powers et al. 1990). Potential productivity (Douglas-fir site index) is similar between the sites, but large differences exist in precipitation and soil properties (Table 1). The first site (hereafter referred to as Matlock) is located on the Olympic Peninsula in Washington, approximately 45 km northwest of Olympia near 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% (US Department of Agriculture, Natural Resources Conservation Service, Soil Survey Staff, Lincoln, Nebraska; http://soils.usda.gov/technical/c1assification/osd/index.html). The second site (hereafter referred to as Molalla) 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 fine-loamy, isotic, mesic Andie Dystrudepts, formed in basic agglomerate residuum with slopes ranging from 2% to 40% (US Department of Agriculture, Natural Resources Conservation Service, Soil Survey Staff, Lincoln, Nebraska). The regional climate is Mediterranean, with mild, wet winters and dry, warm summers with periods of prolonged drought (>2 months) being common. Precipitation falls mostly as rain, with some snowfall during winter months.

Experimental design and treatment application

Sites were initially clear-cut with chainsaws in March (Molalla) and April (Matlock) 2003. Trees were removed with ground-based mechanized equipment along marked machine trails that were evenly distributed across plots to minimize experimental error associated with soil disturbance. Following harvest, a 2 x 2 randomized complete block factorial design was installed on 0.3 ha plots (50 m x 60 m) replicated four times at each site. The factors were harvest type (two levels: bole only or whole tree) and CVC (two levels: initial CVC or annual CVC). 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 with annual CVC were treated with herbicides in the spring of each year. Annual CVC treatments included broadcast applications of glyphosate, clopyralid, or atrazine to control herbaceous species and directed applications of triclopyr to control woody species. Mean competing-vegetation coverage was 65% and >90% at Matlock and Molalla, respectively, when initial CVC was applied but was <5% following annual CVC (T.B. Harrington, unpublished data). Both sites were planted with plug+l bare-root Douglas-fir seedlings in February (Molalla) and March (Matlock) 2004 at a 3 m x 3 m spacing (1111 trees·ha^{-1}), Volume growth of planted Douglas-fir seedlings that received annual CVC was between two and three times greater than that with initial CVC during the study period (T.B. Harrington, unpublished data). Each site was enclosed with a 2.5 m high fence to prevent browse damage to seedlings.

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

Characteristic or property	Molalla	Matlock
Latitude (°N)	45.196	47.206
Longitude (°W)	122.285	123.442
Elevation (m)	549	35
Mean annual temperature (°C)	11.2	10.7
Mean annual precipitation (cm)[a]	160	240
Site index at 50 years (m)	36.2	35.9
Soil texture (% sand, silt, and clay)	37, 34, 29	65, 14, 21
Bulk density (Mg·m^{-3})[b]	0.98±0.02	1.45±0.05
Coarse fragments by mass (%)[b]	32.2±2.2	65.8±1.3
Total soil N (kg·ha^{-1})[b]	4338±173	2246±88
Total soil C (Mg·ha^{-1})[b]	102.2±4.7	66.5±3.6

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

In March 2005, three subplots within each of the whole-tree harvest treatment plots (n = 8) were identified for application of a subplot logging debris retention treatment. Subplots encompassed a 2 m x 2 m area centered on a single planted Douglas-fir seedling. This design modification was chosen to reduce experimental error associated with treatment application (e.g., discontinuous logging-debris coverage at the whole-plot level) and spatial variability of soil properties.. Use of the whole-tree treatment plots was arbitrary (i.e., compared with use of the bole-only plots, which were excluded from analysis) because 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 factor given the level of replication. Woody logging debris was applied at a visually estimated surface coverage of 0%, 40%, or 80% to a randomly assigned subplot within each whole plot. For each assigned treatment application, logging debris 5.0-12.5 cm in diameter (mostly branches without needles) that was within the associated whole plot was stacked in an approximate criss-cross fashion (for stability until the assigned coverage (±10% by visual determination) was reached). In the case of the 0% treatment, all logging debris was removed from the subplot, but no attempt was made to remove preharvest legacy wood if present. The overall modified design used in this study is a randomized complete block split plot with one whole-plot factor (CVC treatment) and one subplot factor (logging-debris coverage).

Lysimeter installation and soil water collection

Tension lysimeters were fabricated with high-flow (100 kPa) porous ceramic cups (maximum pore size of 2.5 um; Soil Moisture Corp., Santa Barbara, California) and polyvinyl chloride tubing. One lysimeter was installed to a depth of 60 cm in the center of each subplot replication in early October 2005. The 60 cm depth was chosen to approximate the zone below which most roots of Douglas-fir seedlings would have occupied in the first 4 years after planting to limit the possibility of any root uptake at or below the soil water sampling depth. A steel tube with the same diameter as the lysimeter was hammered into the ground at a 45° angle to limit soil disturbance above the ceramic cup. The steel tube was removed from the hole, and a slurry was made with sieved soil from the bottom 10 cm of each hole. The slurry was guided to the bottom of each hole, and lysimeters were seated firmly to create a tight seal between the ceramic cup and soil. Bentonite pellets were placed around the outer 5 cm of each lysimeter to a depth of 2.5 cm to inhibit preferential flow along the side of the lysimeter tube.

Lysimeters were primed and purged (sample discarded) monthly for 2 months prior to initiation of sample collection. Soil water samples were collected once a month at each site beginning in December 2005 at Molalla and in January 2006 at Matlock. Sampling continued into the 2007 growing season until summer drought conditions prevented further soil solution collection. A 50 kPa vacuum was applied with a hand pump 2 days before collection. Lysimeters were purged of any water between collection periods. Following collection, samples were. placed on ice, transported to the laboratory, and stored at 4 °C until analysis. Samples were typically analyzed the day after collection, but some samples were stored for up to 2 days before analysis. Lysimeter data are reported as concentrations ($mg{\cdot}L^{-1}$) and mass flux ($kg{\cdot}ha^{-1}.year^{-1}$).

Soil sampling and incubations

Soil samples were collected at four periods at each site and incubated under controlled laboratory conditions to assess treatment effects on DOC, inorganic N (nitrate-N and ammonium-N), and DON production without the confounding influence of vegetation and in situ differences in soil microclimate among treatments. Samples were collected in April, July, and September 2006, and July 2007. At each sample period, mineral soil was collected to a depth of 20 cm at three random locations in each replication and composited in the field, taking care to remove any large organic material prior to compositing. Samples were collected with a volumetric core sampler attached to a slide hammer. Composite samples were placed in plastic bags on ice and transported that day to the laboratory for processing. Samples were air-dried, sieved to pass a 2 mm mesh, and then stored at 4 °C until analysis.

Approximately 50 g of air-dried sieved soil was placed in a microlysimeter constructed of benchtop filtration units (Falcon filter; Becton Dickinson Labware, Franklin Lakes, New Jersey) as described by Nadelhoffer (1990). Samples were incubated for 17 days at 25°C and a soil water potential of -22 kPa. Soil in each incubation unit was initially leached with 100 mL of ultrapure water by applying a tension of -22 kPa with the use of a vacuum pump. Water was allowed to equilibrate with soil for 30 min before the vacuum was applied. Incubation unit mass was periodically checked during the incubation period, and ultrapure water was added as needed to maintain the initial soil water content following wetting. After 17 days, soil was leached again with 100 mL of ultrapure water as described above. Leachate volume was measured with a graduated cylinder, and an aliquot was separated for chemical analyses. Incubation units without soil were processed in the same manner to serve as controls. Final incubation leachate and lysimeter samples were analyzed for inorganic N (nitrate-N and ammonium-N), total N, and DOC. Nitrate-N and ammonium-N were determined calorimetrically on a Lachat Quick Chern 4200 analyzer (Hach Co., Loveland, Coloarado). Dissolved organic C and total dissolved N (TDN) were determined on a Shimadzu total organic carbon analyzer (TOC-VCSH) attached to a total N measuring unit (TNM-l) (Shimadzu Corp., Columbia, Maryland). Dissolved organic N was calculated as the difference between TDN and inorganic N (sum of nitrate-N and ammonium-N), Detection limits were 0.02 and 0.04 $mg{\cdot}L^{-1}$ for nitrate-N and ammonium-N, respectively, and 0.05 $mg{\cdot}L^{-1}$ for DOC and TDN. Values below detection limits were assumed to be zero. Leachate concentration was multiplied by leachate volume to determine mass of water-leachable DOC and N forms removed at the end of the incubation. Incubation leachate values are reported on a dry soil mass basis ($mg{\cdot}(kg\ soil)^{-1}$ $*17\ days^{-1}$).

