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Responses of available soil nitrogen and litter decomposition to openings of different sizes in dry interior Douglas-fir forests in British Columbia

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Abstract

Selection of an appropriate silvicultural system that maintains productivity requires an understanding of the effects of harvest type on post-harvest changes in nitrogen availability. The effects on inorganic nitrogen availability and litter decomposition of various harvesting systems, including partial canopy removal and a range of clearcut opening sizes, were investigated in a dry Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest in southern British Columbia. We measured concentrations of ammonium and nitrate after 6-week buried bag incubations of forest floor and mineral soil samples in replicated plots within uncut forest, within partially harvested forest, and in openings of 1.7, 0.4, and 0.1 ha, from two to seven growing seasons after harvest. Post-incubation nitrate and the proportion of inorganic N as nitrate in forest floor and mineral soil were elevated from 2 to 7 years after harvesting in the 1.7 ha openings. There was no consistent trend of higher ammonium concentration in either uncut forest or 1.7 ha openings. The proportion of inorganic N as nitrate was consistently the lowest in the uncut forest, and often significantly different from any opening treatment, including partial cutting. The increased proportion of inorganic N as nitrate occurred within 11 m of the uncut forest edge. At very low moisture contents, nitrate concentrations tended to zero only in the uncut forest. Leaching of the increased available nitrate is unlikely because of the large increase in grass biomass that occurs after harvesting, and the dry soil moisture conditions during the growing season. Decomposition of Douglas-fir, lodgepole pine and trembling aspen litters, or forest floor was inconsistently, or not affected by any harvest treatment or by distance from, or aspect of, the edge of the forest. The post-harvest increases in nitrate concentrations cannot be attributed to faster decomposition.
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Keywords: Nitrogen; Decomposition; Silvicultural system; Nitrate; *Pseudotsuga menziesii*; Mineralization

1. Introduction

The influence of opening size on nitrogen (N) cycling processes is of interest in the selection of an appropriate silvicultural system because N availability limits productivity in many forest ecosystems. There are also concerns that increased N leaching from forested systems following harvesting may reduce both water quality levels and soil productivity (Bormann et al., 1974; Schimel et al., 1997). Changes in N mineralization following clearcut harvesting have been well documented in a wide range of ecosystems (Vitousek et al., 1979; Binkley and Hart, 1989). The effects of smaller opening sizes and partial overstory

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removal on microbial communities, N availability and nitrification are less clear.

There are indications that N mineralization is increased, relative to uncut forest, even in very small openings. Nitrogen mineralization rates increased within openings of approximately 0.025 (Parsons et al., 1994) and 0.25 ha (Prescott et al., 1992) created in lodgepole pine forests, and in European beech forests in openings of 30 m diameter during the first year after cutting (Bauhus, 1996). The effects of small openings on nitrification and nitrate concentrations in the soil have been inconsistent. Nitrate concentrations in soil increased in small gaps in Costa Rica (Denslow et al., 1998), and in the interior of British Columbia (Prescott et al., 2003), but rates of net nitrification and nitrate leaching in small patch cuts and partial openings were not different from those in uncut forests in coastal British Columbia (Prescott, 1997; Feller et al., 2000). Any changes in N availability may also vary with aspect and distance from the forest edge (Bauhus, 1996; Edmonds et al., 2000). In coastal Douglas-fir, 5 years after harvest there were no differences in N mineralization or nitrification between uncut forests and partial cut or clearcut sites (Barg and Edmonds, 1999). The magnitude and duration of the increased nitrate production observed after harvest appears to vary with forest type (Vitousek et al., 1982).

The mechanism that leads to increased nitrate levels in clearcuts is unclear. In many ecosystems it is thought that tree removal increases temperature and moisture levels in forest soils, resulting in changes to microbial communities and increased microbial activity. Larger ammonium and nitrate concentrations in clearcuts have often been attributed to accelerated decomposition by more active microbial communities. However, in drier climates, overstory removal may result in reduced growing season moisture in the forest floor (Redding et al., 2003), but not generally in the mineral soil. Lower moisture content may result in reduced microbial activity and mineralization of N (Miller and Johnson, 1964; Stanford and Epstein, 1974; Meyers et al., 1982). Reductions in the amount of litterfall and changes in the nature of litter inputs that occur after harvesting as early successional species and understory shrubs dominate the site may also influence nitrate production. A reduction in the annual amount of carbon reaching the forest floor in litter may reduce microbial immobilization, leading to increased rates of nitrification (Hart et al., 1994).

In order to test many long-held assumptions about the effects of harvesting on the ecology of dry forests, a long-term examination of silvicultural options in British Columbia's interior Douglas-fir forests was initiated at the Opax Mountain study site (Klenner and Vyse, 1998). Key soil processes identified for study at the site were decomposition and mineralization of organic matter, and availability of N. The principal objectives of the present study were to investigate the magnitude and duration of any effect of various sizes of harvested openings, including partial canopy removal and a range of clearcut opening sizes, on inorganic N availability and decomposition. Secondary objectives were to investigate if the processes affecting N availability and decomposition were influenced by distance into the opening and relate changes in these processes to soil microclimatic factors.

2. Methods

2.1. Study site

The Mud Lake study site is within the Opax Mountain Silvicultural Systems Trial, located approximately 20 km northwest of Kamloops, BC, in the interior Douglas-fir very dry, hot (IDFxh) biogeoclimatic unit (Lloyd et al., 1990). The mean annual precipitation for this subzone is 379 mm, with an average of 185 mm occurring during the May–September season (Lloyd et al., 1990). Snow begins to accumulate on site by mid-November and disappears in late April. Soil water deficits develop on site by mid-August of most years. Mean annual temperature for the subzone is 4.8 °C. Mean monthly temperatures in May–September during 1997–2001 in a clearing approximately 200 m above the study site were 11.2, 12.8, 16.1, 15.6, and 9.7 °C, respectively (R. Adams and A. Orchansky, unpublished data). Elevations range from 950 to 1100 m, and slopes range between 0 and 20%, with variable aspects.

Prior to harvesting, the overstory consisted mainly of Douglas-fir with a few ponderosa pine (*Pinus ponderosa*) on dry slopes, and aspen (*Populus tremuloides*) and spruce (*Picea engelmannii* × *glauca*) on

Table 1
Selected chemical properties of material from the uncut control forest or used in decomposition studies

Material	C (g kg^{-1})	N (g kg^{-1})	C:N	pH	Lignin[a] (g kg^{-1})
Forest floor (LFH)	347	13	27.0	5.4	338
Mineral soil (0–20 cm)	26	1.2	20.5	5.3	–
Fresh Douglas-fir litter	511	4.6	111	–	128
Lodgepole pine litter	521	4.6	113		188
Trembling aspen litter	487	7.9	62		96

[a] Klason lignin, the acid insoluble residue remaining after digest.

wetter sites. Trees range in age from 70 to 220 years (Bealle-Statland, 1998). The understory on well-drained sites is dominated by pinegrass (*Calamagrostis rubescens*), with minor cover of snowberry (*Symphoricarpos albus)*, birch-leaved spirea (*Spiraea betulifolia*), tall Oregon grape (*Mahonia aquifolium*), and *Aster* species.

