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# Soil solution nitrogen concentrations and leaching rates as influenced by organic matter retention on a highly productive Douglas-fir site

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**Abstract**

Forest harvesting and organic matter management practices may affect the cycling of nutrients, particularly nitrogen (N), through the removal of different organic matter components (e.g. branches, foliage, coarse woody debris) from a site, and the associated changes in carbon-source quantity and quality. This study examined the influence of intensive harvesting and organic matter retention practices on soil N dynamics on a highly productive (site index I–II+) coastal Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) site in southwestern Washington, while controlling for all competing vegetation. The specific focus of this investigation was to determine the effects of bole-only (BO) harvesting and total-tree harvesting plus coarse woody debris removal (TP) on soil solution N concentrations and leaching rates (to a depth of 1.0 m) during the third through fifth years following harvest. Additional comparisons were made between the harvested treatments and adjacent non-harvested portions of the same forest stand (FS). Soil solution monitoring over 3 years indicated that the increased organic matter retention associated with BO harvesting increased the total N concentrations and leaching flux to a depth of 1.0 m by roughly three times relative to TP harvest treatments. Nitrate comprised a majority of the 75, 29 and 4.5 kg ha$^{-1}$ yr$^{-1}$ of total N leached in the BO, TP and FS observations, respectively. The cumulative quantity of N leached to a depth of 1.0 m over 3 years was a small percentage (BO = 1.5%, TP = 0.6% and FS < 0.1%) of the 15 mg ha$^{-1}$ total mineral soil N pool to a similar depth. In the two different organic matter retention treatments, this cumulative N flux was proportional (~30%) to the amount of N left on site in the form of forest floor and coarse woody debris.

*Keywords:* Harvest intensity; Lysimeters; Nitrate leaching; Nitrogen pools; Nutrient fluxes

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## 1. Introduction

Efforts to increase forest productivity to meet the growing demand for wood products have raised

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questions about the long-term sustainability of some intensive forest management practices (Dyck and Mees, 1990; Fox, 2000). Intensifying harvest removals and biomass utilization (such as whole-tree harvesting) may greatly increase the biomass yields from a given site (Weetman and Webber, 1972). However, when compared with conventional bolewood harvesting, whole-tree harvesting removes a disproportionate quantity of nutrients relative to the gain in biomass, because of the high nutrient concentrations in foliage, branches and bark. This, along with some intensive site preparation practices, has aroused concern that the depletion of organic matter and nutrients resulting from either intensive harvesting or slash removal practices may cause a reduction in soil quality and subsequent stand productivity (Keeves, 1966; Compton and Cole, 1990).

Studies of successive rotations of Radiata pine (*Pinus radiata*) plantations in sandy, nutrient-poor areas of Southeastern Australia have led to management practices that conserve logging residues and litter on site in order to improve moisture and nutrient availability to seedlings (Squire, 1983; Balneaves, 1990). Logging residues contain significant quantities of nutrients, particularly N, which may be equivalent to the amount removed during conventional bolewood harvesting (Bigger and Cole, 1983). This is of particular importance as N availability commonly limits forest productivity in the Pacific Northwest USA (Gessel et al., 1973). This organic matter will act as a potential source of nutrients as it decomposes and mineralizes (Wells and Jorgensen, 1979), leading to increases in long-term nutrient availability where slash is retained (Smethurst and Nambiar, 1990). In addition to the leaching of soluble nutrients from slash, the physical presence of organic matter itself may also stimulate mineralization through its beneficial effects on microclimate and soil moisture (Emmett et al., 1991).

However, nutrient availability following harvest is dynamic over time and strongly influenced by the capacity of microbial populations to immobilize N and utilize available carbon (C). In the absence of organic matter inputs (logging residues, litterfall and root exudates), microbial populations are limited by the supply of available C, and therefore their capacity to immobilize N may lead to greater short-term nutrient availability following whole-tree harvest (Vitousek, 1981).

Changes in nutrient availability following harvest, coupled with decreased vegetative uptake (particularly if competing vegetation is controlled), and increased soil-water flux, may alter the potential for nutrients to be leached from the rooting zone. The high mobility of nitrate ($NO_3^-$), combined with the low anion exchange capacity of most soils, makes $NO_3^-$ the form of N most often leached from terrestrial ecosystems. The leaching of inorganic N may be elevated in recently clear-cut forests compared to mature reference stands (Sollins and McCorison, 1981; Stevens and Hornung, 1990) or may remain unchanged (Cole and Gessel, 1965; Silkworth and Grigal, 1982). The effects of conventional harvesting compared to whole-tree harvesting on nutrient leaching has been studied across a range of sites, and remains equivocal (Rosen and Lundmark-Thelin, 1987; Johnson et al., 1982). Data from 11 different forest types across the USA indicated that the differences in $NO_3^-$ losses between these two harvest treatments were generally small despite differences in species composition and stand productivity (Mann et al., 1988), although vegetation competition for available nutrients may account for the magnitude of the net losses observed.

In the Pacific Northwest, large amounts of C-rich organic matter on the forest floor, and presumed small nitrifier populations in these N-limited systems, generally ensure that leaching losses of N are low (Vitousek et al., 1982). Leaching losses following harvest are also generally quite small, in the order of $<5$ kg N ha$^{-1}$ yr$^{-1}$ (Johnson and Lindberg, 1992), and are unlikely to have a long-term detrimental effect on site productivity (Cole, 1981). However, many investigations assessing the effect of harvest intensity and organic matter removal on N leaching in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands have taken place in low- and medium-productivity forests (Bigger, 1988; Compton and Cole, 1990). Little information exists concerning the effects of harvest residual levels on N dynamics of high-productivity sites. As high-productivity sites are likely to be managed more intensively for wood production in the future, they should be a primary focus of such investigations (Katzensteiner, 2003).

The specific objectives of this study were to: (i) characterize the soil solution N concentrations at a depth of 1.0 m as a function of organic matter retention in two harvest/coarse woody debris removal treatments representing operational extremes relative to a non-harvested portion of the original stand, in terms of both total N and specific N forms [nitrate ($NO_3^-$), ammonium ($NH_4^+$) and organic N], (ii) determine potential differences in the annual soil solution N flux for each set of observations over a 3-year period, and (iii) relate the total N flux at a depth of 1.0 m to the total soil N pool for a high-productivity Douglas-fir site in southwestern Washington, USA.