Soil water flux estimation

Monthly soil water budgets were calculated for estimation of C and N mass flux below the rooting zone via leaching at each site. Net soil water flux was calculated as the difference between total monthly precipitation and potential ET estimated with the Thomthwaite method (Dunne and Leopold 1978). Precipitation and mean monthly air temperature (measured at 0.25 m above the soil surface) were measured daily at each site with a meteorological station located approximately at the center of each experimental area. Daily estimates were summed (precipitation) or averaged (air temperature) to determine total monthly precipitation and mean monthly air temperature at each site, which were then used to estimate soil water flux. When precipitation exceeded potential ET (i.e., a positive soil water flux), we assumed the net difference in water moved vertically below the rooting zone. This assumption is valid if soil water storage remains at or in excess of field capacity during the rainy season, which is likely at these sites given the frequent rainfall and low temperature that occur during the rainy season (i.e., winter). In addition, the Thornthwaite method does not account for differences in vegetation abundance or form on potential ET, possibly leading to an underestimation of potential ET and overestimation of soil water flux (Dunne and Leopold 1978). Given the regional climate where rainfall is greatest when vegetation growth is low, we assumed that any error arising from unaccounted vegetation effects would be low. We did not adjust the water budget for surface runoff because infiltration rates are generally much higher than maximum precipitation rates in this region and, at no time, has standing or flowing water been observed at the soil surface.

Statistical analysis

A mixed modei approach with repeated-measures analysis of variance was used to assess treatment effects for both in situ soil water and incubation leachate. 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 month or sample period), and their interactions were modeled as fixed effects. For each dependent variable at each site, the covariance matrix used for repeated measures was identified by fitting the model to all possible candidate matrices and then choosing the matrix that resulted in the lowest fit criteria statistic. Examination of the residuals after model fit indicated that assumptions of homogenous variance and normality were valid for incubation data and in situ nitrate-N concentration, but the variables DOC, DON, and TDN determined in situ required logarithmic transformations to meet assumptions. of homogenous variance. For those variables, mean values were back-transformed and, thus, represent median values as reported. Arnmonium-N concentrations were almost always below detection limits and were not statistically analyzed for in situ measurements. Flux estimates were calculated as the product of water flux and nutrient concentration. Because of missing data associated with lysimeter failure (i.e., sample collection did not hold a vacuum), we were unable to sum e and N flux within each of the replications and, therefore, were unable to test if total annual flux was different between treatments. Annual estimates when reported are the annual sum of the monthly product of the mean or median concentration and estimated soil water flux within a given treatment.

When significant interaction was observed between the subplot factor and time, a priori orthogonal contrasts were performed to test for significance of difference between *(i)* the absence and presence of debris (0% coverage vs. the mean of the 40% and 80% coverage treatments), and *(ii)* the 40% and 80% logging-debris coverage treatments. When significant interaction was observed for the time x whole plot x subplot term, treatment effects were initially assessed by slicing with time (either period or month) held constant to determine time periods with significant differences, followed by slicing with either the subplot or whole-plot factor held constant depending on the significance of lower order interactions. For some of the incubation data, Tukey's honestly significant difference test was used to determine significant differences among means. An alpha level of 0.05 was used to assess statistical significance in all evaluations. All analysis was performed in SAS version 9.1 (SAS Institute Inc. 2005).

Results

Water budget

Net soil water flux followed a seasonal pattern: positive and similar to monthly precipitation during winter months when precipitation was high and air temperature was low and negative during summer months when precipitation was low or absent and air temperature was high (Fig. 1). Annual soil water fluxes were 250 and 220 cm at Matlock in 2006 and 2007, respectively, and 110 and 70 cm in 2006 and 2007, respectively, at Molalla.