Soils are loam and sandy loam textured Orthic Gray Luvisols and Orthic Eutric Brunisols (Soil Classification Working Group, 1998), with a range in average forest floor thickness of 2.5–4.0 cm and a Hemimor humus form (Green et al., 1993). The chemical properties of the forest floor, mineral soil, and fresh litter in the uncut forest is summarized in Table 1 (Hope, unpublished data).

2.2. Experimental design

A range of opening sizes and residual stem densities was created by harvesting on the site. Five different opening size treatments were sampled in the present study: control (uncut) forest; single-tree selection, or ''partial cut'' (50% canopy removal in a 20 ha block); 0.1 ha (31 m^2) ''small'' openings within a 20 ha patch cut block; 0.4 ha (60 m^2) ''medium'' openings within a 20 ha patch cut block; and 1.7 ha (120 m^2) ''large'' openings within a 20 ha patch cut block. Harvesting treatments were randomly allocated to 20 ha blocks. The site was harvested in the winter of 1993/1994. Site preparation using excavators to create screefed microsites approximately 1 m^2 and spaced approximately 3 m apart occurred in the spring of 1994 and the area was planted immediately afterwards with Douglas-fir, lodgepole pine (*Pinus contorta* var. *latifolia*) and ponderosa pine seedlings.

To investigate opening size effects, 10 m × 10 m plots were established near the centre of each of three replicate openings of each size (0.1, 0.4 and 1.7 ha), and in three replicate locations within the 20 ha single-tree removal and uncut treatment blocks. Plots in the single-tree removal and uncut forest blocks were located in representative areas that ranged from dense canopies to small gaps. Additional 10 m × 5 m plots were established along north–south transects across two of the 1.7 ha blocks for 1996 nitrogen sampling and 1997–1999 decomposition sampling. All plots were located on mesic (midslope, well-drained) sites in all treatments.

2.3. Sampling and data analysis

2.3.1. Inorganic N concentration

Ammonium (NH_4-N) and nitrate (NO_3-N) concentrations were determined after field incubations of forest floor and mineral soil from two to seven growing seasons (1996–2001) after harvest. During 1996 (28–32 months after harvest), only a single transect across one 1.7 ha opening was sampled. Samples of forest floor and mineral soil were incubated in plots (approximately 5 m × 10 m) along a straight line transect across the centre of the opening. A total of nine plots were located along this transect, in the uncut forest 25 m from the north and south edges, at 2, 10 and 25 m into the opening from the north and south edges, respectively, and in the centre of the opening. During the incubation period from 16 May to 19 June 1996, only three plots along the transect were sampled (the uncut forest at the south end, 2 m from the south end, and the centre of the opening). In 1997, the three replicate plots of the five opening size treatments were sampled, i.e., only the plots at the centre of each of three replicate openings of each size (0.1, 0.4 and 1.7 ha), and in three replicate locations in the partial cut and uncut treatment blocks. In 1998 and 2001, samples were incubated in the three replicate plots of the 1.7 ha and control treatments. Actual incubation

dates and the approximate number of months after harvest that the incubations ended were as follows: 16 May–19 June 1996 (28); 19 June–7 August 1996 (30); 7 August–1 October 1996 (31); 1 October–31 October 1996 (32); 8 May–18 June 1997 (40); 18 June–30 July 1997 (42); 30 July–10 September 1997 (44); 11 August–22 September 1998 (56); 24 May–3 July 2001 (90).

At each sampling time, between 8 and 10 samples of the forest floor and the upper 10 cm of mineral soil were collected from randomly selected, undisturbed (by site preparation) locations within each plot. Roots and live vegetation were removed and about 100 g of forest floor or mineral soil was placed in a 12 cm × 20 cm polyethylene bag, sealed, and reburied in the forest floor or soil near the place from which it had been removed (Prescott et al., 1992). After about 6 weeks, the bags were retrieved. A portion of each sample was oven-dried at 70 °C for 48 h and reweighed, to determine gravimetric moisture content (moisture content as % of oven-dry mass). Final concentrations of NH_4-N and NO_3-N were determined following extraction in 2 M KCl (Page et al., 1982). Analyses were completed from 1996 to 1998 at Griffin Laboratories in Kelowna, BC, using a Technicon autoanalyzer, and in 2001 at UBC Soil Science Laboratory, Vancouver, BC, using a Lachat Quik-Chem AE (2001) autoanalyzer.

Our purpose was to characterize inorganic N in the rooting environment of seedlings, not examine the mineralization–nitrification–immobilization process. Post-incubation concentrations were the most appropriate index for this purpose because they integrate both initial concentrations and rates of net production of mineral N during incubation. All inorganic N concentrations presented are post-incubation values.

2.3.2. Litter decomposition

Decomposition rate was determined by measuring the weight loss of needle and leaf litter and forest floor using the litterbag technique, in which known-weight samples are enclosed in fiberglass mesh bags and incubated on site. Three types of litter were used: Douglas-fir, lodgepole pine (*P. contorta* Loudon) and trembling aspen (*P. tremuloides* Michx.). Freshly fallen Douglas-fir foliar litter and forest floor FH material was collected in August 1995 from the uncut forest at the study site. The pine needle litter was collected from a lodgepole pine site in the Kananaskis Valley of Alberta described by Prescott et al. (1989). The aspen leaf litter was collected from a nearby aspen grove described by Taylor et al. (1989). All litters were collected in 0.125 m^2 plastic trays with fiberglass mesh in the bottom to minimize leaching. Roots and wood were removed from the forest floor material. The litterbags containing the Douglas-fir, pine and aspen litter were constructed of fiberglass screening (Alpha Tent and Awning, Burnaby, BC, Canada), 10 cm × 10 cm, with 1.5 mm rectangular pores. Bags used to contain forest floor material were made of fiberglass mesh (Alpha Tent and Awning) with approximately 0.55 mm pores. Two grams of oven-dried (at 65 °C) litter or forest floor were inserted into the bags and the open end was stapled shut. All bags were transported to the site in separate envelopes and spillage into the envelope was weighed and subtracted from the original weight.