## 2. Materials and methods

### 2.1. Site description

This project was conducted as part of the Fall River long-term soil productivity (LTSP) study described by Terry et al. (2001), which is an affiliate installation to the U.S. Forest Service Long-Term Soil Productivity research program that encompasses numerous sites across the United States and Canada (Powers et al., 1990). The study site is located in the Twin Harbors South operating area of the Weyerhaeuser Company (46°43′N, 123°24′W) in Pacific County, Washington, USA. The site supports a high-productivity Douglas-fir stand with an elevation of 300 m and a westerly aspect ranging in slope from 9 to 16%. The soil is of the Boistfort series (mesic, Typic Fulvudand) and is a very deep, well drained, medium- to moderately fine textured silt loam that developed from Miocene basalt with andic properties in the surface horizon (Soil Survey Staff, 1999; Steinbrenner and Gehrke, 1966).

The region has a maritime climate characterized by cool, dry summers and moderate, wet winters. During the 3-year study period (April 2001–March 2004), the mean annual air temperature (at 0.25 m) was 8.3 °C, with a mean monthly air temperature of 14.7 °C in July and 3.8 °C in January. Mean annual precipitation over the study period was 1718 mm, with 1887, 1560 and 1708 mm falling during the first, second and third year, respectively. The predominant form of precipitation occurred as rain, with nearly 80% falling during the 6-month period from October through March.

The study area is in the *Tsuga heterophylla* zone as described by Franklin and Dyrness (1988). Prior to clear-cut harvest during April–July of 1999, the study site consisted of second-growth planted Douglas-fir and naturally regenerated western hemlock (*T. heterophylla* (Raf.) Sarg.). Since 1970, this second-generation stand had received 842 kg N $ha^{-1}$ of urea fertilizer: 173 kg $ha^{-1}$ in 1970, 230 kg $ha^{-1}$ in 1979 and again in 1984, and 209 kg $ha^{-1}$ in 1995. At the time of harvest, stand age was approximately 47 years, and estimated mean height was 40 m (site index I–II+, site classes 41–43 in 50 years; King, 1966). Following harvest, a broadcast application of Oust® (sulfometuron methyl) and Accord Concentrate® (glyphosate) herbicides was applied on 6–7 March 2000 using a backpack sprayer to control competing vegetation. The site was subsequently planted on 20–21 March 2000 with 2-year-old (1 + 1) Douglas-fir seedlings selected for minimum height and caliper variability. Seedlings were planted at a density of 1600 trees $ha^{-1}$ on a 2.5 m × 2.5 m spacing. Further, suppression of competing vegetation was also achieved the second, third and fourth growing seasons using broadcast, banded, or spot-application treatments of herbicides including Oust®, Accord Concentrate®, Atrazine® (atrazine), Transline® (clopyralid), and VelparL® (hexazinone). This vegetation control regime was implemented to eliminate any confounding effects associated with potential differential development of understory vegetative communities across treatments, and does not represent a typical operational vegetation control treatment.

### 2.2. Experimental design

The Fall River LTSP study is a randomized complete block design consisting of four replications of 12 treatments, including four levels of harvest organic matter removal intensity and two levels of vegetation control, with three additional factors including N-fertilization, compaction and tillage (Terry et al., 2001). Within the treatment plots all trees were directionally hand-felled with a chain saw so that all tops remained within the treatment boundary. For the treatments used in this study, harvesting was accomplished using a cable–yarder system (CAT 330L 2-drum shovel yarder with a CAT tail-hold tractor) to minimize soil compaction. All treatments also were traversed with a shovel excavator in the buffer around the tree measurement plot to uniformly scatter logging slash or remove coarse woody debris to treatment specifications. In addition, fine coarse woody debris was removed by hand in the most intensive organic matter removal treatment. Each treatment plot is 30 m × 85 m (0.25 ha), with all soil solution collection occurring central to a 7.5 m buffer zone from any plot boundary. Holding all other factors constant (i.e. no fertilization, complete vegetation control, no compaction and no tillage), this study focused on the two harvest intensity levels that differed the most in terms of organic matter retention (BO and TP). There are currently eight replications each of these treatments within the study design; however, there are plans to fertilize half of these plots at a future date. The two organic matter retention treatments studied in this investigation were:

1. Bole-only (BO) harvest. In the conventional bole-only harvest treatment, only the merchantable bolewood (up to 8–13 cm diameter top) was removed from the plot. All butt-cuts and non-merchantable wood were left on site. Logging slash (foliage and branches) was retained and distributed uniformly across the plot.
2. Total-tree plus (TP) coarse woody debris removal. In the TP treatment, all aboveground biomass was removed from the plot, in addition to all forest floor coarse woody debris. Most forest floor material was retained, although some inadvertent removal, displacement and mixing with mineral soil occurred during the mechanical removal of the logging slash and coarse woody debris.

In addition to the two harvest treatments described above, four additional lysimeter monitoring stations were located within two non-harvested portions of the same forest stand (FS). Lysimeter stations were located within the forest stand in areas with similar soil, slope and aspect as the treatment blocks. Small non-harvested plots could not be established as part of the main study design because standing trees in plots of this size and shape would not be wind-firm in the winter when soils are wet and storm fronts are frequent. Further, growth of seedlings on harvested plots adjacent to forest stand plots would likely be confounded by forest edge influences. Some blow-down was experienced along the edges of the remaining forest stand despite these precautions.

### 2.3. Soil solution collection and analysis

Tension lysimeters (Cole, 1958) were used to collect soil solution at a depth of 1.0 m, which was assumed to be below the rooting zone of newly established seedlings. Tube lysimeters were constructed from PVC pipes and 0.1 MPa (1 bar), high-flow, round-bottom, neck-top porous ceramic cups (Soilmoisture Equipment Company, Goleta, CA) with a maximum pore size of 2.5 μm. Lysimeters were randomly located within each of the eight BO and TP treatment plots to provide eight full replicates until the time of fertilization (projected to occur at time of crown closure). Lysimeter locations were based on randomly selected coordinates within the central 0.1 ha measurement core of each 0.25 ha treatment plot, and installed in the closest area with representative forest floor conditions for the desired treatment (areas directly adjacent to stumps, mounds of red-rot, or old-growth logs were avoided). In addition, four lysimeters were installed in the non-cut forest stand in December 1999. FS lysimeters were installed more than 40 m inside the forest-block boundaries to minimize potential edge effects. All lysimeters were installed at an angle of 35° to minimize disturbance to the soil profile above the ceramic cups, and capped with a bentonite clay seal at the junction of the PVC tube and mineral soil surface to reduce preferential flow down the lysimeter tube.