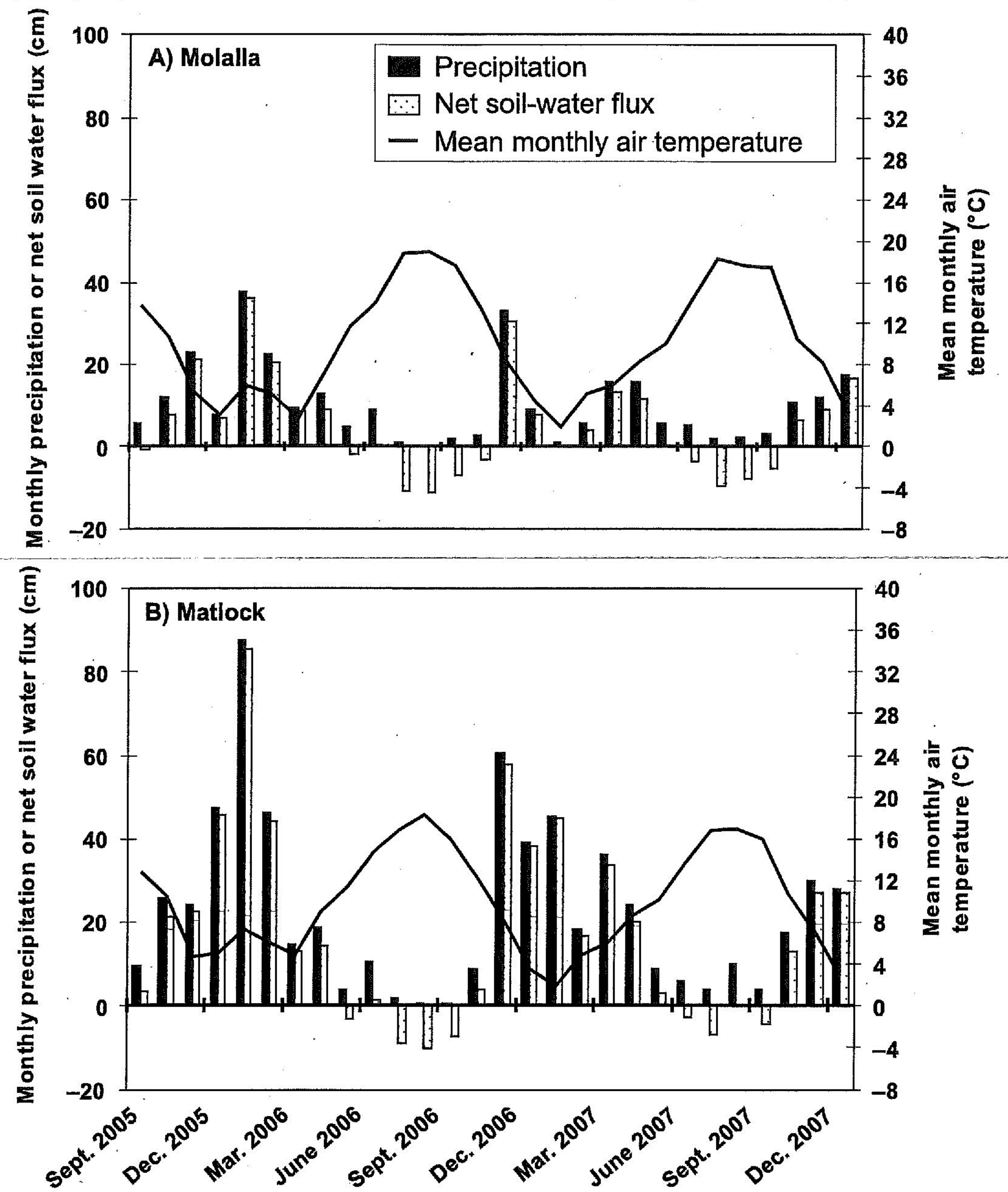
Soil water dynamics in situ

Soil water inorganic N was composed almost entirely of nitrate-N; amrnonium-N was found in only a few samples at random periods and concentrations were generally near detection limits (0.04 mg-L^{-1}). Annual eve was associated with increased mean nitrate-N concentrations at both sites in 2006 (Table 2), with the greatest increases observed at Molalla (Fig. 2). Greater soil water flux at Matlock resulted in similar estimates of nitrate-N mass flux for each site (15 and 14 kg N·ha-^{1} at Molalla and Matlock, respectively). Most of the increase with annual eve at Matlock could be attributed to treatments where logging debris was retained (Table 2, Fig. 2B inset). Nitrate-N concentrations remained elevated at Molalla in the annual eve treatment in 2007 (estimated net flux of 14kg N*ha^{-1}) but there was no difference between eve treatments at Matlock that year (estimated net flux of 2 kg N·ha^{-1}). Median DON concentration increased with annual eve in March of both sample years at Molalla (Fig. 2A), but the estimated mass flux increase was small (approximately 0.5 kg N ha^{-1}) because DON concentrations were low relative to nitrate-No At Matlock, DON dominated TDN, and there was no effect of eve treatment on DON concentration (Fig. 2A). Treatment effects on TDN were similar to those on nitrate-N at Molalla (Fig. 3B), with estimated median TDN fluxes of 22 and 11 kg N·ha^{-1} in 2006 and 2007, respectively, when annual eve was applied. In contrast, there was no difference in TDN concentrations between eve treatments at Matlock (Fig. 3B) despite the differences observed for nitrate-N.

Analysis of variance revealed fewer effects of logging debris on soil water N than those for eve (Table 2), and there were no consistent patterns in response within or between years. In 2007 at Molalla, the 40% logging-debris coverage had higher DON concentration than the 80% coverage in January (by 0.22 mg N-L^{-1}), but the 80% coverage was significantly higher than the 40% coverage in June (by 0.27 mg N·L^{-1}) (data not shown). There was no difference in DON concentration between the presence and absence of logging debris during these same months. In 2006 at Matlock, TDN was higher in the 80% coverage compared with the 40% coverage during January (increase of 3.3 mg N·L^{-1}), and the 40% and 80% coverage had significantly higher TDN than the 0% coverage in July (median increase of 2.7 mg N-L^{-1}) (Fig. 4B).

There were no differences among logging-debris or eve treatments on DOC concentrations at either site (Table 2). At both sites in 2006, mean DOC concentrations were consistently higher (nonsignificant) in the 0% coverage resulting in estimated mass flux of 53, 42, and 41 kg C·ha^{-1}.$year^{-1}$ in the 0%, 40%, and 80% coverage at Molalla, respectively, and 36, 28, and 29 kg C·ha^{-1}.$year^{-1}$ in the 0%, 40%, and 80% coverage, respectively, at Matlock. There was little difference in DOC concentrations among treatments or between sites in 2007 (Fig. 4). The mean estimated DOC annual flux at both sites was 24 kg C-ha^{-1}.$year^{-1}$ in 2007.

Fig. 1. Monthly total precipitation, estimated net soil water flux, and mean monthly air temperature at the (A) Molalla and (B) Matlock sites



Laboratory incubations

Regardless of treatment, water-leachable nitrate-N at Molalla was two to three greater than that at Matlock (Fig. 5). Application of annual eve increased water-leachable nitrate-N at Molalla during the September 2006 and July 2007 incubation periods and increased TDN during the July 2007 incubation (Table 3, Fig. 5). In contrast, there was no effect of eve treatment on nitrate-N or TDN in any period at Matlock, but DON increased with annual eve in the July 2007 period. There was a significant interaction among logging debris, eve, and incubation period effects on nitrate-N at both sites (Table 3), which was associated with the July incubation in each year. Means separation with Tukey's honestly significant difference test indicated general patterns of higher water-leachable nitrate-N with logging-debris retention during those incubation periods, with the exception of the annual eve treatment in July 2006 at Molalla where the opposite pattern was observed (data not shown). The main effect of logging debris on ammonium-N approached statistical significance at Matlock ($P = 0.06$; Table 3), where means of 2.00, 2.25, and 3.06 mg N·(kg soil)$^{-1}$ (SE for all = 0.30) were leached at each incubation in the 0%, 40%, and 80% coverage, respectively. A similar pattern was observed at Molalla.

There was a significant interaction among logging debris, CVC, and incubation period effects on water-leachable DOC at both sites (Table 3), but effects were variable. During the April 2006 incubation for Matlock, mean DOC in the initial

Table 2. *F*-statistic probabilities and degrees of freedom from analysis of variance by year on nitrate-N, total dissolved N (TDN), dissolved organic N (DON), and dissolved organic carbon (DOC) at the Molalla and Matlock sites.

		Denominator df		Molalla				Matlock			
Effect	Numerator df	Molalla	Matlock	NO_3-N	DON	TDN	DOC	NO_3-N	DON	TDN	DOC
2006											
CVC (C)[a]	1	3	3	0.014	0.113	0.008	0.695	0.012	0.216	0.145	0.350
Debris (D)	2	12	12	0.489	0.959	0.551	0.426	0.501	0.702	0.312	0.799
C × D	2	12	12	0.513	0.575	0.635	0.769	0.595	0.572	0.594	0.338
Month (M)	7, 5[b]	106	68	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001
C × M	7, 5	106	68	<0.001	0.010	0.002	0.885	0.001	0.287	0.628	0.487
D × M	14, 10	106	68	0.227	0.644	0.063	0.900	0.005	0.509	0.094	0.864
C × D × M	14, 10	106	68	0.261	0.478	0.325	0.503	0.088	0.708	0.025	0.270
2007											
C	1	3	3	0.065	0.167	0.028	0.957	0.121	0.570	0.366	0.589
D	2	12	12	0.682	0.559	0.223	0.764	0.278	0.702	0.632	0.849
C × D	2	12	12	0.686	0.923	0.353	0.484	0.270	0.331	0.117	0.877
M	6	65	67	0.233	0.001	0.002	<0.001	0.001	<0.001	<0.001	<0.001
C × M	6	65	67	0.232	0.047	<0.001	0.395	0.065	0.521	0.054	0.055
D × M	12	65	67	0.809	0.037	0.953	0.261	0.734	0.970	0.625	0.526
C × D × M	12	65	67	0.805	0.477	0.512	0.532	0.989	0.993	0.759	0.782

[a]CVC, competing-vegetation control.
[b]Numerator degrees of freedom for Molalla and Matlock, respectively.

Table 3. *F*-statistic probabilities and degrees of freedom from analysis of variance following a 2 week incubation at four sample periods on ammonium-N, nitrate-N, total dissolved N (TDN), dissolved organic N (DON) and dissolved organic carbon (DOC) at the Matlock and Molalla sites.

Effect	Numerator df	Denominator df	NH_4-N	NO_3-N	TDN	DON	DOC
Molalla							
CVC (C)[a]	1	3	0.981	0.075	0.277	0.493	0.548
Debris (D)	2	12	0.248	0.281	0.807	0.787	0.465
C × D	2	12	0.613	0.136	0.438	0.227	0.695
Period (P)	3	54	0.001	<0.001	0.102	<0.001	<0.001
C × P	3	54	0.495	0.022	0.042	0.275	0.651
D × P	6	54	0.375	0.131	0.199	0.627	0.861
C × D × P	6	54	0.358	0.002	0.059	0.367	0.019
Matlock							
C	1	3	0.244	0.184	0.308	0.747	0.504
D	2	12	0.056	0.307	0.235	0.183	0.326
C × D	2	12	0.370	0.567	0.666	0.576	0.946
P	3	54	0.001	0.006	0.003	<0.001	<0.001
C × P	3	54	0.546	0.333	0.162	0.040	0.691
D × P	6	54	0.400	0.516	0.343	0.072	0.138
C × D × P	6	54	0.691	0.013	0.011	0.201	0.046

[a]CVC, competing-vegetation control.