In October 1995, five litterbags of each type were placed at each of seven sub-plots within the three replicate 10 m × 10 m plots of the five treatments. The same replicate plots were used for mineralization studies. In October 1996, five litterbags of Douglas-fir and pine litter, and forest floor were placed at seven sub-plots within each of eight plots located along a straight line across the centre of a single 1.7 ha opening. The plots along the transect were located in the uncut forest at the north end, at 2, 10 and 25 m from the north and south edges, respectively, and in the centre of the opening. Bags containing needle litter were pinned to the surface of the forest floor; bags containing forest floor material were buried in the forest floor. One bag of each type was collected from each sub-plot annually for 5 years from the opening treatment plots ($n = 7$ per plot), and for 3 years from the transect study plots ($n = 7$ for forest floor and pine, $n = 5$ for Douglas-fir). The contents of each bag were dried at 65 °C for 48 h, and the mass of litter remaining was measured.

2.3.3. Statistical analysis

All analyses were conducted using SAS for Windows software (version 8.02, SAS Institute, Cary, NC, 2001). For all analyses, data were log or arcsine transformed where needed to meet the assumptions of ANOVA. Where ANOVA showed significant

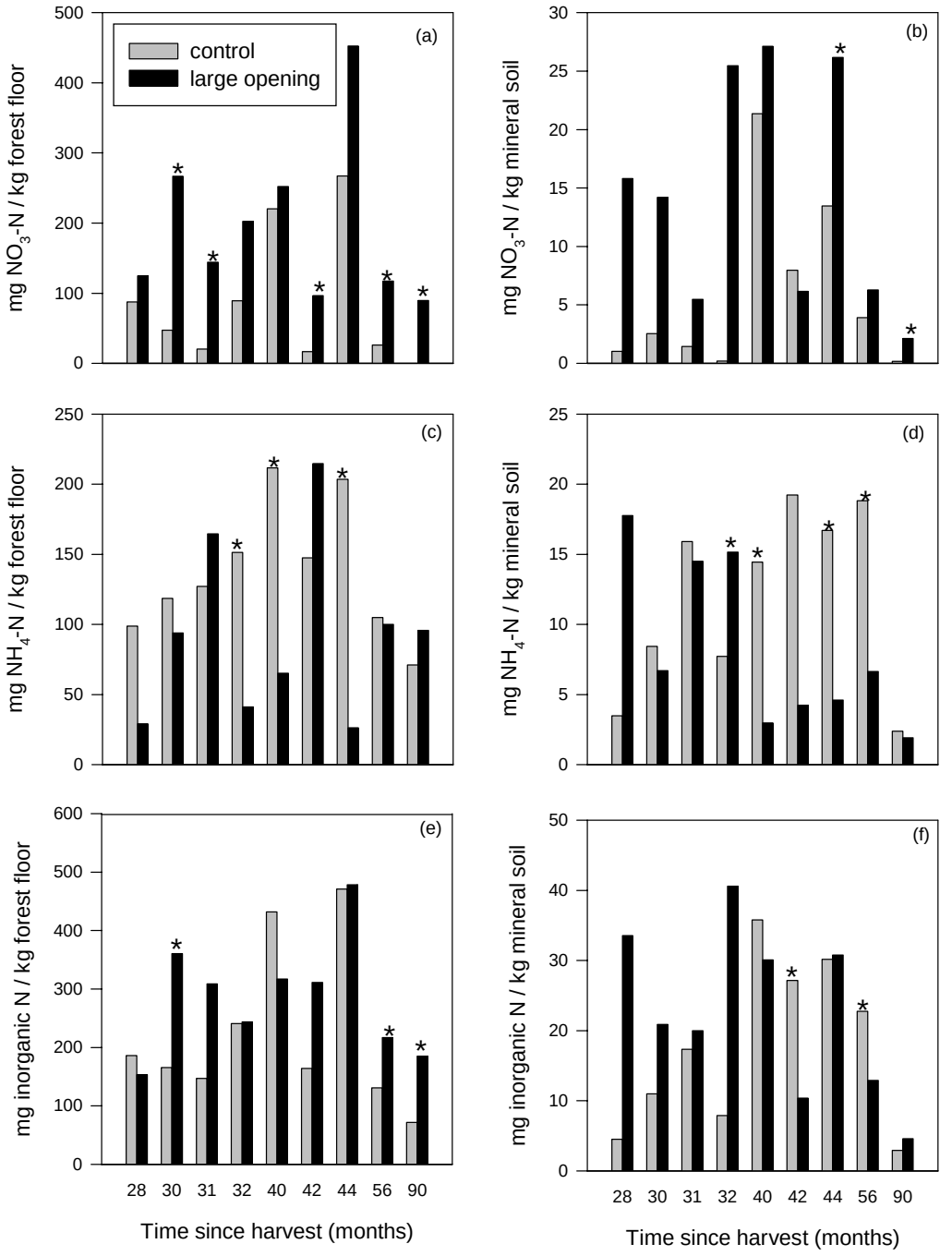

Fig. 1. Forest floor and mineral soil concentrations of NO_3-N (a and b), NH_4-N (c and d), and total inorganic N (e and f), and the proportion of inorganic N as NO_3 (g and h) following incubation in uncut forest and large (1.7 ha) openings. Significant differences ($P < 0.10$) are indicated with an asterisk. Values for 28 months after harvest are the means of eight subsamples taken in one location in an opening and in one forested area; no statistical analyses were performed on these data. Data for 30–32 months after harvest are from three plots (8–10 subsamples/plot) along a transect in one large opening and from two forested areas. All other data are from three replicate treatment plots.