All lysimeters were charged via a hand pump (−50 kPa vacuum), allowed to collect soil solution for a period of 7–10 days, and purged of all collected leachate on a monthly basis for a minimum of 3 months. This allowed the exchange sites on the lysimeters to equilibrate with the soil solution, and reduce potential disturbance effects associated with installation prior to soil solution collection and analysis. Lysimeter installations occurred in two successive fall seasons: 1999 (prior to a pilot study with four replicates beginning in April 2000 to assess treatment variances and the adequacy of replication by treatment) and 2000 (providing an additional four replicates in the harvest treatments in order to better detect differences in mean total N concentrations at the Type I error rate of 0.05). Beginning in April 2001, soil solutions were collected monthly from all 20 lysimeters (8 BO, 8 TP and 4 FS) via the same method used during the equilibration period.

Soil solutions were transported from the field to the laboratory packed in a cooler with ice, and immediately analyzed for pH (Orion Research Model 230A, 1997) upon return to the lab. Concentrations of $NH_4^+$-and $NO_3^-$-N were determined on an autoanalyzer (Perstorp Analytical 500 Series Flow-injection, Silver Spring, MD) within 24 h of sample collection. Organic N was also determined, and defined as the difference in $NH_4^+$-N concentrations before and after digestion in a mixture of $H_2SO_4/CuSO_4$ (US EPA, 2001) in a block digestion unit (Technicon BD-40). Total N was defined as the sum of the organic and inorganic N fractions. All samples were stored at 4 °C during periods of inactivity.

### 2.4. Leaching calculations

Monthly water budgets were calculated to determine the volume of water moving vertically below the rooting zone by comparing measured precipitation with estimates for potential evapotranspiration as determined by the Thornthwaite method (Dunne and Leopold, 1978). All precipitation and temperature measurements required were recorded on site using a weather station located in the planted buffer zone between two study blocks. For months in which precipitation values were higher than potential evapotranspiration, the net soil-water flux favored leaching beyond the rooting zone. When the converse was true, no leaching was assumed to have occurred. Due to the nature of the precipitation in this region, and with an overwhelming majority falling during October–March when evapotranspirative demands are relatively low, we assumed that once the soil profile became saturated, it remained at or above field capacity throughout the duration of the rainy season. Due to the lack of movement of a wetting front, it was not necessary to factor net soil-water storage into the monthly water budget as described by Iseman et al. (1999). Given the nature of both the slope and the precipitation, as well as soil infiltration rates greater than precipitation, it was also determined that unlike Ring (1995), surface runoff was not a necessary addition to the water budget calculation. At no time has standing water or runoff ever been observed at the site, even during the wettest times of the year, or the most intense rainfall events.

The Thornthwaite method has been shown to underestimate potential evapotranspiration at equatorial latitudes (Dunne and Leopold, 1978), which would lead to overestimates of net soil-water leaching fluxes. We assumed, however, that at temperate latitudes characterized by less intense solar radiation inputs, and specifically in maritime climates with greater intrannual variability in temperature and precipitation regimes, the magnitude of the differences would be lower. In order to assess the potential for errors in the estimation of potential evapotranspiration to alter the conclusions of this study, a sensitivity analysis was performed by observing the change in leaching estimates by dramatically exaggerating potential evapotranspiration.

### 2.5. Total soil N pool

Prior to harvest, 64 vertical soil cores were extracted from locations within the randomized complete block design. Four cores were taken from within each of four randomly chosen plot locations in each of the four treatment blocks. Soil was excavated using a JMC Backsaver soil probe (Clements Associates, Inc., Newton, IA) to an average depth of 80 cm. Each soil core was divided into sections for further analysis. A horizons were separated from the remaining mineral soil material after recording horizon thickness. The remaining mineral soil was then divided into four additional depth increments (DI) from the bottom of the A horizon as follows: DI 1 = 0–10 cm, DI 2 = 10–30 cm, DI 3 = 30–50 cm and DI 4, representing the remaining core depth. Separate, homogenized sub-samples of each core segment were then oven-dried (105 °C for greater then 24 h) and weighed for bulk density calculation. This method of determining bulk density was determined not to be significantly different from excavating a soil pit, and measuring bulk density with traditional horizontal soil cores. The remainder of each sample was then ground to pass through a 2 mm sieve and thoroughly homogenized before further sub-sampling for total N analysis using a Perkin-Elmer Model 2400 CHN analyzer (Perkin-Elmer, Wellesley, MA) and pH (Orion Research Model 230A, 1997) using a 1:1 ratio of soil to distilled deionized water. Total N pools for each depth increment were then expressed in terms of kg $ha^{-1}$.

### 2.6. Statistical analysis

Differences in monthly soil solution N concentrations and leaching rates were tested using a one-way ANOVA across all three observations (BO, TP and FS). The desire to relate treatment observations (BO and TP) to the adjacent stand (FS), coupled with the uniformity of the study area in terms of soil characteristics, slope and aspect, required the performance of statistical analyses via a model without the benefit of the blocking factor typically utilized in randomized complete block designs. This was done because the portions of the initial stand retained for investigations such as this one were not a part of the original randomized block study design. In addition, annual leaching rates for the various N forms were tested using a one-way ANOVA across the three observations for each individual year, as well as for the mean annual values. Where significant differences occurred ($p < 0.05$), the ANOVA procedure was followed by a Tukey's honestly significant difference (HSD) post hoc test to separate treatment effects (SPSS, Version 11.0, 2003).

## 3. Results

### 3.1. N forms and concentrations

A 3-month pilot study, with four lysimeter replicates located in the BO, TP and FS, was conducted from March through June 2000 (nearly 1 year following harvest). Mean monthly total N concentrations ranged from 0.7 to 2.3 mg $L^{-1}$ across all observations. N concentrations were low and there were no significant treatment differences. Mean concentrations (±S.D.) were: BO = 1.8 (±1.0) mg N $L^{-1}$; TP = 1.3 (±0.8) mg N $L^{-1}$; FS = 1.0 (±1.2) mg N $L^{-1}$ (Flaming, 2001). Nitrate was the predominant form of N in solution in the BO and TP treatments, comprising 71 and 88%, respectively.

The data collected from the four replicates was used to assess the variance associated with monthly total N concentrations for the three observations. Based on this analysis, and the objective of detecting significant differences in mean total N concentrations at the Type I error rate of 0.05, eight replications were required in the harvest treatments and no additional replication was necessary in the FS.

