## INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

**The quality of this reproduction is dependent upon the quality of the copy submitted.** Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®

University of Alberta

# NET AND GROSS NITROGEN MINERALIZATION AND NITRIFICATION IN UPLAND STANDS OF THE MIXEDWOOD BOREAL FOREST FOLLOWING HARVESTING

by

**NADIA CARMOSINI** ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Science

in

Environmental Biology and Ecology
Department of Biological Sciences

Edmonton, Alberta
Fall 2000

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

0-612-59788-1

Canada

**University of Alberta**

**Library Release Form**

**Name of Author:** Nadia Carmosini

**Title of Thesis:** Net and Gross Nitrogen Mineralization and Nitrification in Upland Stands of the Mixedwood Boreal Forest Following Harvesting

**Degree:** Master of Science

**Year this Degree Granted:** 2000

Nadia Carmosini

3 Bradbrook Rd
Toronto ON M8Z 1Y2
Canada

Date: Aug. 25, 2000

# University of Alberta

## Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **NET AND GROSS NITROGEN MINERALIZATION AND NITRIFICATION IN UPLAND STANDS OF THE MIXEDWOOD BOREAL FOREST FOLLOWING HARVESTING** submitted by **NADIA CARMOSINI** in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** in **ENVIRONMENTAL BIOLOGY AND ECOLOGY**.

Ellie E Prepas
Dr. E. E. Prepas (co-supervisor)

Kevin Devito
Dr. K. Devito (co-supervisor)

Dr. S. Bayley

Dr. B. Kotak

Dr. W. B. McGill

Date: Aug. 24, 2000

# ABSTRACT

Net and gross soil nitrogen (N) mineralization and nitrification were quantified for uncut and cut areas of three upland forests following harvest disturbance. In the first growing season after disturbance, net N mineralization and nitrification did not differ detectably between uncut and cut plots in two aspen stands, and rates were within the range expected for this forest type. In contrast, net N mineralization was lower ($X^2 > 27.2$, $P < 0.01$) and net nitrification was higher ($X^2 > 37.2$, $P < 0.001$) in cut than uncut plots of an aspen/conifer stand, and rates were among the lowest reported in the literature. In the second growing season, gross and net N mineralization and nitrification in the aspen/conifer stand did not differ detectably between uncut and cut plots, however, gross mineralization was very high compared to rates reported in the literature, while gross nitrification rates were very low or below detection.

*Dedicated with love to my parents,*
*Gilda and Angelo Carmosini*

## ACKNOWLEDGEMENTS

This study was funded by two Natural Sciences and Engineering Research Council (NSERC) of Canada grants: a Collaborative Special Projects and university/industry grant to the Terrestrial and Riparian Organisms Lakes and Streams (TROLS) project to E.E. Prepas. Thank-you to all TROLS partners: Alberta Pacific Forest Industries Ltd., Weyerhaeuser Canada Ltd., Alberta Environmental Protection, Manning Diversified Forest Products, Syncrude Canada Ltd., Ainsworth Lumber Company Ltd., C & S Resources, Nation Research Council of Canada (NRC) Industrial Reserach Assistantship Program (IRAP), RL & L Environmental Services Ltd., National Water Research Institute, Alberta Economic Development and Tourism. Funding was also provided by the Canadian Circumpolar Institute (Canadian Boreal Alberta Research Grant). Personal financial assistance was provided by a post-graduate industrial NSERC grant sponsored in part by Alberta Pacific Forest Industries Ltd., as well as a Walter H. John's Memorial Fellowship grant, and a graduate student teaching award from the Department of Biological Sciences, University of Alberta.

I am grateful to my supervisors, Dr. Ellie Prepas and Dr. Kevin Devito, for their guidance, expertise and encouragement throughout this study. I am also very grateful to Dr. Bill McGill, who patiently shared his expertise on soil nitrogen ecology with me, and who was particularly instrumental in the experiments for gross N transformations. Thank you to Heather Bears, Michelle Keohane and Lisa Matsuba for cheerful and untiring field assistance. Field help was also provided by Matthew Dance and Greg Taylor. Kind assistance with soil analyses was provided by Clive Figueiredo and Monica Molina-Ayala in the Department of Renewable Resources, and by Patricia Burgess and Greg Taylor in the Department of Biological Sciences. Thank-you to fellow graduate students in the Prepas and Devito lab groups for support and encouragement. In particular, discussions, suggestions and comments from Cherie Westbrook and Mari Veliz were invaluable.

I am especially thankful for the support and love of my parents, Gilda and Angelo Carmosini.