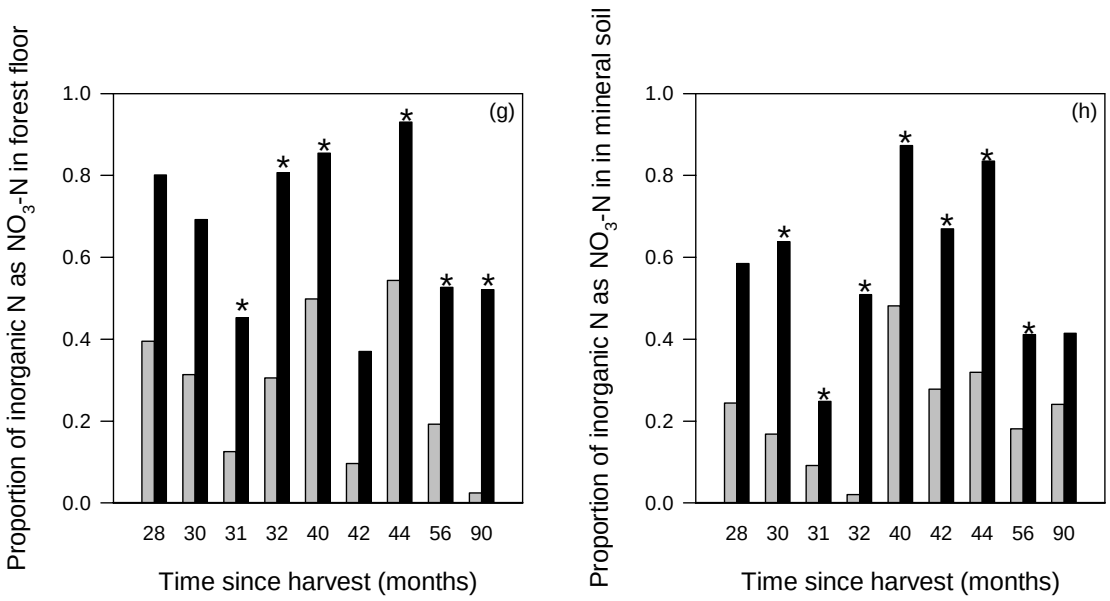

Fig. 1. (*Continued*)

treatment effects, means were separated using Tukey's multiple range test. The accepted level of significance was $P < 0.1$, unless stated otherwise.

To test the effect of large openings on nitrate and ammonium concentrations, data from 1996 to 2001 were used. For 1997–2001, data from centre plots in the three replicate 1.7 ha openings and uncut forest were analyzed as a completely randomized experiment using a one-way ANOVA. For 1996 only, two plots in the forest at either end of the transect and the three plots in the opening located 25 m or greater distance from the forest edge were used and the data were analyzed using a one-way ANOVA. To test the effect of opening size treatment on inorganic N, the 1997 nitrogen data were analyzed as a completely randomized design using a one-way ANOVA. Exploratory statistical analyses only were conducted on the 1996 repeatedly sampled transect data; means and standard deviations only are presented.

To test if opening size influenced decomposition rate, the mass of litter remaining each year was analyzed using a one-way ANOVA. The effect of distance from the edge of the clearcut on decomposition was determined by performing a one-way ANOVA on the mass of litter remaining in each year at each station along the transect.

3. Results

There was a weak trend, occasionally significant, of increased total inorganic N concentrations in the forest floor, but not in the mineral soil, in the large openings compared to the uncut forest (Fig. 1a). The differences in inorganic N were primarily caused by increased NO_3 concentrations in the openings (Fig. 1a and b). During the 7 years following harvest there were some significant differences in NH_4 concentrations between the forest and the clearcut, with an inconsistent trend of higher NH_4 in the uncut forest (Fig. 1c and d). The proportion of inorganic N as NO_3 was consistently higher in the large opening than in the uncut forest in both the forest floor and the mineral soil (Fig. 1g and h). The proportion of inorganic N that was NO_3 increased by 27–57% in forest floor and by 16–51% in mineral soil. These increases in the proportion of NO_3-N occurred consistently between 2 and 7 years following harvesting.

The size of the opening did not significantly affect concentration of total inorganic N or NO_3-N in forest floors and mineral soils (Fig. 2a and c). Significant differences in NH_4-N between the forest and some opening sizes were sometimes observed, although these differences were small and inconsistent. However,

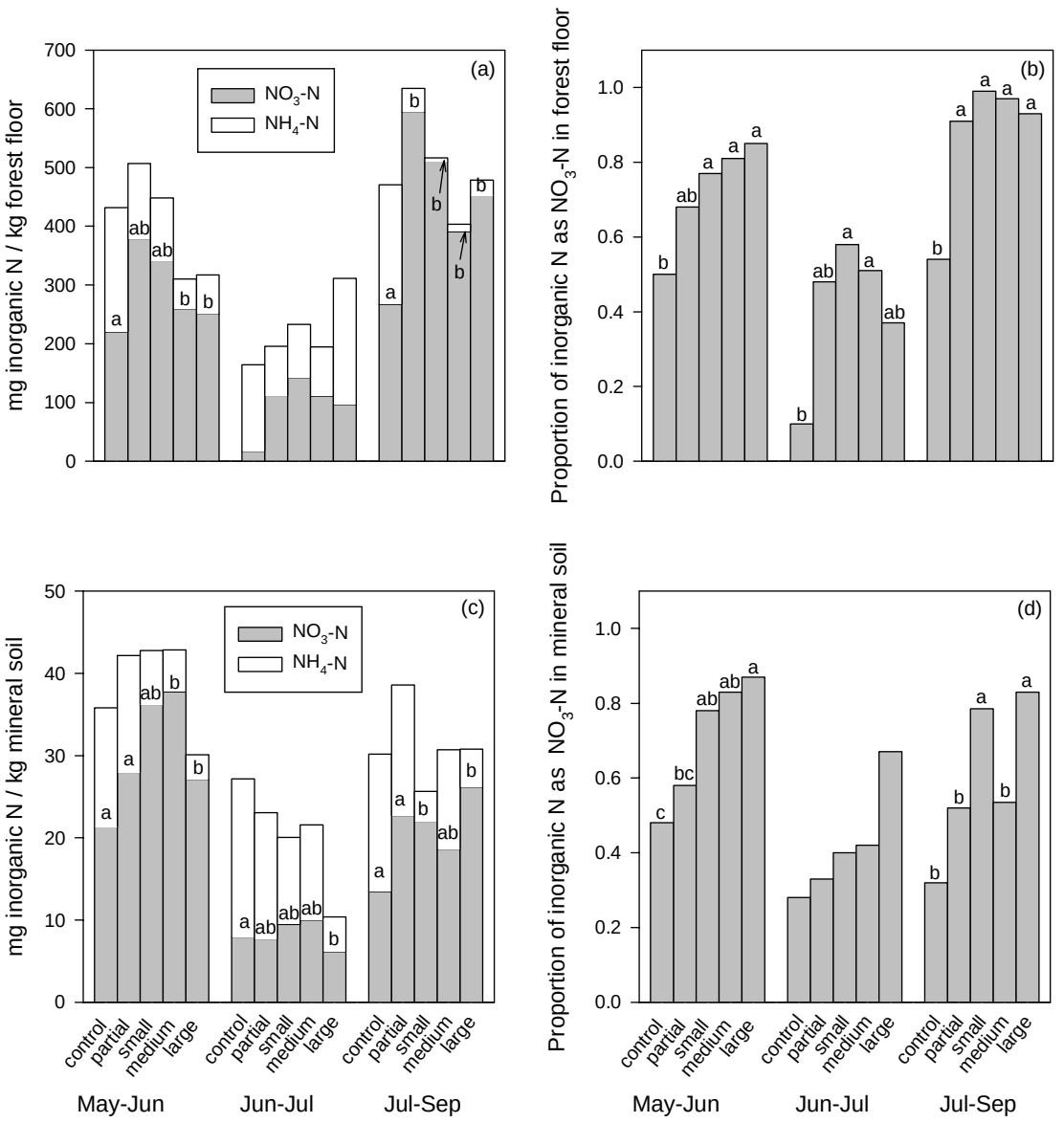

Fig. 2. Concentrations of inorganic N (NO_3-N + NH_4-N) and proportion of inorganic N as NO_3 in forest floor (a and b) and mineral soil (c and d) samples following incubation in several opening treatments at Mud Lake. Samples were incubated during the 1997 growing season, 40–44 months after harvest. Three incubation periods are included. Each value is the mean of three replicates (8–10 subsamples per replicate). Means with different letters are significantly different. ($P < 0.10$).