During the pilot study of March–June 2000, and from the inception of sampling in this study in April 2001 (nearly 2 years following harvest) to January 2002, total N concentrations in the BO and TP treatments were similar. There was a sharp peak in concentrations in all treatments during the August–September period in 2001 (Fig. 1a). This is believed to be a sampling anomaly associated with soil solution being drawn into the lysimeters over a period of acute, heavy rainfall preceded by dry conditions.

The BO treatment began yielding increased concentrations relative to the other treatments in late 2001 (third year after harvest), with clear differences observed between the two treatments starting in February 2002, and continuing through most of 2003 (fourth and fifth years after harvest) (Fig. 1a). The BO treatment generally had total N concentrations two to three times those in the TP treatment during this period. Starting in September 2003 and continuing to the end of the sampling period in March 2004, total N concentrations in the BO and TP treatments exhibited decreasing trends, and were no longer significantly different from one another. Further, there appeared to be a slight trend in the BO treatment for total N concentrations to be higher in the warmer months and lower in the colder months. Excluding the first year of observations in this comparison because of the perceived anomaly, mean (±S.E.) total N concentrations (mg $L^{-1}$) in the BO treatment for the December–February periods of 2002 and 2003 were 5.0 (±0.5), as opposed to 7.5 (±0.2) for the June–August periods of the same years.

The FS consistently showed very low total N concentrations throughout the entire study period, with the exception of the August–September 2001 period. Total N concentrations in the TP treatment were generally an order of magnitude larger than the FS treatment, but because of the relatively low concentrations and variability about these low total N values, differences between these two treatments were never statistically significant (Fig. 1a).

Total N concentrations are predominately driven by $NO_3^-$-N, with $NO_3^-$-N constituting 91, 83 and 58% of the total N values in the BO, TP and FS treatments, respectively. This is further reinforced through identical trends in significant differences of $NO_3^-$-N concentrations between the treatments with respect to those observed for total N concentrations (Fig. 1b).

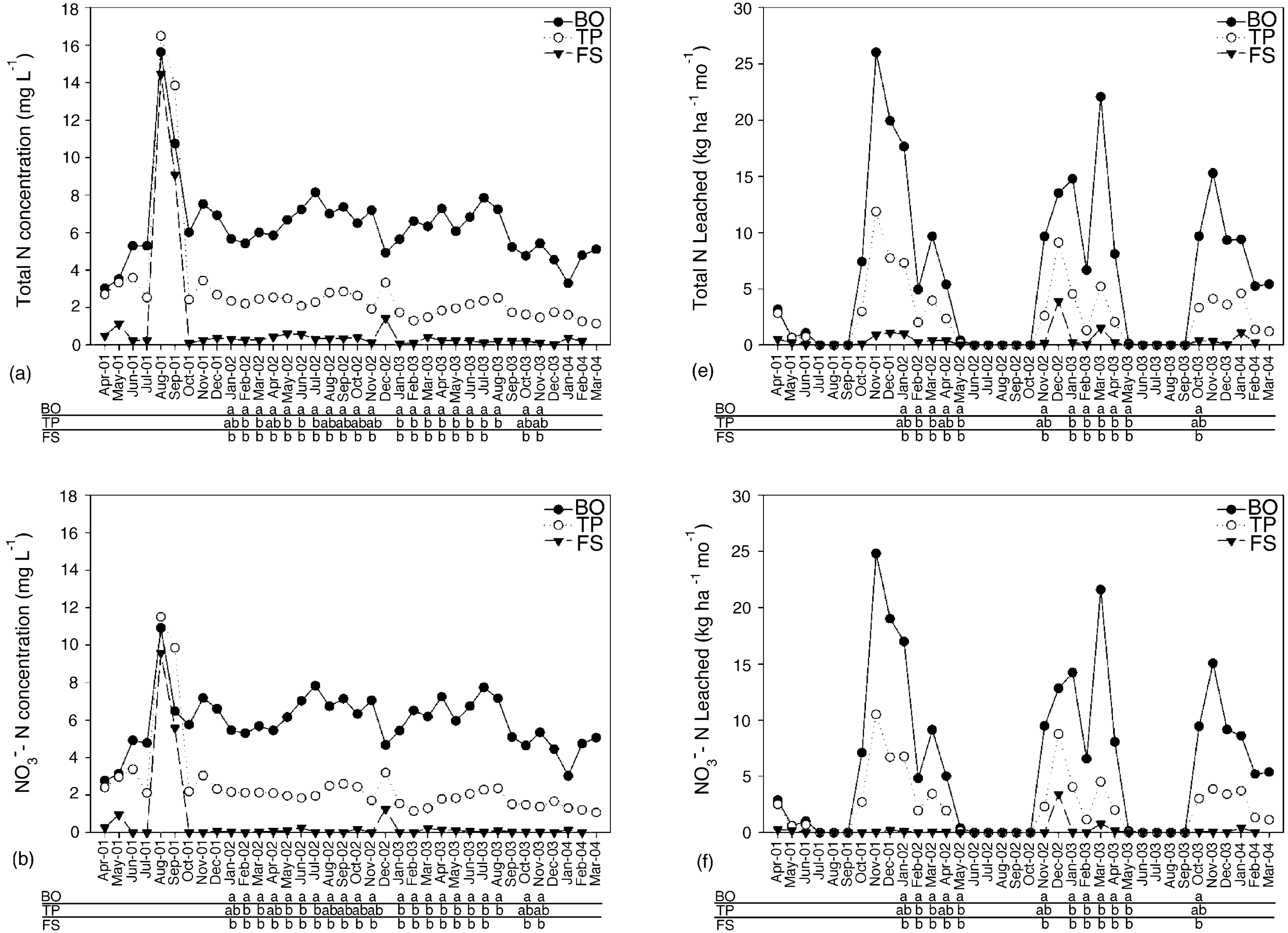

Fig. 1. Concentration (mg N L$^{-1}$) and leaching rate (kg N ha$^{-1}$ yr$^{-1}$) for total N and individual forms of N at 1.0 m depth for BO (solid circles), TP (open circles) and FS (solid triangles) given from 3 to 5 years after harvesting. Different letters represent significant differences ($p < 0.05$, ANOVA, Tukey's HSD) between treatment observations for a given month.