## Table of Contents Page

**Chapter 1** General Introduction

**Chapter 2** Net Nitrogen Mineralization and Nitrification in Aspen-Dominated and Aspen-Conifer Stands in the Boreal Mixedwood Forest

**Chapter 3** Gross Nitrogen Mineralization and Nitrification in an Aspen/Conifer-Mixed Stand in the Boreal Mixedwood Forest

**Chapter 4** General Discussion

## List of Tables

Page

### Chapter 2

### Chapter 3

**Appendix A**

## List of Figures

Page

### Chapter 2

**Chapter 3**

# Chapter 1. General Introduction

## 1.0 Introduction

The Mixedwood Boreal forest ecozone in Alberta, Canada (classification by Rowe, 1972) is experiencing intensive timber harvesting pressure by expanding forestry, and oil and gas industries. Sixty percent of productive forestland in Alberta has been allocated to timber harvesting activities (Alberta Environmental Protection 1996). Timber harvesting disturbance in other forest ecosystems has been associated with increased rates of net soil nitrogen (N) mineralization, nitrification, and N leaching from the terrestrial environment (Likens et al. 1970; Vitousek et al. 1982; Krause 1982). Nitrogen is most often the limiting soil nutrient controlling forest productivity, hence, terrestrial loss of N may further limit forest growth, and leaching of N into adjacent water bodies may increase primary productivity and create water quality problems (Vitousek et al. 1982; Van Miegroet and Johnson 1993; Veliz 1999). The extent to which N mineralization and nitrification in the Boreal Mixedwood may differ between undisturbed and disturbance areas has not been studied. This information for the Boreal Mixedwood will help predict impacts from watershed disturbance on surface waters. The objective of this research was to quantify net and gross N mineralization and nitrification rates in uncut and cut areas of upland aspen-dominated and aspen/conifer-mixed stands. This study focused on the LFH horizon and surface mineral soils during the first two years following harvesting disturbance.

## 1.1 Nitrogen Dynamics in Forest Ecosystems

Nitrogen is most often the limiting element controlling forest production, and hence has been an intensively studied soil nutrient. Only a small fraction of the total N in a terrestrial ecosystem occurs as ammonium ($NH_4^+$-N) and nitrate ($NO_3^-$-N) ions, the forms of N produced by microbial mineralization and nitrification processes and most available to higher plants. Interest in the rates of these microbially-mediated processes has increased since studies have shown that watershed disturbances can elevate net mineralization and nitrification rates and, in certain cases, cause N to leach from the plant-rooting zone to groundwater, lakes and streams (Vitousek 1981; Vitousek et al. 1982; Krause 1982). The extent of N leaching varies among forest ecosystems and logging practices employed (Likens et al. 1970; Vitousek et al. 1982). However, in a study of 17 North American forests, Vitousek et al. (1982) concluded that N leaching is highly dependent on: (1) the amount of N mineralized prior to disturbance, and the increases in mineralization after disturbance; (2) $NH_4^+$-N uptake and factors which delay nitrification; (3) the re-establishment of vegetation and N uptake.

Studies on timber harvesting effects on soil N transformations have focused primarily on temperate forests in the United States or eastern Canada (Likens et al. 1970; Vitousek et al. 1982; Hendrickson et al. 1985, 1989), or boreal forests in eastern Canada and northern Europe (Krause 1982; Rosen and Lundmark-Thelin 1987; Persson and Wiren 1995; Kubin 1998). Timber harvesting has been shown to temporarily reduce plant uptake of water and N, elevate soil temperature, increase the frequency of wetting and drying cycles, and either increase or decrease soil pH (Boring et al. 1981; Frazer et al. 1990; Adams et al. 1991; Schmidt et al. 1996; Berg et al. 1997; Berden et al. 1997). These changes may increase the production of $NH_4^+$-N by N mineralizing bacteria, particularly in regions where the soil C:N content is low (i.e. less than 25) (Vitousek et al. 1982). In aerobic soil conditions where nitrifying bacteria are present, $NH_4^+$-N may be converted to $NO_3^-$-N, a mobile anion in soil solution that may leach from the plant-rooting zone (Paul and Clark 1996). In temperate forests where soil C:N is naturally low, or in forests where soil C:N is anthropogenically reduced by fertilizer addition or atmospheric N deposition, gross N mineralization in excess of immobilization can increase quickly after harvest disturbance. In boreal regions where soil C:N is relatively high and low temperatures inhibit microbial activity, post-disturbance $NH_4^+$-N immobilization can be very high, and nitrification rates exceedingly low (Vitousek et al. 1982; Van Miegroet et al. 1992). Incorporation of logging slash with a high C:N (100-280) may further inhibit N mineralization in boreal soils (Vitousek 1981; Walley et al. 1996). Net N mineralization may occur after a lag period during which immobilization processes reduce organic substrate C:N content. The critical soil C:N ratio required for net N mineralization can vary among ecosystems and litter types, and the controlling factors are not well understood (Berg and Staaf 1981). Net N mineralization, when it does occur in these environments, is typically less pronounced than in warmer climates. However, recent studies in the Boreal Mixedwood have shown that soils in this ecozone may be more susceptible to disturbance than other studies would indicate (Walley et al. 1996; Maynard 1997). Therefore, research on soil N transformations in this ecozone is warranted to evaluate potential impacts of watershed disturbance to future forest productivity and the quality of adjacent surface waters.