the proportion of N as NO_3 was consistently the lowest in the uncut forest, and often significantly different from any opening treatment. Single-tree selection harvesting also increased the proportion of NO_3 relative to the uncut forest; this change was more apparent in the forest floor than mineral soil. The effect of size of opening on N concentrations was not affected by sampling time during the growing season.

Data for samples collected at defined distances from the forest edge along a north–south transect (Fig. 3) 2 years after harvest suggest that, for any one sampling

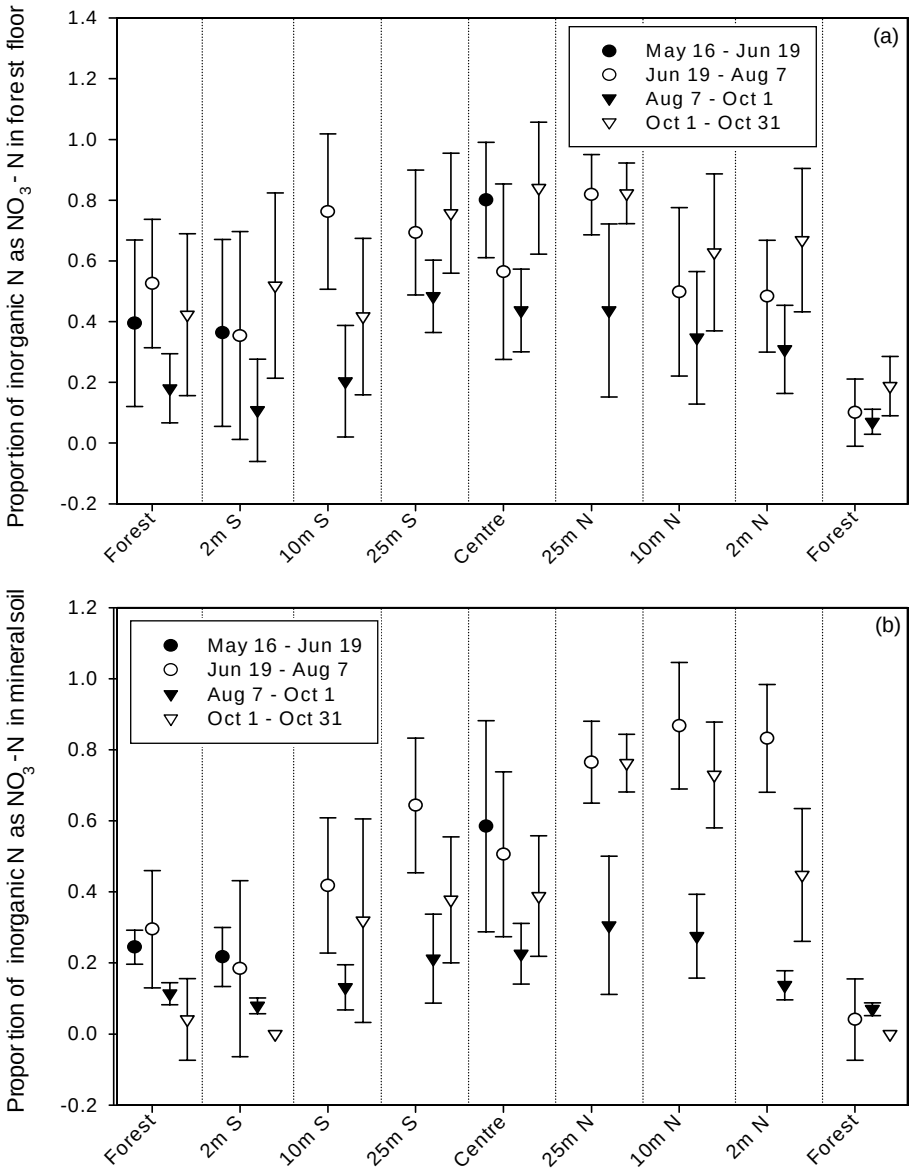

Fig. 3. The proportion of inorganic N as NO_3 in forest floor (a) and mineral soil (b) along a transect across a 1.7 ha clearcut at Mud Lake. Samples were incubated during the 1996 growing season, 28–32 months after harvest. Four incubation periods are included. Values are the means of eight subsamples at each plot. Error bars represent standard deviations. Means within a plot are offset for clarity.

period, the proportion of inorganic N as NO_3 was lower within the forest and along the south edge than at other points out in the opening or along the north edge, i.e., the increase in the proportion of inorganic N as NO_3 occurred between 2 and 10 m on the south (north-facing) edge, but within 2 m from the north edge of the large opening. Although variability was high and lack of replication prevents statistical testing, the same trend was apparent throughout the snow-free season.

Differences between the moisture contents of the forest floor or mineral soil in the large openings and the uncut forest were rarely significant and there was no consistent trend in the differences (data not shown).