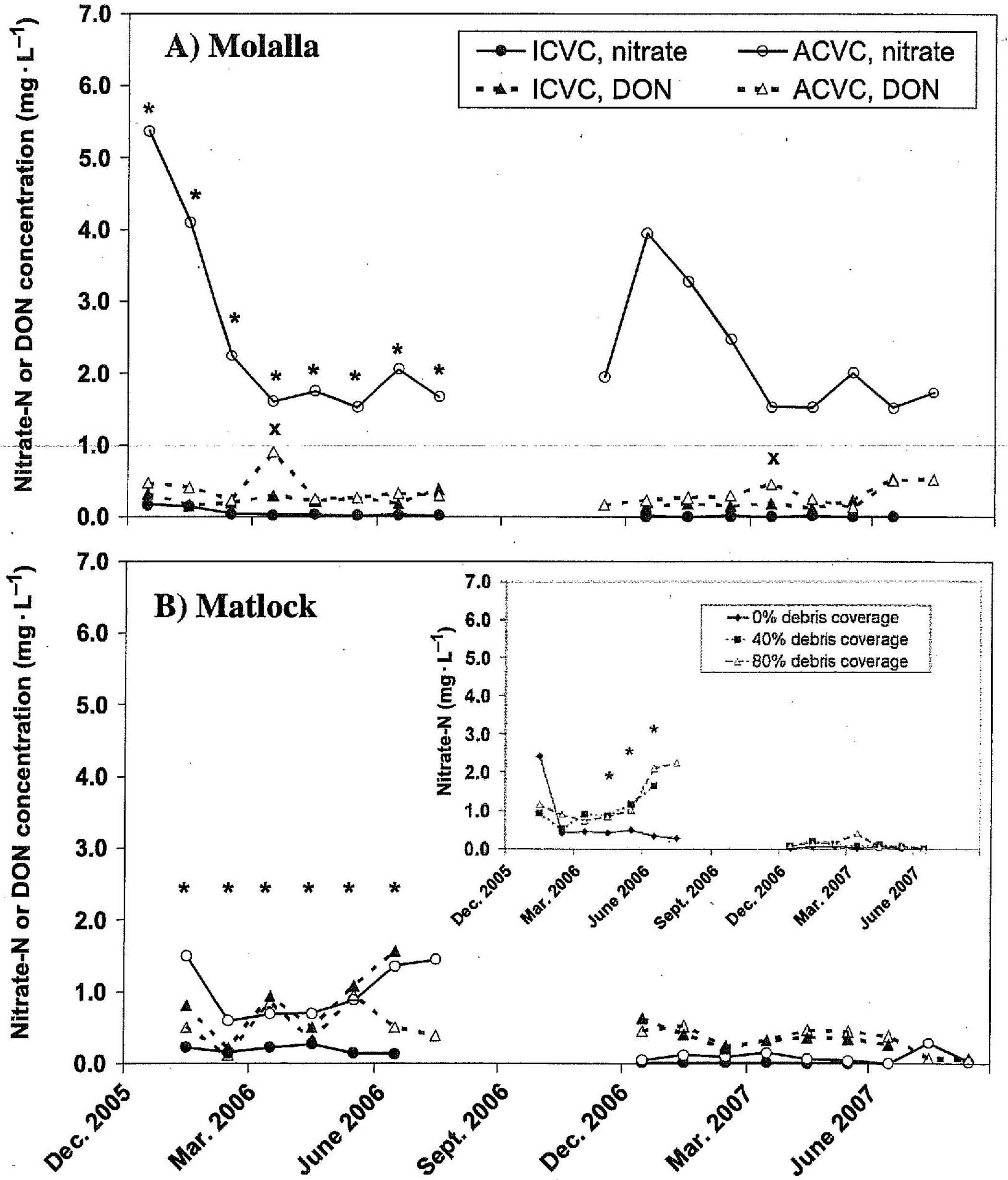
CVC treatment increased with increasing logging-debris retention. The opposite pattern occurred at Molalla during the July 2007 incubation (data not shown). With the exception of these instances, CVC and logging-debris treatments had no significant effect on DOC, and there were no apparent trends or differences between treatments at either site.

Discussion

Soil water N concentrations

Annual CVC had a pronounced effect on N leaching following harvesting. The increase in soil water nitrate-N concentration following annual CVC at both sites agrees with past studies (Vitousek and Matson 1985; Smethurst and Nambiar 1995; Briggs et al. 2000), demonstrating the importance of revegetation following harvesting for N retention across a variety of site conditions. However, there were distinct differences between sites, most notably in the duration of response and the relative contribution of inorganic and organic N to TDN. By the end of the study period, N availability continued to be greater than vegetation N demand at Molalla, but N loss at Matlock was very low regardless of CVC treatment. The contrast in duration of response between sites was at least partly caused by a difference in total

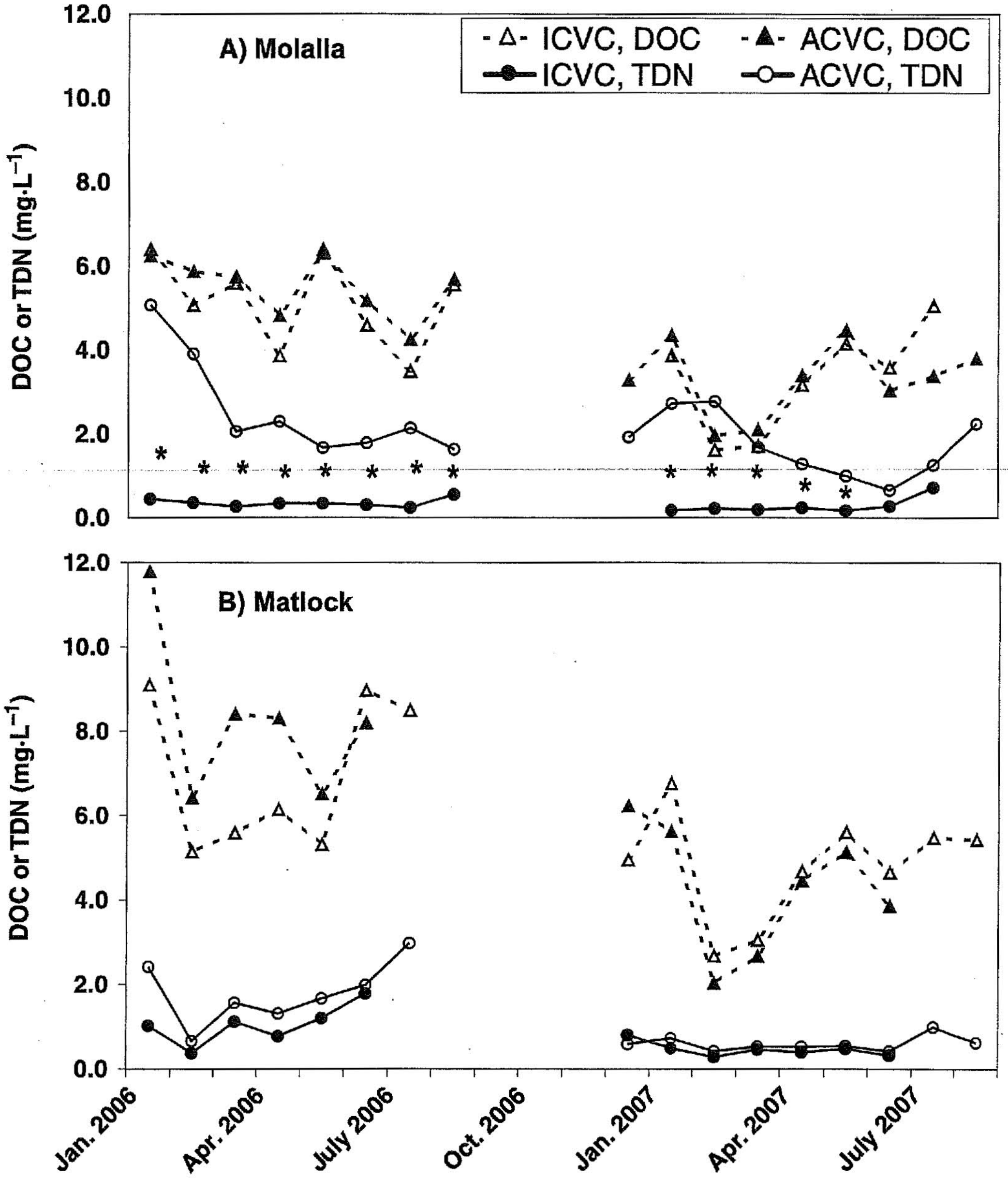
Fig. 2. Effect of competing-vegetation control (CVC) treatments on soil water nitrate-N and dissolved organic N (DON) concentrations at 60 cm depth at (A) Molalla and (B) Matlock. Effect of logging-debris retention when annual CVC was applied on nitrate-N at Matlock is shown in the inset. Values with asterisks and xs are significantly different at $\alpha = 0.05$ between treatments for the associated month in nitrate-N and DON, respectively. Values are monthly means (nitrate-N) or medians (DON) ($n = 12$). ICVC, initial competing-vegetation control; ACVC, annual competing-vegetation control.