## 1.2 The Mixedwood Boreal Forest

The Boreal Mixedwood forest ecozone is a mosaic of deciduous (*Populus tremuloides*, *Populus balsimifera*, *Betula papyrifera*) and coniferous (*Picea glauca*, *Picea mariana*, *Pinus banksiana*, *Abies balsamea*) tree species historically maintained by frequent natural fire, insect and disease disturbances (Maynard 1997). This low-relief forest landscape extends from southwestern Manitoba to northeastern British Columbia, but its largest areal extent occurs in Alberta where it currently covers about 40% of the province (Rowe 1972). Soils are predominantly N-poor luvisolic, gleysolic and brunisolic soils formed since the last glaciation that overlie in excess of a hundred meters of till and associated glacial deposits (Canadian System of Soil Classification, Canadian Soil Survey Committee 1987). The growing season is short and cool, anthropogenic N deposition tends to be low, and aspen regrowth by root suckering following disturbance is usually rapid.

The relatively cool climate and N-poor soils of the Boreal Mixedwood combine to create a forest ecosystem where net N mineralization and nitrification are not expected to increase substantially after harvest disturbance, however, studies have shown that aspen forests, including those in the Boreal Mixedwood, may be susceptible to disturbance. In a study of 11 forest ecosystems across the United States, Vitousek et al. (1982) found that soil $NO_3^-$-N in aspen stands in northern New Mexico increased from about 0 $\mu g\ g^{-1}$ in undisturbed areas to about 25 $\mu g\ g^{-1}$ in disturbed areas, and these concentrations were similar to, or greater than, concentrations in deciduous stands in warmer regions. Within the Boreal Mixedwood in Saskatchewan, Walley et al. (1996) compared soil $NO_3^-$-N in an undisturbed aspen-dominated control stand and a 4-yr-old clear-cut, and found that $NO_3^-$-N was higher in the young forest despite the fact that the soil C:N was higher in the young forest. In Alberta's Boreal Mixedwood, a study investigating soil N transformations following herbicide (Hexazinone) application in clear-cut areas has shown that soil $NH_4^-$-N and $NO_3^-$-N concentrations in study plots receiving the herbicide were higher than concentrations in control plots or plots receiving low levels of herbicide (Maynard 1997). Direct comparisons among the studies are difficult due to differences in methodology, and the degree and type of disturbance. However, these studies suggest that relatively cold-climate aspen forests, including those in Boreal Mixedwood, may respond to watershed disturbance, contrary to what results from other studies might predict.

## 1.3 The Importance of Gross and Net Estimates of Soil N Transformations

Assessing differences in soil N mineralization and nitrification between uncut and cut areas is best accomplished by monitoring both net and gross N transformations. Our understanding of soil N mineralization and nitrification in forest soils is limited when only net rates are quantified because net rates are the sum of $NH_4^-$-N and $NO_3^-$-N production and immobilization processes, and reflect plant available N. In contrast, gross mineralization and nitrification rates separate production from immobilization processes and assess the total amount of N cycled between organic and inorganic N fractions, and between $NH_4^-$-N and $NO_3^-$-N concentrations. Studies that have only measured net N transformations show that N cycling in N-limited boreal forests is slow (Van Cleve and Alexander 1981). However, recent studies measuring both net and gross rates in forest soils show that these rates are often not correlated, and that net rates may underestimate N turnover when production and immobilization of small inorganic N pools is rapid (Davidson et al. 1992; Stark and Hart 1997; Neill et al. 1999; Stottlemyer and Toczydlowski 1999). Hence, measurements of net rates may not reveal the actual impacts of watershed disturbance to gross N mineralization and immobilization processes. In forests where net rates remain relatively unchanged after disturbance, it is possible that increases in gross production rates were coupled to increased gross immobilization rates. When net rates do appear stimulated by disturbance, information on gross rates would reveal to what degree changes result from altered gross production or gross immobilization. Because disturbance can affect production and immobilization processes to varying degrees, a more complete picture of N transformations in forest soils emerges with measurements of both net and gross rates.