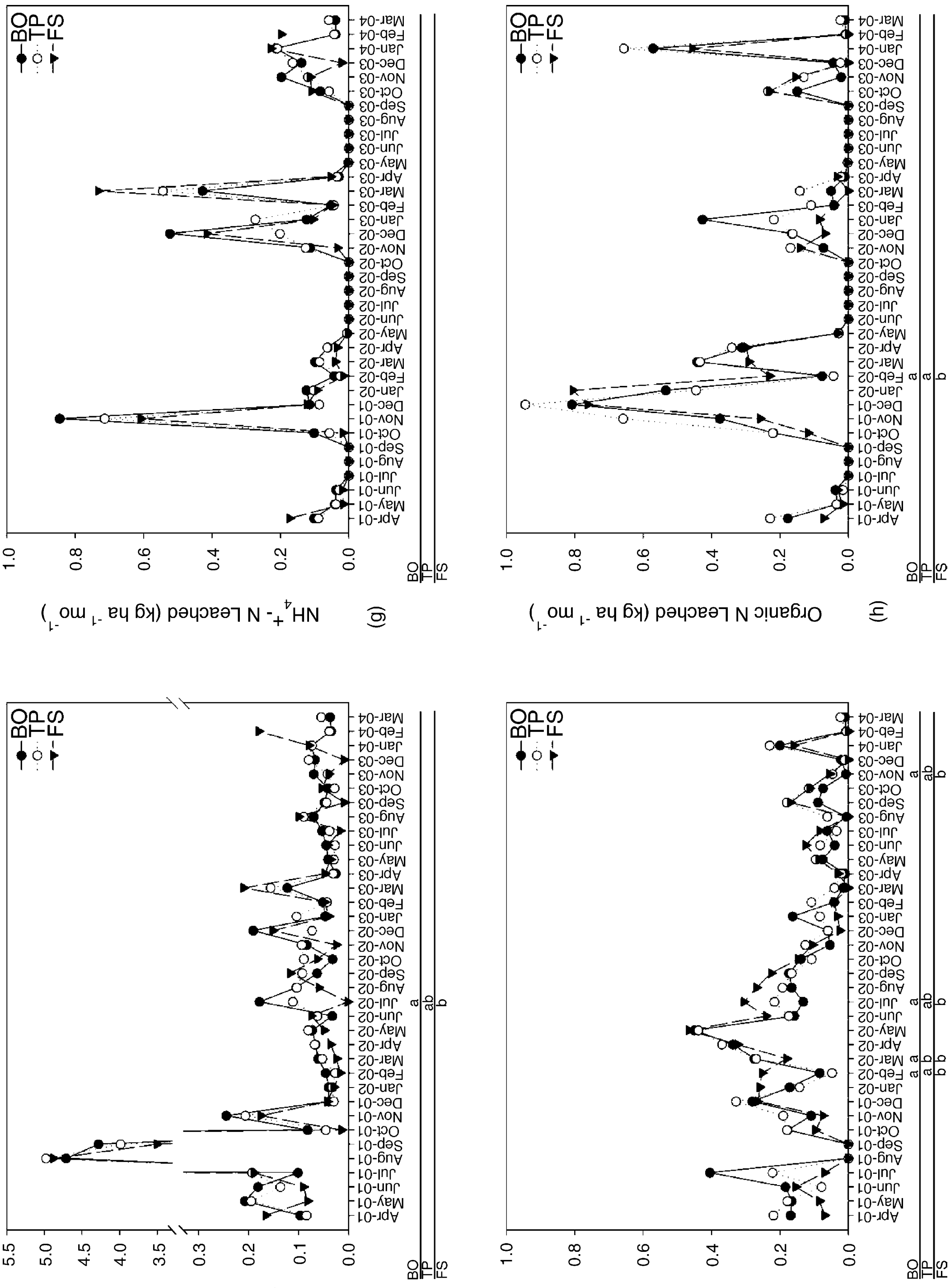

Fig. 1. (*Continued*).

Ammonium contributed considerably less to the total N concentration, particularly in the two harvest treatments. While comprising only 7% of the total N in the BO, and 13% in the TP, $NH_4^+$-N constituted 31% of the N concentration at a depth of 1.0 m in the FS. Ammonium also exhibited a large spike in concentration during the August–September 2001 sampling period, reaching nearly 5 mg $NH_4^+$-N $L^{-1}$ in all three treatments. However, throughout the rest of the study, $NH_4^+$-N concentrations remained consistently below 0.25 mg $L^{-1}$, and showed no clear trend with respect to treatment (Fig. 1c).

Organic N made up the smallest fraction of total N, representing only 2, 5 and 11% of the total N concentration in solution at 1.0 m depth in the BO, TP and FS treatments, respectively. Similar to $NH_4^+$-N however, organic N comprised a larger portion of the total N pool in the FS than in either of the two harvest treatments. Additionally, organic N showed no clear trend in terms of concentration with treatment, and remained consistently less than 0.5 mg N $L^{-1}$ throughout the study (Fig. 1d).

### 3.2. Net soil-water flux

In 12 of the 36 months observed in this study, net soil-water flux did not favor the leaching of soil-water beyond the rooting zone (Fig. 2). Three of those months occurred during the summer of 2001 (July–September), five more occurring consecutively from June through October 2002, and four additionally during the period of June–September 2003. The discrepancy in the duration of the soil-water leaching period of the 3 years of observation is reflective of the specific water budgets for those years. An estimated 1465 mm of the 1887 mm of precipitation leached beyond a depth of 1.0 m for the year April 2001–March 2002 (year 3 since harvest). The following 12-month period (year 4 since harvest), both leaching and precipitation decreased to 1219 and 1560 mm, respectively. The final 12-month period (year 5 since harvest) fell between the two previous observations, with an estimated soil-water leaching flux of 1361 mm and recorded precipitation of 1708 mm. Despite the difference in precipitation inputs, roughly the same proportion left the system via leaching (∼78%) each year.