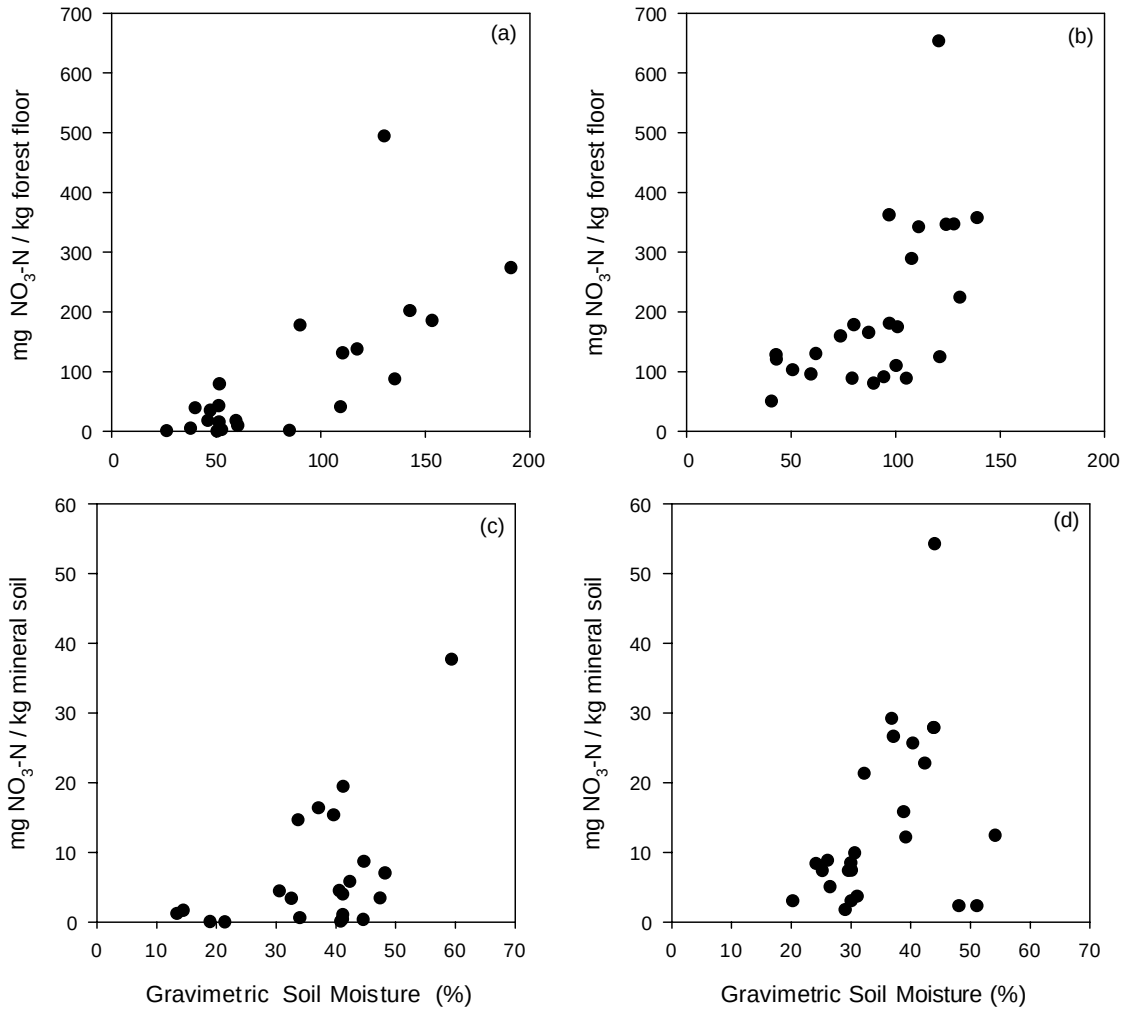

Fig. 4. Mean NO_3-N concentrations in forest floor samples from uncut plots (a) and 1.7 ha openings (b), and of mineral soil samples from uncut plots (c) and 1.7 ha openings (d) as a function of mean gravimetric moisture content. Data are for samples collected in 1996–2001.

The relationship between moisture content and post-incubation NO_3 (Fig. 4) was non-linear, yet exhibited some noticeable general features. In the uncut forest, nitrate concentrations approached zero at moisture contents below 40% in the forest floor, below 25–30% in mineral soil (Fig. 4a and c). In the opening, nitrate concentrations were above zero over the measured range of moisture contents (Fig. 4b and d). NO_3 concentrations in forest floor and mineral soil increased with increasing moisture content in both treatments, and a maximum concentration of NO_3 was not reached within the measured range of moisture contents.

Differences in rates of decomposition of the three litters or forest floor among opening size treatments were small, variable and generally not significant. For aspen, the medium and large openings had significantly less mass remaining after 5 years than the control (Fig. 5c), with partial and small openings intermediate. For Douglas-fir litter, the rate of mass loss in small (0.1 ha) openings was significant greater than the control and large opening over the 5-year period (Fig. 5a). And after 4 years, the partial and control treatments had significantly greater mass loss of forest floor than small and medium openings, although the differences were not apparent at year 5