soil N (Table 1) and its effect on water-leachable N production (Fig. 5). Differences in crop tree N uptake probably also contributed to the contrasting site response. Tree growth data and measures of available N during the study period indicated greater utilization of increased available N by planted seedlings at Matlock following annual CVC compared with Molalla (Slesak 2008), which would have contributed. to the large reduction in soil water nitrate concentrations in 2007 at Matlock.

Dissolved organic N contributed a larger proportion to TDN at Matlock than at Molalla, such that no difference in TDN existed between CVC treatments at Matlock despite the increases in nitrate-N with annual CVC. Factors that control DON loss are poorly understood (Kalbitz et al. 2000; McDowell 2003), but it seems likely that the difference between sites is at least partly related to retention mechanisms in each soil (e.g., differences in soil mineralogy or degree of weathering). Qualls et al. (2000) hypothesized that DON loss following harvesting is controlled by hydrologic and geochemical mechanisms rather than biological processes. At Matlock, soil texture is coarse, making it likely that soil water contact (both actual surface area and

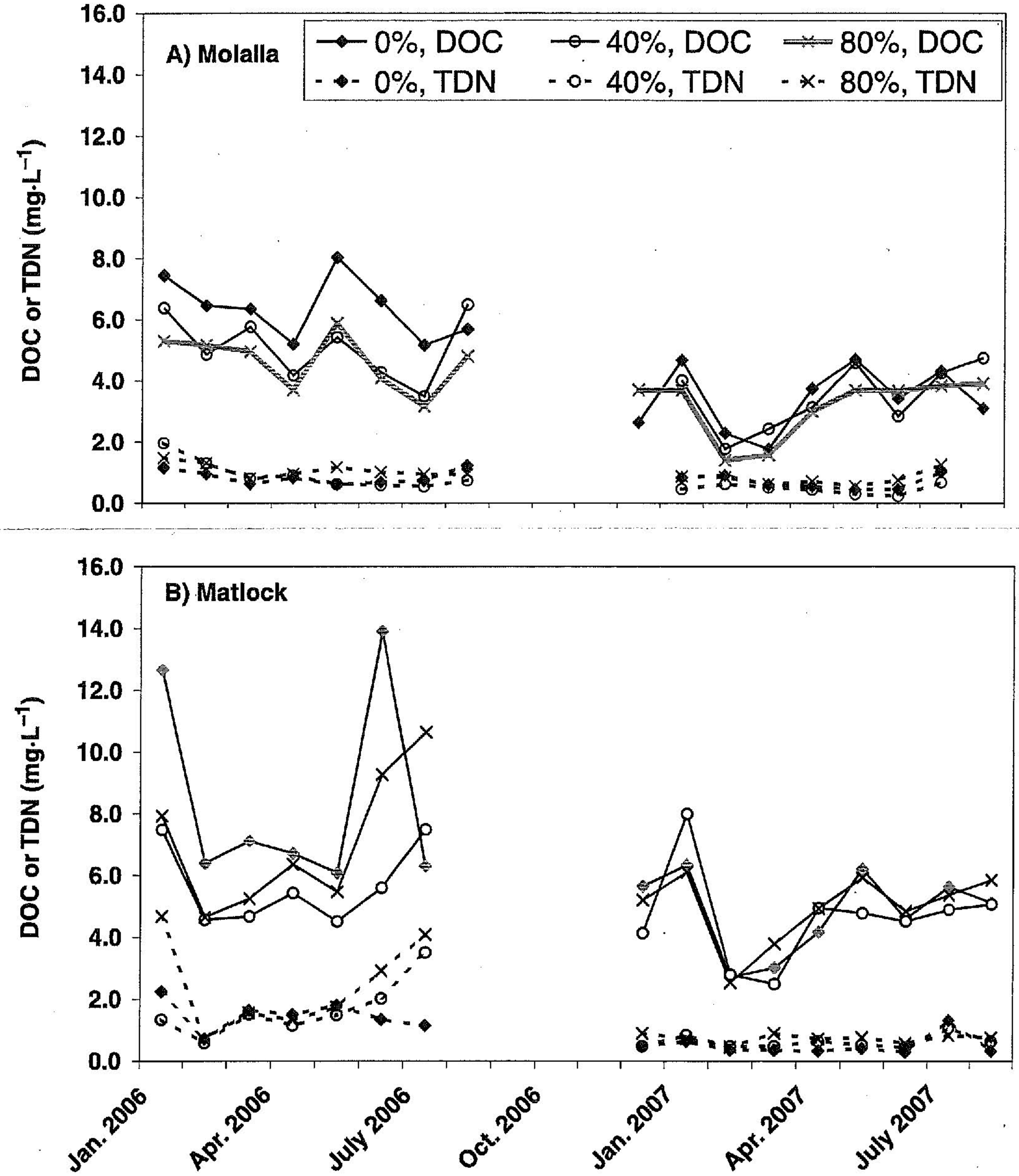
Fig. 3. Effect of competing-vegetation control treatments on soil water total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) at 60 cm depth at (A) Molalla and (B) Matlock. Values with asterisks are significantly different at $\alpha = 0.05$ between treatments for the associated month in TDN. Values are monthly medians ($n = 12$). ICVC, initial competing-vegetation control; ACVC, annual competing-vegetation control.



time of contact) with mineral surfaces is much lower than at Molalla, which would decrease potential sorption of DON, Results from the incubations support this, because DON was a small proportion of TDN at Matlock under controlled conditions when water was allowed to equilibrate with incubated soil prior to leaching, Although a geochemical mechanism likely contributed to the different site responses, there is also evidence for a biological mechanism, The seasonal transitory increase in DON following annual CVC at Molalla occurred when soil temperature began to increase from low winter temperatures in March of each year (Slesak 2008), The increase in soil temperature corresponded with an increase in microbial activity (Slesak 2008), possibly increasing net DON production because of lower C availability in the annual CVC treatment (Shan et al. 2001), Whatever the mechanism, the contribution of DON to N leaching following annual CVC was relatively small at Molalla, contributing only 2% and 4% to TDN leaching estimates in 2006 and 2007, respectively.