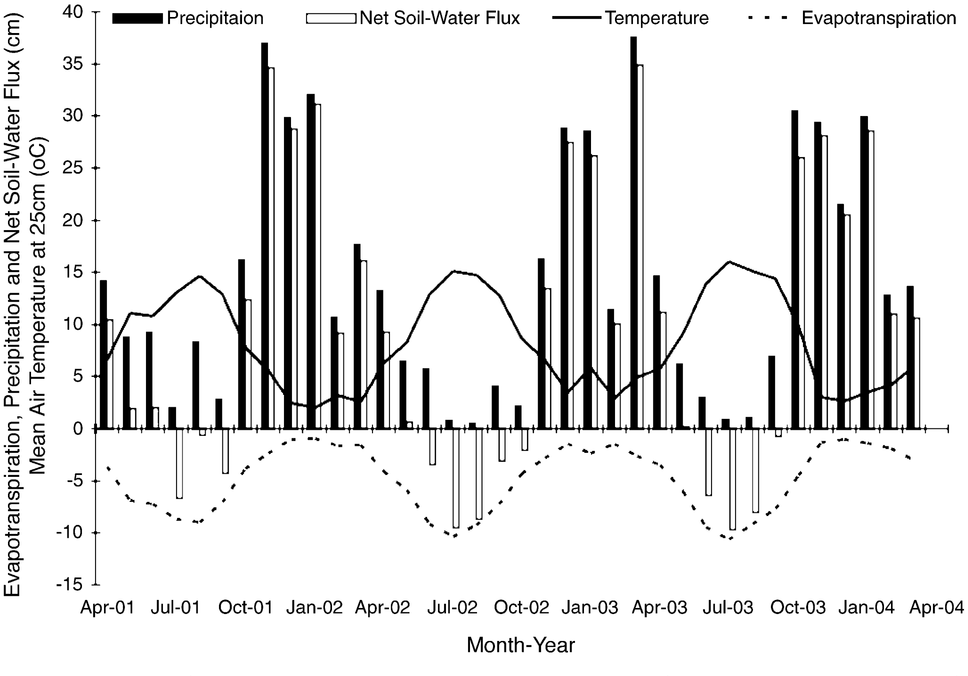

Fig. 2. Evapotranspiration (cm $mo^{-1}$), air temperature (°C) at 0.25 m, precipitation (cm $mo^{-1}$) and net soil-water flux (cm $mo^{-1}$) over the study period. (Net soil-water flux is the difference between precipitation and evapotranspiration so that a positive net soil-water flux value indicates a leaching flux.)

### 3.3. N leaching

Coupling monthly soil solution concentrations (Fig. 1a–d) with monthly estimates for net soil-water flux (Fig. 2), gives an estimate of monthly soil solution N leaching rates (Fig. 1e–f), and allows for the estimation of annual leaching rates (Table 1) by summing consecutive monthly values. Monthly evaluations of leaching for the various N components and total N exhibited similar patterns in significance to those observed for concentration (Fig. 1), with the exception of the months in which no leaching was assumed to have occurred.

Mean annual total N leaching rates for the 3-year period observed were higher in the harvested treatments than observed in the forested stand (Table 1), with the BO treatment leaching significantly more ($p < 0.05$) than the other two treatments. Significant differences in annual leaching rates were observed among treatments for $NO_3^-$-N and total N, but not for $NH_4^+$-N or organic N (Table 1). Total N leaching rates averaged over the study period (years 3–5 since harvest) were 75, 29, and 4.5 kg ha$^{-1}$ yr$^{-1}$ for the BO, TP, and FS treatments, respectively. An additional 47 kg ha$^{-1}$ yr$^{-1}$ total N leaching to a depth of 1.0 m thus resulted from retaining the conventional logging residues and forest floor coarse woody debris on site, as opposed to removing this material.

Table 1

Annual leaching of N (kg ha$^{-1}$) after harvesting (year 3: April 2001–March 2002, year 4: April 2002–March 2003, year 5: April 2003–March 2004) and mean annual leaching rates for the 3-year period

| | Bole-only | | | Total-tree+ | | | Forest | | |
|---|---|---|---|---|---|---|---|---|---|
| Year 3 | | | | | | | | | |
| $NO_3^-$-N | 86 | (28) | a | 36 | (7.2) | a,b | 0.9 | (0.1) | b |
| $NH_4^+$-N | 1.5 | (0.2) | a | 1.2 | (0.1) | a | 1.1 | (0.2) | a |
| Organic N | 2.3 | (0.4) | a | 2.6 | (0.4) | a | 2.3 | (0.2) | a |
| Total N | 91 | (28) | a | 40 | (7.3) | a,b | 4.6 | (0.4) | b |
| Year 4 | | | | | | | | | |
| $NO_3^-$-N | 70 | (13) | a | 23 | (3.4) | b | 4.4 | (0.6) | b |
| $NH_4^+$-N | 1.3 | (0.3) | a | 1.3 | (0.3) | a | 1.4 | (0.5) | a |
| Organic N | 1.5 | (0.1) | a | 1.5 | (0.2) | a | 1.0 | (0.1) | a |
| Total N | 73 | (13) | a | 25 | (3.5) | b | 6.4 | (0.4) | b |
| Year 5 | | | | | | | | | |
| $NO_3^-$-N | 61 | (15) | a | 19 | (4.8) | a,b | 0.8 | (0.2) | b |
| $NH_4^+$-N | 0.7 | (0.1) | a | 0.7 | (0.0) | a | 0.7 | (0.1) | a |
| Organic N | 0.9 | (0.5) | a | 1.2 | (0.2) | a | 0.9 | (0.2) | a |
| Total N | 63 | (14) | a | 20 | (4.7) | a,b | 2.4 | (0.4) | b |
| Annual mean | | | | | | | | | |
| $NO_3^-$-N | 73 | (9.8) | a | 26 | (3.4) | b | 2.0 | (0.1) | b |
| $NH_4^+$-N | 1.2 | (0.1) | a | 1.1 | (0.1) | a | 1.1 | (0.1) | a |
| Organic N | 1.5 | (0.1) | a | 1.8 | (0.1) | a | 1.4 | (0.1) | a |
| Total N | 75 | (9.9) | a | | | b | 4.5 | (0.1) | b |

Standard errors of the means are in parentheses. Different letters across rows represent significant differences ($p < 0.05$, ANOVA, Tukey's HSD) between treatment observations for N components. Rounding to two significant digits may prevent proper summation of total N values.

### 3.4. Pre-harvest mineral soil N pool

The average depth of the A horizon across the 64 measured cores was 12.3 cm, or 15% of the total soil depth sampled. However, it represented a larger proportion of the total soil N pool, comprising a mean of 2813 kg N ha$^{-1}$ (21%) of the total 13,143 kg N ha$^{-1}$ pool to 80 cm. Total N concentration decreased with depth (0.46–0.11%), but bulk density increased from 0.54 g cm$^{-3}$ in the A horizon to 1.08 g cm$^{-3}$ in the DI 4 sampling strata (Table 2). (Forest floor and coarse woody debris pools were assessed in a separate investigation and results are noted in the next section.)