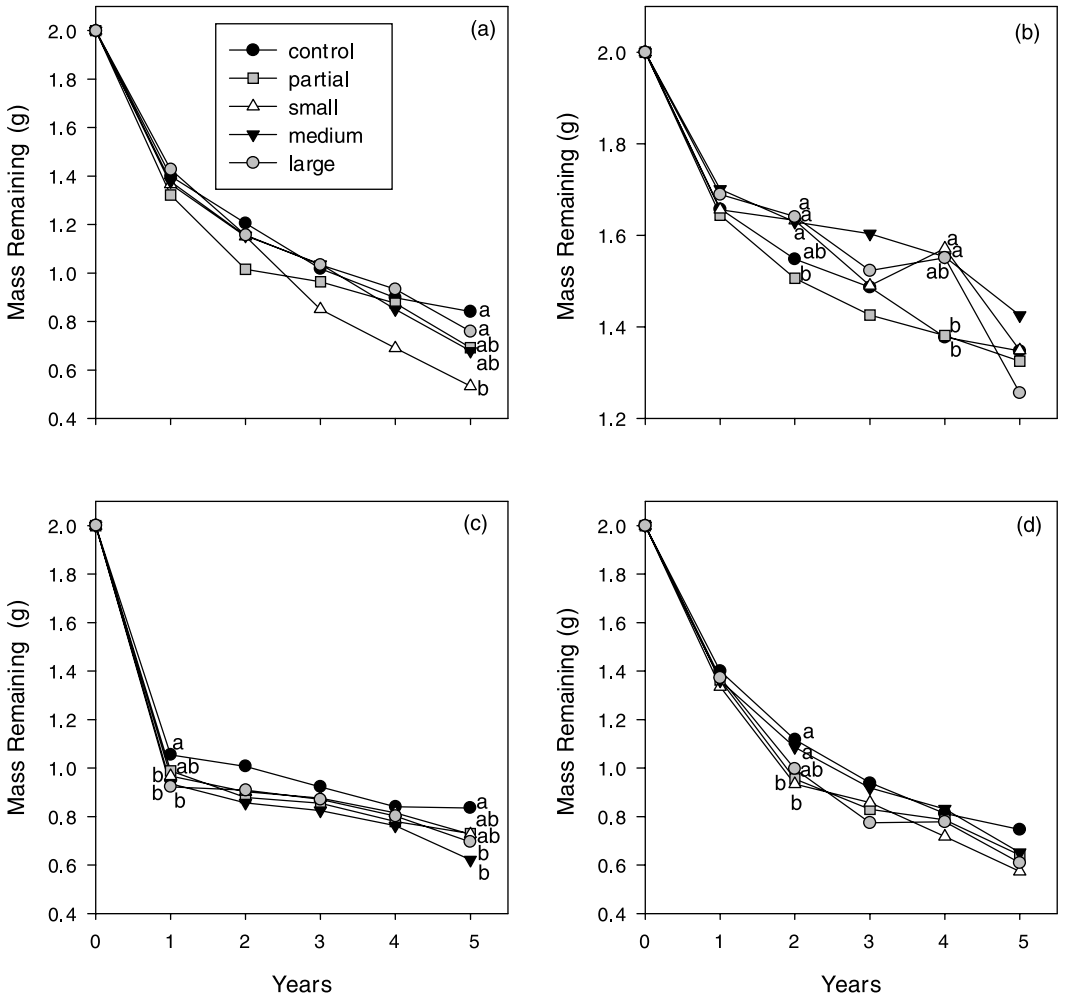

Fig. 5. Mass of Douglas-fir foliar litter (a), forest floor material (b), trembling aspen leaf litter (c), and lodgepole pine foliar litter (d) remaining in the five opening treatments during the 5-year incubation. Means with different letters are significantly different ($P < 0.10$) within a year.

(Fig. 5b). Lodgepole pine showed small, significant differences in rates of mass loss at year 2 (Fig. 5d), but not for other years. All three litters lost between 60 and 70% of their original mass during the 5-year incubation, whereas the forest floor material lost about 35%. Decomposition rates did not show any clear and significant pattern with distance from the edge of the forest. There was a slight trend of the greatest mass loss of forest floor and lodgepole pine after 3 years at the south (north-facing edge) and the least mass loss at the north edge (Fig. 6); this trend was not observed for Douglas-fir litter.

4. Discussion

The most consistent change in the three measured inorganic N pools after harvesting was an increase in the concentration and proportion of NO_3; total inorganic N increased in the large harvested openings only in the first year of sampling, two years after harvest, and NH_4 changes were small and inconsistent. This is consistent with other studies reporting increased abundance and prevalence of NO_3 in clearcuts, and little change in NH_4 pools or rates of net N mineralization (Gordon and Van Cleve, 1987; Mladenoff, 1987;

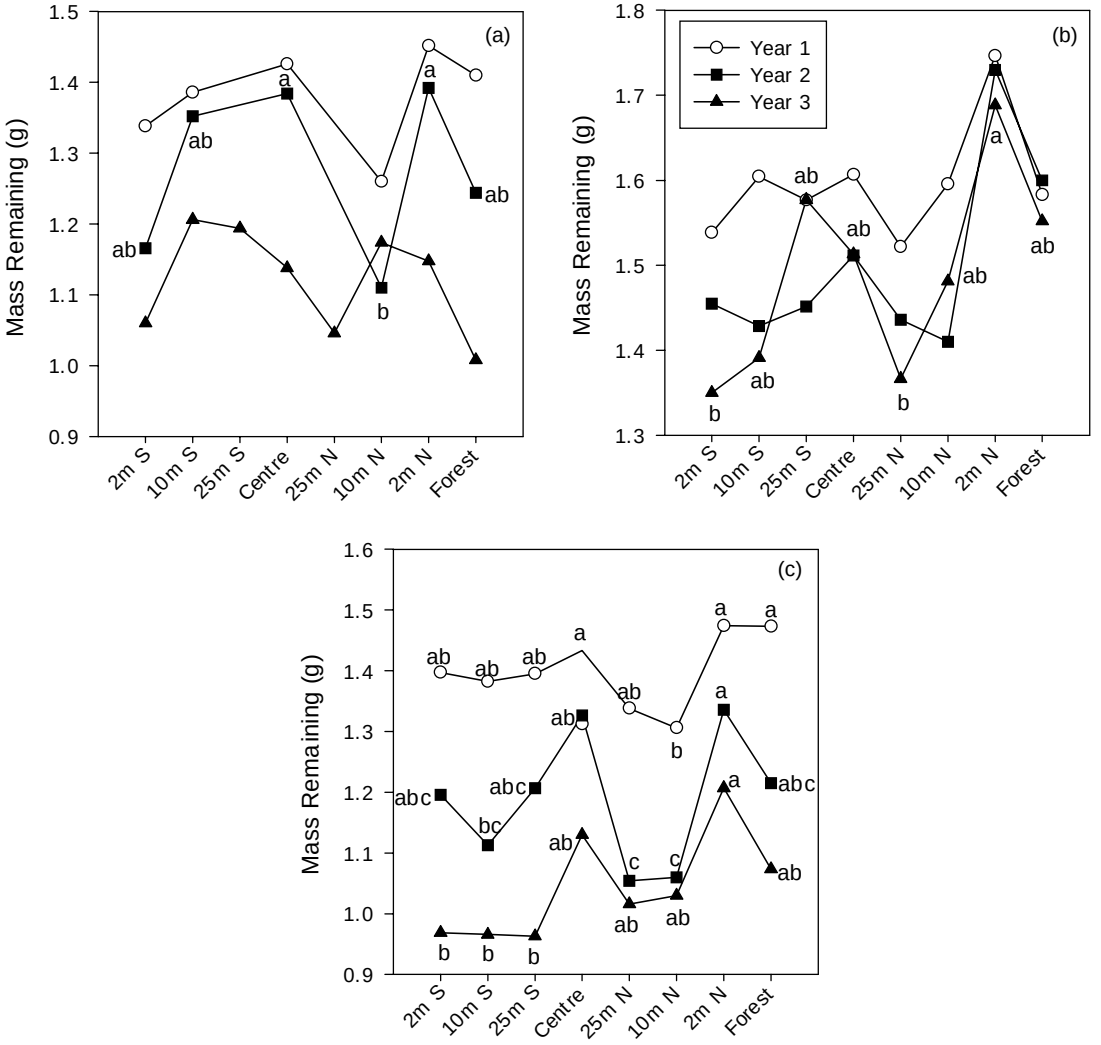

Fig. 6. Mass of Douglas-fir foliar litter (a), forest floor material (b), and lodgepole pine foliar litter (c) remaining at plots along a transect across a 1.7 ha clearcut, during a 3-year incubation. Within 1 year, significant differences ($P < 0.1$) among treatments are indicated by different letters.

Fisk and Fahey, 1990; Denslow et al., 1998). Increases in NO_3 concentrations in large openings that had occurred 2 years after harvest were still evident in the seventh year after harvest. In other studies elevated NO_3 levels began between 0 and 2 years after harvest, and lasted between 2 and up to 6 years (Martin and Pierce, 1980; Feller and Kimmins, 1984; Hendrickson et al., 1989; Dahlgren and Driscoll, 1994; Prescott et al., 2003).