Given these findings, there is potential for annual applications of CVC to increase soil N loss, with greater potential at the Molalla site given the continued elevation of TDN flux. Assuming that increased flux in years before sampling was similar to that observed during the study period, total N

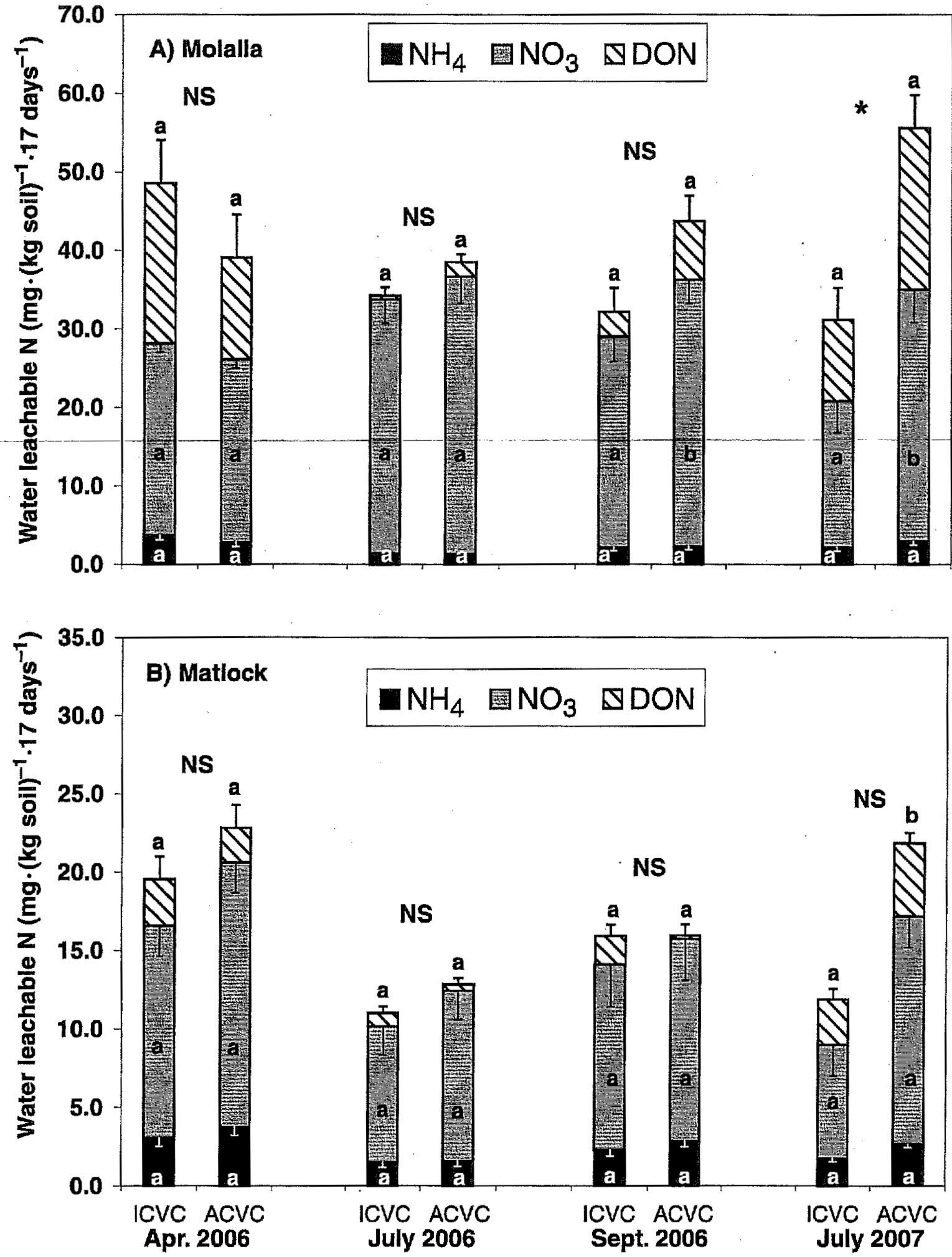
Fig. 4. Effect of 0%, 40%, and 80% logging-debris coverage treatments on soil water total dissolved nitrogen (TDN) and dissolved organic carbon (DOC) at 60 cm depth at (A) Molalla and (B) Matlock. Values are monthly medians (n = 12).



loss below 60 cm since harvest is a relatively small percentage (<1.5%) of the soil N pool in surface soil (Table 1). Strahm et al. (2005) also found that estimated N leaching fluxes following harvesting of Douglas-fir were a small percentage (<1.5%) of total soil N. At Matlock, greater nitrate-N flux with annual CVC could also reduce soil N given the relatively low initial total soil N pool at that site (Table 1). However, most of the increase in soil water nitrate-N with annual CVC was attributed to treatments where logging-debris was retained, and a significant increase in soil N was observed in those treatments at the end of the study period (Slesak 2008). At Matlock, it appears that logging debris increased soil N, which caused a greater availability of ammonium (as indicated in the incubations) and subsequent higher rates of nitrate production when soil temperatures began to increase (Knoepp and Swank 2002). Consequently, it is unlikely that the observed flux below the rooting zone would have negative impacts on future soil productivity because it is related to greater soil N. Further, N inputs over the course of the rotation are sufficient to offset any losses (assuming a 40 year rotation, 1 kg N $year^{-1}$ deposition and 2 kg N $year^{-1}$ fixation) that occur at time of harvest in response to annual eve.

Clearly, there was an effect of logging-debris retention on soil water N, but the effect was small compared with that of CVC and, in many cases, occurred in no discernable pattern. These results generally agree with those of Mann et al. (1988) who found no significant effect of logging-debris re-

Fig. 5. Effect of competing-vegetation control on water leachable ammonium-N, nitrate-N, dissolved organic nitrogen (DON), and total dissolved nitrogen (TDN; sum of all three sources) in soil by incubation period at (A) Molalla and (B) Matlock. Means within an incubation period with different letters are significantly different at $\alpha = 0.05$ ($n = 12$). The TDN values with asterisks are significantly different between treatments. Error bars are SEs; no error bars are shown for TDN. Note the difference in scale between Figs. 5A and 5B. ICVC, initial competing-vegetation control; ACVC, annual competing-vegetation control; NS, not significant.



tention on N leaching across a variety of site and climate conditions. However, other studies have found either an increase (Hendrickson et al. 1989; Strahm et al. 2005) or decrease (Vitousek and Matson 1985; Carlyle et al. 1998) in soil water nitrate following varying levels of logging-debris retention, indicating the potential for logging debris to modify N loss following harvesting. Although the results observed here agree with those from Mann et al. (1988), the lack of any pronounced effect could be due to the experimental design that was employed. Subplot logging-debris treatments were located in whole plots that had received the whole-tree harvest treatment at time of logging, which would have had significantly less needle and small branch retention than the bole-only treatments. Because needles contain the majority of N in logging debris, it is possible that different results would have been observed if subplots were located in the bole-only whole plots. Inferences from these results should be applied accordingly.

Soil water DOC

The lack of any difference in DOC concentrations between CVC treatments indicates that DOC loss (below the rooting zone) after harvest is largely independent of OM inputs from recently fixed C at these sites. Companion soil respiration measures during the study period indicated rapid consumption of OM inputs from competing vegetation (Slesak 2008), likely reducing the potential for the movement of DOC to deeper portions of the soiL However, the labile portion (i.e., readily metabolized) of DOC is generally thought to be small (Qualls and Haines 1992; Lajtha et a1. 2005), and it is likely that DOC retention via adsorption to mineral surfaces also occurred. Although the relative contribution of consumption or adsorption is uncertain, results from the laboratory incubations (i.e., no significant differences among treatments) suggest that these processes occur rapidly in situ.

Logging debris has been shown to be a significant source of DOC to mineral soil (Mattson et al. 1987; Qualls et al. 2000; Robertson et al. 2000), and it is likely that DOC inputs to mineral soil were increased in this study following logging-debris retnetion. The lack of any significant effect of logging-debris retention on soil water DOC concentrations below the rooting zone indicates increased inputs were retained or consumed in the mineral soiL Both Qualls et al (2000) and Piirainen et al. (2002) concluded that Doe inputs from logging debris were effectively retained in mineral soil. Qualls et al (2000) attributed the retention mechanism to adsorption to mineral surfaces but also acknowledged potential for losses via microbial consumption. At these sites, microbial respiration was lower when logging debris was.retained (Slesak 2008), making it likely that e inputs were retained rather than consumed.

Despite the lack of statistical significance, soil water DOC concentrations were greater in almost all months when no logging debris was retained in 2006 at both sites, resulting in a higher estimated annual flux. A few recent studies have shown that DOC in deeper soil (>50 cm) is derived from mineral soil OM or root litter rather than surface inputs (Froberg et al. 2007; Uselman et al 2007). Increased production from these sources could potentially result in increased DOC loss if not adsorbed to mineral soil. Soil temperature was significantly greater in the 0% logging-debris coverage at both sites (Slesak 2008), likely causing an increase in root decomposition (Chen et al. 2000) and greater soil water DOC concentrations. The limited effect of logging debris on DOC production during incubations does not provide evidence to support or refute increased DOC production, given that incubations were performed at constant temperature and roots >2 mm were sieved from soil prior to incubation. If DOC loss was greater in the 0% logging-debris coverage, it appears to have been a relatively short-lived response given no apparent differences between treatments in 2007.