Table 2

Bulk density, pH and N concentration and content for each mineral soil horizon or sampling depth increment (DI)

| Horizon/depth increment | Mineral soil depth (cm) | pH 1:1; soil:DI $H_2O$ | Bulk density (g cm$^{-3}$) | N (%) | N (kg ha$^{-1}$) |
|---|---|---|---|---|---|
| A | 0–12.3 | 4.62 (0.06) | 0.54 (0.05) | 0.46 (0.02) | 2813 (247) |
| DI 1 | 12.3–22.3 | 4.75 (0.03) | 0.65 (0.02) | 0.35 (0.01) | 2241 (74) |
| DI 2 | 22.3–42.3 | 4.81 (0.03) | 0.75 (0.02) | 0.25 (0.01) | 3693 (105) |
| DI 3 | 42.3–62.3 | 4.83 (0.03) | 0.94 (0.02) | 0.14 (0.01) | 2668 (224) |
| DI 4 | 62.3–80.0 | 4.78 (0.04) | 1.08 (0.06) | 0.11 (0.01) | 1728 (153) |
| Total | 0–80.0 | | | | 13143 (565) |

Standard errors of the means are given in parentheses.

## 4. Discussion

Leaching has been identified as a principle mechanism for N loss in Pacific Northwest Douglas-fir ecosystems (Gessel et al., 1973). Nitrogen leaching is often exacerbated by disturbances to the biological and hydrological regimes of these systems that can occur following harvesting practices (Quails et al., 2000). As N is widely regarded as a limiting nutrient for plant growth in these systems, it is important to understand the potential role of harvest utilization on the N dynamics of a highly productive stand in order to guide management practices and ensure long-term site productivity. Understanding the N dynamics and changes in soil solution N concentrations over time may also illuminate potential mechanisms affecting seedling growth differences among organic matter retention treatments within the study.

### 4.1. Temporal trends

While numerous studies have documented a gradual increase in total N leaching over the first few years following harvest (Dahlgren and Driscoll, 1994; Hornbeck and Kropelin, 1982; Katzensteiner, 2003), most N leaching pulses have been shown to return to pre-harvest levels by the third year (Briggs et al., 2000; Hornbeck and Kropelin, 1982; Hornbeck et al., 1990; Katzensteiner, 2003; Titus et al., 1998). On this site, total N concentrations did not reach maximum values until the fall of the third year following harvest, and N concentrations continued to remain elevated relative to those observed in the non-cut stand into the sixth year. These observed trends are likely due to numerous site-specific characteristics, including the high-productivity level of the site, total nitrogen content of the soil, soil mineralogy and differing climatic regimes of this study compared with those of the Northeastern USA (Briggs et al., 2000; Dahlgren and Driscoll, 1994; Hornbeck and Kropelin, 1982; Hornbeck et al., 1990) and in the case of Katzensteiner (2003), the Austrian Alps. Additionally, there were marked differences in the stand fertilization histories and treatment of competing vegetation in other studies versus our investigation. None of the other studies included stands with similar fertilization histories, nor did they have continued complete vegetation control as applied in the BO and TP treatments of this study. Work by Ring (1995) illustrated increased N leaching following clear-cut harvesting of previously fertilized stands in which leaching was positively correlated with stand fertilization history. However, even at comparable fertilization levels with those of the Fall River LTSP site, the annual N leaching rates estimated by Ring were one to two orders of magnitude lower than those seen here, a difference likely attributable to the cooler climate in Sweden (annual mean air temperature is 1–2 °C), the lower rainfall (mean precipitation is 558 mm) and differing vegetation control management strategies. On the same site as Nohrstedt et al. (1994) reported N leaching to a depth of 50 cm 3 years following a clear-cut of a previously fertilized *Pinus sylvestris* stand. The concentrations of the differing N fractions in soil solution tended to decrease in all treatments from pre-harvest conditions during the first 2 years (with lower than normal precipitation). Before harvest and during the 2 years following clear-cutting, $NO_3^-$ predominated only in the plots receiving the maximum fertilization dose (three times over a 20-year period at 600 kg N ha$^{-1}$). During the third year increases in N occurred in the treatments receiving the three highest fertilization levels. No total N leaching rates were derived, but N concentrations were mostly less than 1 mg L$^{-1}$, with the highest mean values less than 2.5 mg N L$^{-1}$ during the coarse of the study. Despite similar fertilization levels, the differences in soil solution N concentrations between those observed in Sweden and at the Fall River LTSP study are likely due to lower temperature and precipitation values as well as the lack of vegetation control.

Flaming (2001) conducted mineralization studies on the same BO and TP treatments as in our study during March and June of the first growing season (2000) and observed that net organic N in the forest floor increased by 18% in the BO treatment but decreased by 8% in the TP treatment. It was also observed that the concentration of N present in soil solution collected from lysimeters at 0.2 m decreased with increasing levels of organic matter retention. A subsequent mineralization study in these same treatments was conducted by Licata (2004). Using the resin core technique in the forest floor and 0–0.2 m mineral soil depth for the period from the end of the first growing season through the middle of the second, Licata showed no significant treatment effect for N mineralization, with N-mineralization rates of 65 and 50 kg $ha^{-1}$ $yr^{-1}$ for the BO and TP treatments, respectively. Mineralization studies were not conducted in the third growing season when the N concentrations at 1.0 m were observed to differentiate by treatment. It appears that the forest floor and coarse woody debris in the BO treatment was acting as an N sink for the first 2 years following harvest, since solution N concentrations in the BO treatment did not significantly increase compared to the TP treatment until the third year after harvest.

As seen here and in other studies (Goodale et al., 2000; Iseman et al., 1999), N leaching exhibits seasonal trends, often elevated by precipitation inputs and reduced by biological uptake associated with the growing season, as reflected in the net soil-water budget. With regard to N concentrations however, this study did not exhibit strong trends by season, regardless of N form or observed treatment, despite these factors. There was a slight trend toward higher N concentrations in the BO during the warmer summer months versus the colder winter months in the third and fourth year after harvest which may be best explained by the ability of increased precipitation in the winter to dilute soil solution concentrations with respect to N, while the warmer months may have been more favorable for increased N mineralization of the available forest floor biomass.