Neither increasing size of opening nor partial harvesting appeared to consistently affect concentration of NH_4 or NO_3. The strong trend of an increased proportion of post-incubation NO_3 and the weak trend of decreases in NH_4 concentrations occurred in both forest floor and mineral soil after any size of harvesting disturbance, even partial harvest. In similar Douglas-fir–ponderosa pine forests, DeLuca and Louhar (2000) found no effect of partial cutting on extractable NO_3 and NH_4, nor mineralizable N. In other forest types, gaps rather than partial removal of trees are required before increased NO_3 is detected (Parsons et al., 1994; Bauhus, 1996; Prescott, 1997;

Barg and Edmonds, 1999; Denslow et al., 1998; Prescott et al., 2003).

Because samples with increased NO_3 concentrations were collected between 11 and 16 m from the forest edge in 0.1 ha opening plots, and from between 2 and 11 m away from uncut forest in the partial cuts, these data indicate that the influence of the forest edge on nitrate production disappears within 16 m of the edge. The data from the single N–S transect further suggest that increases in NO_3 occurred between 2 and 10 m from the edge, with possible variation with edge aspect. Redding (2001) found that increased NO_3 occurred between 2 and 6 m from the edge of an Engelmann spruce–subalpine fir forest in the interior on BC. In the same study, edge aspect influenced soil temperature and moisture but not the observed rate of increase in nitrification. The present study also suggests that the forest influence on net nitrification is limited to a relatively narrow strip into the opening from the forest edge. More detailed sampling is required to distinguish the specific distance of influence of the forest, and possible aspect influences, on nitrogen processes in these Douglas-fir forest openings.

Gravimetric moisture contents were converted to soil water potentials using bulk density data from the site and the moisture retention curves for a similar mineral soil from a nearby site (Hope, unpublished data), or for forest floor using the procedure of Redding et al. (2003). The threshold below which significant nitrification in the uncut forest occurs in the forest floor corresponds to an approximate soil moisture potential of −3 MPa, that for the mineral soil of approximately −1.5 MPa. Other studies have also reported very low, but not zero, rates of N mineralization and nitrification below a value of −1.5 MPa in mineral soils (Miller and Johnson, 1964; Stanford and Epstein, 1974). In the dry Douglas-fir forests, moisture contents of both mineral soil and forest floor are predominantly at levels well below field capacity (R. Adams, G. Hope, and A. Orchansky, unpublished data). The fact that higher NO_3-N concentrations in large openings, compared to the forest, occurred over the entire range of moisture contents from wet to dry suggest that nitrification occurs at higher levels after harvest throughout the growing season.

The large proportion of inorganic N that was present as NO_3 at this site was surprising, as coniferous forests are characterized as having low soil NO_3 concentrations. Even in the uncut forest, NO_3 usually comprised a third to a half of the post-incubation inorganic N. This is in keeping with other studies in Douglas-fir forests, which have demonstrated surprisingly high amounts of NO_3 in the forest floors (Prescott and Preston, 1994; Thomas and Prescott, 2000). The elevated NO_3 in Douglas-fir forest floors was not attributable to characteristics of Douglas-fir needle litter, and the reason for the elevation is not known.

Increased NO_3 production after harvesting suggests the potential for leaching losses, which have been observed in wetter and warmer forests (Dahlgren and Driscoll, 1994; Feller et al., 2000). However, other supporting vegetation information from the Mud Lake site suggest such losses are unlikely in these dry Douglas-fir ecosystems. Pinegrass and other herbs dramatically increase in cover after harvest. The nutrient concentration of the pinegrass in the openings is not different from that in the forest (Hope, unpublished data). Consequently the increased grass abundance represents a large sink for the increased inorganic N in openings. Moreover, soil moisture contents in these dry grassy ecosystems are generally less than field capacity for the majority of the year, except for a 4–6-week period after snow melt. NO_3 losses during this period in the first year after harvest have been detected using tension lysimeters on a similar site to the Mud Lake site (Hope, unpublished data). In subsequent years, however, no increased losses of NO_3-N compared to unlogged forest were detected even during the short period of relatively high soil moisture content.

The commonly proposed theory that harvesting–related increases in inorganic N availability are related to faster decomposition of litter or humus (Bormann et al., 1974; Edmonds and McColl, 1989; Frazer et al., 1990) was not supported in our study. Although openings had surface soil temperatures 1–3 °C warmer during the growing season (D.A. Lloyd, unpublished data), and were often wetter during the early spring period (R. Adams and A. Orchansky, unpublished data), few consistent, significant differences in decomposition rates over 5 years were observed. This finding is consistent with other studies in which decomposition rates in larger openings were slower or the same as those in uncut forests (Blair and Crossley, 1988; Zhang and Liang, 1995; Denslow et al., 1998; Prescott et al., 2000). Only aspen litter showed a weak trend of increasing rate of decomposition over 5 years with

increasing opening size. Prescott et al. (2000) also found that aspen leaf litter was the only substrate that decayed faster in clearcuts than in adjacent forests. The inconsistent effect of aspect, or direction of the opening edge on both nitrogen release and decomposition at Mud Lake is similar to that observed by Edmonds et al. (2000) in coastal Washington state forests. The differences in individual litter decomposition rates observed in the different treatments or edges at Mud Lake are more likely related to microsite differences than to an opening effect. Because moisture contents of the forest floor during the summer period were similar in all harvest treatments, including uncut forest, moisture levels may have precluded microbial response to the warmer temperatures in the openings. Summer drying of litter exposed on the surface in clearcuts has been proposed to explain the lack of increase in decomposition rates in clearcuts (Prescott, 1997).

5. Conclusions

Harvesting these dry Douglas-fir forests caused a prolonged increase in soil and forest floor NO_3-N concentrations. The increase in NO_3-N occurred in either partially harvested or in a size-range of clearcut-harvested areas, and was observed within 10 m of the undisturbed forest. NH_4-N concentrations, however, were not significantly affected. Decomposition of Douglas-fir, lodgepole pine and aspen litter or forest floor was not consistently affected by any harvest treatment or by distance from, or aspect of, the edge of the forest. Consequently, the post-harvest increase in nitrate concentrations cannot be attributed to faster decomposition after harvest. The results of the present study imply that a range of harvest options in these dry forests will not have a negative impact on N availability and capital. Because of the similarity in response from single-tree removal through to 1.7 ha cuts, patch cutting with a range of opening sizes, partial cutting, and conventional, larger clearcutting all should result in increased availability of NO_3-N, if not total inorganic-N. The large increase in grass biomass that occurs after any of these harvesting options, and the relatively dry soil moisture conditions that occur through most of the growing season, should ensure that the increased available nitrate is retained on site.

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