Conclusions

Increased soil water nitrate-N following annual CVC reflects a potential for soil N loss following harvesting when this practice is employed, but the estimated loss was small compared with total N pools at each site. At Molalla, which has a relatively large pool of soil N, greater production of nitrate-N led to higher soil water nitrate-N concentrations following annual CVC compared with Matlock, which has a relatively small pool of soil N, lower nitrate production, and greater crop tree utilization of available N. Dissolved organic N was also increased following annual cve at Molalla, but the contribution from this source was small compared with the estimated increase in annual TDN flux. Site-specific factors that control nitrate production and tree N demand appear to be strong indicators of potential N loss when annual CVC is applied.

Almost all of the increase in nitrate-N concentration at Matlock was associated with logging-debris retention when annual CVC was applied, demonstrating the potential for greater N loss at some sites when these practices are combined. However, the biological significance of these losses at Matlock is unclear, because total soil N increased in those treatments during the 2 year study period (Slesak 2008). Absence of any logging-debris effect at Molalla may be due to the greater total soil N pool at that site, because inputs from logging debris were small compared with total soil N.

Absence of any increase in DOC concentration when competing vegetation was present and logging debris was retained indicates that potential DOC inputs from these sources were either consumed or retained in the mineral soiL Higher DOC concentrations when no logging debris was retained may indicate greater DOC production and loss in those treatments, which would likely be caused by greater belowground decomposition associated with higher soil temperature. Given that soil C content tended to increase during the 2 year study regardless of treatment (Slesak 2008), the significance of greater DOC loss to soil productivity is probably of minor importance.

Acknowledgments

This is a product of the sustainable forestry component of Agenda 2020, a joint effort of the USDA Forest Service Research and Development and the American Forest and Paper Association. Funds were provided by the Pacific Northwest Research Station. Research partners included Green Diamond Resource Company, Port Blakely Tree Farms LLC, Oregon State University, and Virginia Polytechnic Institute and State University. We gratefully acknowledge the assistance of Machelle Nelson and Don Streeter in sample preparation and analysis.

References

Adams, W.T., Hobbs, S., and Johnson, N. 2005. Intensively managed forest plantations in the Pacific Northwest: conclusions. J. For. 103: 99-100.

Boyle, J.R., and Ek, A.R. 1972An evaluation of some effects of bole and branch pulpwood harvesting on site macronutrients. Can. J. For. Res. 2: 407-412. doi:10.l139/x72-062.

Briggs, R.D., Hornbeck, J.W., Smith, C.T., Lemin, RC; Jr., and McCormack, M.L., Jr. 2000. Long-term effects of forest management on nutrient cycling in spruce-fir forests. For. Ecol. Manage. 138: 285-299. doi:10.1016/S0378-1127(00)00420-5.

Carlyle, J.C., Bligh, M.W., and Nambiar, E.K.S. 1998. Woody residue management to reduce nitrogen and phosphorus leaching from sandy soil after clear-felling *Pinus radiata* plantations. Can. J. For. Res. 28: 1222-1232. doi:10.1139/cjfr-28-8-1222.

Chen, H., Harmon, M.E., Griffiths, R.P., and Hicks, W. 2000. Effects of temperature and moisture on carbon respired from decomposing woody roots. For. Ecol. Manage. 138: 51-64. doi:10.1016/S0378-1127(00)00411-4.

Devine, W.D., and Harrington, C.A. 2007. Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. Agric. For. Meteorol. 145: 125-138. doi:10.1016/j.agrformet.2007.04.009.

Dunne, T., and Leopold, L.B. 1978. Water in environmental planning. W.H. Freeman and Co., San Francisco, Calif.

Fleming, R.L., Black, TA, and Eldridge, N.R 1994. Effects of site preparation on root zone soil water regimes in high-elevation forest clearcuts. For. Ecol. Manage. 68: 173-188. doi:10.1016/0378-1127(94)90044-2.

Food and Agricultural Organization of the United Nations (FAO). 2006. Global forest resources assessment 2005: progress towards sustainable forest management. FAO, Rome. FAO For. Pap. 147.

Fox, T.R 2000. Sustained productivity in intensively managed forest plantations. For. Ecol. Manage. 138: 187-202. doi:10.1016/S0378-1127(00)00396-0.

Froberg, M., Jardine; P.M., Hanson, P.J., Swanston, C.W., Todd, D.E., Tarver, J.R., and Garten, C.T., Jr. 2007. Low dissolved organic carbon input from fresh litter to deep mineral soils. Soil Sci. Soc.Am. J. 71: 347-354. doi:10.2136/sssaj2006.0188

Giesler, R., Hogberg, M.N., Strobel, B.W., Richter, A, Nordgren, A., and Hogberg, P. 2007. Production of dissolved organic carbon and low-molecular weight organic acids in soil solution driven by recent tree photosynthate. Biogeochemistry, 84: 1-12. doi:10.1007/sl0533-007-9069-3.

Gundersen, P., Schmidt, LK., and Raulund-Rasmussen, K 2006. Leaching of nitrate from temperate forests - effects of air pollution and forest management. Environ. Rev. 14: I-57. doi:10.1139/A05-015.

Harrington, T.B., Wagner, R.O., Radosevich, S.R, and Walstad, J.D. 1995. Interspecific competition and herbicide injury influence 10-year responses of coastal Douglas-fir and associated vegetation to release treatments. For. Ecol. Manage. 76: 55-67. doi:10.1016/0378-1127(95)03558-R.

Hendrickson, O.Q., Chatarpaul, L., and Burgess, D. 1989. Nutrient cycling following whole-tree and conventional harvest in northern mixed forest. Can. J. For. Res. 19: 725-735. doi:10.1139/x89-112.

Homann, P.S., Bormann, B.T., and Boyle, J.R 2001. Detecting treatment differences in soil carbon and nitrogen resulting from forest manipulations. Soil Sci. Soc. Am. J. 65: 463-469.

Johnson, D.W. 1992. Nirogen retention in forest soils. J. Environ. Qual. 21: 1-12.

Johnson, D.W., Knoepp, J.D., Swank, W.T., Shan, J., Moms, L.A., Van Lear, D.H., and Kapeluck, P.R. 2002. Effects of forest management on soil carbon: results of some long-term resampling studies. Environ. Pollut. 116(Suppl. 1): *S201-S208.* doi:10.1016/S0269-7491(01)00252-4.

Kalbitz, K., Solinger, *S.,* Park, I.-H., Michalzik, B., and Matzner, E. 2000. Controls on the dynamics of dissolved organic matter in soils: a review. Soil Sci. 165: 277-304. doi:1O.1097/00010694-200004000-00001.

Keeney, D.R 1980. Prediction of soil nitrogen availability in forest ecosystems: a literature review. For. Sci. 26: 159-171.

Knoepp, J.D., and Swank, W.T. 2002. Using soil temperature and moisture to predict forest soil nitrogen mineralization. BioI. Ferti\. Soils, 36: 177-182. doi: 10.1007/s00374-002-0536-7.

Lajtha, K, Crow, S.E., Yano, Y., Kaushal, *S.S.,* Sulzman, E., Sollins, P., and Spears, J.D.H. 2005. Detrital controls on soil solution N and dissolved organic matter in soils: a field experiment. Biogeochemistry, 76: 261-281. doi:l0.1007/s10533-005-5071-9.

Mann, L.K, Johnson. D.W., West, D.C., Cole, D.W., Hornbeck, J.W., Martin, C.W., Riekerk, H., Smith, C.T., Swank, W.T., Tritton, L.M., and Van Lear, D.H. 1988. Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital, and regrowth. For. Sci. 34: 412-428.