The peak concentrations associated with the August and September 2001 samplings are most likely due to the rapid movement of mineralized forms of N in response to intense and acute precipitation events that occurred during the period of sample collection immediately following warmer, drier periods in which net N mineralization is presumed to be high. During the period in which the August 2001 samples were being collected, the site received over 70% of the monthly precipitation total, including a single day precipitation event of 40 mm (nearly half of the monthly total). Similarly, the sample collection period preceding the September 2001 sampling event received 60% of the total monthly precipitation. Despite the effect of such precipitation events on $NO_3^-$-N, $NH_4^+$-N and total N concentrations, leaching estimates were not influenced due to a larger evapotranspirative demand relative to precipitation inputs in the water budget calculations for those respective months.

### 4.2. *Sensitivity analysis*

The Thornthwaite water budget calculations can underestimate potential evapotranspiration at equatorial latitudes (Dunne and Leopold, 1978). This would, in effect, result in an overestimation of the volume of water leached vertically through the soil profile and contribute to exaggerated nutrient leaching estimates. While considerable differences in climate associated with the latitude of this study would likely decrease the discrepancy between various methods for modeling potential evapotranspiration, a sensitivity analysis was performed by both dramatically increasing calculated potential evapotranspiration rates by 100 and 200%, and decreasing them to zero in order to determine the effect that these changes would have on annual N leaching rates. Doubling the rate of evapotranspiration depressed total N leaching by 11–12% of the mean annual rate so that 67, 25 and 4.0 kg $ha^{-1}$ were leached in the BO, TP and FS treatments, respectively. Increasing the calculated rates of evapotranspiration three-fold depressed total N leaching between 21 and 23% across all observations. Further, holding evapotranspiration at zero for all months, and considering that all precipitation leached to a depth of 1.0 m, increased the mean annual total N leaching rates to 100, 43 and 11 kg $ha^{-1}$ for the BO, TP and FS treatments, respectively. Through evaluation of the potential range in leaching rates that our sensitivity analysis offered, we have confidence that the use of the Thorthwaite method to estimate potential evapotranspiration can be employed for a site with climate and rainfall patterns similar to this one, where most of the rainfall occurs during the winter months when soils are at or above field capacity.

### 4.3. *N flux versus pool size*

Despite the relatively high-N leaching rates observed in the 3 years of monitoring soil solution in this study, it is important to discuss the leaching flux in terms of the total mineral soil, forest floor and coarse woody debris N pools by treatment. This will aid our ability to assess the potential of N leaching losses to impact future productivity at various levels of harvest utilization and organic matter retention. With a mineral soil N pool in excess of 13,000 kg $ha^{-1}$, to a depth of only 80 cm, the soils of the Fall River LTSP site are N-rich relative to the observations of Gessel et al. (1973), in which other studies in western Washington, on soils of similar parent material, are reported to have total mineral soil N values ranging from 8800 to 14,700 kg $ha^{-1}$ to a depth of 1.2–1.6 m. These values for mineral soil N pools correspond well with productivity indices of the current study, and referenced stands as well.

Relative to the total N pool in mineral soil to a depth of 80 cm, the observed flux in N via soil solution represents a small loss. Extrapolating the mineral soil N pool to a depth of 1.0 m based on increasing the thickness of the B4 depth increment by an additional 20 cm, brings the mineral soil N pool to roughly 15,100 kg $ha^{-1}$. Based on this estimate, the mean annual N leaching losses observed represent 0.5% of the total pool for the BO treatment, 0.2% for the TP treatment, and <0.03% for the FS (cumulative totals of 1.5, 0.6 and <0.1%, respectively).

In a separate study characterizing forest floor and coarse woody debris biomass and nutrient contents for the treatment units following harvest, there was an additional 742 kg N $ha^{-1}$ in the BO (in the forms of forest floor and coarse woody debris biomass-logging slash and remnant old-growth logs) and 309 kg N $ha^{-1}$ for the TP treatment (almost exclusively in the form of residual forest floor biomass) that needs to be added to the site N pools. Thus, there was a difference of 433 kg N $ha^{-1}$ in the BO treatment relative to the TP treatment in these forms of organic matter (Piatek, pers. commun., 2005). Although this study was not designed to determine what proportion of the N leachate actually came from the mineral soil versus the forest floor/logging slash, over the 3 years of observation in this study, N leaching losses were proportional to the forest floor and coarse woody debris N capital in the harvest units, and represent roughly 30% of these pools in the two respective treatments. Despite these nutrient pool additions to the mineral soil N capital of the two treatments, there was little effect on the overall proportion of N leached to a depth of 1.0 m relative to the cumulative N capital, due to the overwhelming influence of mineral soil N on such calculations.

In addition to the considerations of the total mineral soil and harvest residual N pool sizes, it is important to interpret the results of this study within the context of the following site- and study-specific considerations: (1) a fertilization history of over 840 kg N $ha^{-1}$ of urea between 1970 and the present, (2) the complete vegetation control of the observed harvested treatments, (3) the high site quality index of the stand, and (4) and annual precipitation in excess of 1700 mm falling predominately during the period of lowest plant uptake.

The trends observed in this study with regard to the duration and magnitude of N leaching relative to other managed forest stands reinforces the notion of Mann et al. (1988) that long-term observational studies of the nutrient cycling dynamics of such systems are needed to better understand the effects of harvest intensity on future site productivity. This seems particularly valid for highly productive, intensively managed systems as observed in this study, which seem to leach N at higher rates than observed in other Douglas-fir stands (Gessel et al., 1973; Mann et al., 1988), and raises questions regarding the potential of additional cation nutrient losses associated with elevated $NO_3^-$-N leaching.

### 4.4. Implications for productivity

As N is often viewed as a limiting nutrient for plant growth in these ecosystems, it is important to place the N leaching losses observed in this study in the context of subsequent stand productivity. As leaching rates in the BO and TP treatments were significantly different in periods during the third and fourth growing season and then decreased with time in such a manner that there was no statistically significant difference from the FS at the end of the sampling period (corresponding to the beginning of the fifth growing season), comparisons of current seedling growth between treatments may illuminate implications on current and future tree biomass yields. Seedling growth performance in the BO and TP treatments were not different from one another at the end of the third growing season, nor were there differences in foliar N levels (Roberts et al., 2005). Further, seedling growth differences between these two treatments were not observed at the end of fourth growing season either (Terry and Harrington, unpublished data). Although short-term implications of the organic matter removal level in the TP treatment have not been detrimental to tree growth, we plan to continue monitoring N leaching rates, as well as tree growth parameters to further understand the implications of organic matter retention on system nitrogen dynamics and longer term plantation performance.

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