Marks, P.L., and Bormann, F.H. 1972. Revegetation following forest cutting: mechanisms for return to steady-state nutrient cycling. Science (Washington, D.C.). 176: 914-915. doi:l0.1126/science.176.4037.914. PMID:I7829302.

Mattson, KG., Swank, W.T., and Waide, J.B. 1987. Decomposition of woody debris in a regenerating, clear-cut forest in the southern Appalachians. Can. J. For. Res. 17: 712-721. doi:l0.1139/x87-114.

McDowell, W.H. 2003. Dissolved organic matter in soils - future directions and unanswered questions. Geoderma, 113: 179-186. doi: 10.1016/S0016-7061(02)00360-9.

McDowell, W.H., and Likens, G.E. 1988. Origin, composition, and flux of dissolved organic carbon in the Hubbard Brook Valley. Bco!. Monogr. 58: 177-195. doi:1O.2307/2937024.

Meyer, J.L., and Tate, C.M. 1983. The effect of watershed disturbance on dissolved organic carbon dynamics of a stream. Ecology, 64: 33-44. doi:1O.230711937326.

Miller, *I.H.,* Allen; KC'-Zutter --B~R-:;--tidaker;-s.r';:f ," and-Newbold, RA. 2006. Soil and pine foliage nutrient responses 15 years after competing-vegetation control and their correlation with growth for 13 loblolly pine plantations in the southern United States. Can. J. For. Res. 36: 2412-2425. doi:10.1139/X06-164.

Moores, A., Maguire, D., and Puettmann, K 2007. The focus of intensive silvicultural research on coastal Douglas-fir over the last 20 years. West. J. Appl. For. 22: 21-28.

Nadelhoffer, KJ. 1990. Microlysimeter for measuring nitrogen mineralization and microbial respiration in aerobic soil incubations. Soil Sci. Soc. Am. J. 54: 411-415.

Nambiar, E.K.S. 1996. Sustained productivity of forests is a continuing challenge to soil science. Soil Sci. Soc. Am. 1. 60: 1629-1642.

Newton, M., and Preest, D.S. 1988. Growth and water relations of Douglas fir *(Pseudotsuga menziesii)* seedlings under different weed control regimes. Weed Sci. 36: 653-662.

Olsson, B.A., Staaf, H., Lundkvist, H., Bengtsson, J., and Rosen, K 1996. Carbon and nitrogen in coniferous forest soils after clearfelling and harvests of different intensity. For. Eco\. Manage. 82: 19-32. doi:1O.1016/0378-1127(95)03697-0.

Piirainen, S., Finer. L., Mannerkoski, H., and Starr, M. 2002. Effects of forest clear-cutting on the carbon and nitrogen fluxes through podzolic soil horizons. Plant Soil, 239: 301-311. doi:l 0.1023/A: 1015031718162.

Powers, R.F., Alban, D.H., Miller, RE., Tiarks, AE., Wells, C.G.• Avers, P.E., Cline. R.O., Fitzgerald, RO., and Loftus, *N.S.,* Jr. 1990. Sustaining site productivity in North American forests: problems and prospects. *In* Sustained productivity of forest soils. Proceedings of the 7th North American Forest Soils Conference, Vancouver, B.C. *Edited by* S.P. Gessel D.S. Lacate, G.F. Weetman, and R.F. Powers. Forestry Publications, University of British Columbia, Vancouver, B.C. pp. 49-80.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A, Page-Dumroese, D., Elioff. I.D., and Stone, D.M. 2005. The North American long-term soil productivity experiment: findings from the first decade of research. For. EcoJ. Manage. 220: 31-50. doi:l0.1 016/j.foreco.2005.08.003.

Qualls, R.G., and Haines, B.L. 1992. Biodegradability of dissolved organic matter in forest throughfall, soil solution, and stream water. Soil Sci. Soc. Am. J. 56: 578-586.

Qualls, R.G., Haines, B.L., Swank, W.T., and Tyler, S.W. 2000. Soluble organic and inorganic nutrient fluxes in clearcut and mature deciduous forests. Soil Sci. Soc. Am. J. 64: 1068-1077.

Roberts, S.D., Harrington, e.A., and Terry, T.A. 2005. Harvest residue and competing vegetation affect soil moisture, soil temperature, N availability, and Douglas-fir seedling growth. For. Ecol, Manage. 205: 333-350. doi:1O.1016/j.foreco.2004.1O.036.

Robertson, S.M.C., Hornung, M., and Kennedy, V.H. 2000. Water chemistry of throughfall and soil water under four tree sl?ecies at Gisburn, northwest England, before and after felling. For. Ecol, Manage. 129: 101-117. doi:10.1016/S0378-1127(99)00156-5.

Sanchez, F.G., Tiarks, A.E., Kranabetter, J.M., Page-Dumroese, D.S., Powers, R.F., Sanborn, P.T., and Chapman, W.K. 2006. Effects of organic matter removal and soil compaction on fifth-year mineral soil carbon and nitrogen contents for sites across the United States and Canada. Can. J. For. Res. 36: 565-576. doi:10.1139/x05-259.

SAS Institute Inc. 2005. SAS, version 9.1 edition. SAS Institute Inc., Cary, N.e.

Shan, J., Morris, L.A., and Hendrick, RL. 2001. The effects of management on soil and plant carbon sequestration in slash pine plantations. J. AppI. EcoI. 38: 932-941. doi:10.1046/j.1365-2664.2001.00648.x

Slesak, RA. 2008. Soil respiration, carbon and nitrogen leaching, and nitrogen availability in response to harvest intensity and competing vegetation control in Douglas-fir *(Pseudotsuga menziesii)* forests of the Pacific Northwest. Ph.D. Dissertation. Oregon State University, Corvallis, Ore.

Smethurst, PJ., and Nambiar, E.K.S. 1995. Changes in soil carbon and nitrogen during the establishment of a second crop of *Pinus radiata.* For. EcoI. Manage. 73: 145-155. doi:10.1016/0378-1127(94)03491-B.

Sollins, P., and McCorison, F.M. 1981. Nitrogen and carbon solution chemistry of an old growth coniferous forest watershed before and after cutting. Water Resour. Res. 17: 1409-1418. doi: 10.1029/WR017i005p01409,

Strahm, B.D., Harrison, RB., Terry, T.A., Flaming, B.L., Licata, C.W., and Petersen, K.S. 2005. Soil solution nitrogen concentrations and leaching rates as influenced by organic matter retention on a highly productive Douglas-fir site. For. Ecol, Manage. 218: 74--88. doi:10.1016/j.foreco.2005.07.013.

Uselman, S.M., Qualls, R,G., and Lilienfein, 1. 2007. Contribution of root vs. leaf litter to dissolved organic carbon leaching through soil. Soil Sci. Soc. Am. J. 71: 1555-1563. doi:10.2136/sssaj2006.0386.

Vitousek, P.M., and Matson, P,A. 1985. Intensive harvesting and site preparation decrease soil nitrogen availability in young plantations. South. J. AppI. For. 9: 120-125.

Vitousek, P.M., Gosz, J,R, Grier, C,C" Melillo, J.M., Reiners, W.A., and Todd, R.L. 1979. Nitrate losses from disturbed ecosystems, Science (Washington, D.C.), 204: 469--474. doi:10.1126/science.204.4392.469. PMID:17819936,

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.B., Matson, P.A., Schindler, D.W" Schlesinger, W.H and Tilman, D.G. 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecol. Appl. 7: 737-750; doi:10.1890/1051-0761(1997)007[0737:HAOTGN]2.0.CO;2.

Weetman, G.F., and Webber, B. 1972. The influence of wood harvesting on the nutrient status of two spruce stands. Can. J. For. Res. 2: 351-369. *doi:10.1139/x72-054.*

Wells, C.G., and Jorgensen, J.R 1979, Effect of intensive harvesting on nutrient supply and sustained productivity. *In* Proceedings of the Impact of Intensive Harvesting on Forest Nutrient Cycling. *Edited by* A.L. Leaf. State University of New York, Syracuse, N.Y. pp. 212-230.