To date there is little information on net and gross N transformations in the Boreal Mixedwood. This information is needed to assess impacts to future forest productivity and water quality in the region's naturally eutrophic surface waters if timber harvesting disturbance is triggering changes to soil N transformations that may increase the potential for N leaching from the terrestrial ecosystem. Furthermore, predicting the cumulative impacts of other disturbances, such as the adoption of N fertilizer and/or herbicide use in forest plantations, increased atmospheric N deposition, and global climate warming, necessitates an understanding of the gross N transformations occurring in this forest's soils. Results from this study will facilitate understanding the integrity of terrestrial and aquatic systems in the Boreal Mixedwood ecozone, and with the sustainability of current harvesting activities.

## 1.4 Literature Cited

Adams, P.W., Flint, A.L., and Fredriksen, R.L. 1991. Long-term patterns in soil moisture and revegetation after a clearcut of a Douglas-fir forest in Oregon. For. Ecol. Manage. 41: 249-263.

Alberta Environmental Protection. 1996. The Status of Alberta's Timber Supply. Alberta Govt. Publ. NO T/325, Edmonton, AB.

Berden, M., Nilsson, S.I., and Nyman, P. 1997. Ion leaching before and after clear-cutting in a Norway Spruce stand – Effects of long-term application of ammonium nitrate and superphosphate. Water Air Soil Poll. 93: 1-26.

Berg, B. and Staaf, H. 1981. Leaching, accumulation and release of nitrogen in decomposing forest litter. In Clark FE, Rosswall T, Editors. Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies and Management Impacts. Volume 33. Stockholm: Ecol. Bull. p 163-78.

Berg, M.P., Verhoef, H.A., Bolger, T., Anderson, J.M., Beese, F., Couteaux, M.M., Ineson, P., McCarthy, F., Palka, L., Raubuch, M., Splatt, P. and Willison, T. 1997. Effects of air pollutant-temperature interactions on mineral-N dynamics and cation leaching in replicate forest soil transplantation experiments. Biogeochemistry 39: 295-326.

Boring, L.R., Monk, C.D., and Swank, W.T. 1981. Early regeneration of a clear-cut southern Appalachian forest. Ecology 62(5):1244-53.

Canada Soil Survey Committee. 1987. The Canadian system of soil classification 2nd ed. Agriculture Canada. Ottawa. ON Publ. 1646. 164pp.

Davidson, E.A., Hart, S.C. and Firestone, M.K. 1992. Internal cycling of nitrate in soils of a mature coniferous forest. Ecology 73: 1148-1156.

Frazer, D.W., McColl, J.G., and Powers, R.F. 1990. Soil nitrogen mineralization in a clearcutting chronosequence in a northern California conifer forest. Soil Sci. Soc. Am. J. 54: 1145-1152.

Hendrickson, O.Q., Chatarpaul, L. and Robinson, J.B. 1985. Effects of two methods of timber harvesting on microbial processes in forest soil. Soil Sci. Soc. Am. J. 49: 739-746.

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.

Krause, H.H. 1982. Nitrate formation and movement before and after clear-cutting of a monitored watershed in central New Brunswick, Canada. Can. J. For. Res. 12:922-30.

Kubin, E. 1998. Leaching of nitrate nitrogen into the groundwater after clear felling and site preparation. Boreal Environment Research. 3: 3-8.

Likens, G.E., Bormann, F.H., Johnson, N.M., Fisher, D.W., and Pierce, R.S. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Mono. 40(1):23-47.

Maynard, D.G. 1997. Soil nutrient dynamics in a boreal mixedwood cutover following the application of hexazinone. Ecol. Appl. 7: 416-430.

Neill, C., Piccolo, M.C., Melillo, J.M., Steudler, P.A., and Cerri, C.C. 1992. Nitrogen dynamics in Amazon forest and pasture soils measured by $^{15}$N pool dilution. Soil Biol Biochem 31: 567-572.

Paul, E.A., and Clark, F.E. 1996. Soil Microbiology and Biochemistry. 2nd ed. San Diego, California: Academic Press.

Persson, T. and Wiren, A. 1995. Nitrogen mineralization and potential nitrification at different depths in acid forest soils. Plant and Soil 168-169: 55-65.

Rosen, K., and Lundmark-Thelin, A. 1987. Increased nitrogen leaching under piles of slash – a consequence of modern forest harvesting techniques. Scand. J. For. Res. 2:21-29.

Rowe, J.S. 1972. Forest regions of Canada. Publication Number 1300, Department of the Environment, Canadian Forestry Service, Ottawa, Ontario, Canada.

Schmidt, M.G., Macdonald, S.E. and Rothwell, R.L. 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Can. J. For. Res. 531-540.

Stark, J.M. and Hart, S.C. 1997. High rates of nitrification and nitrate turnover in undisturbed coniferous forests. Nature 385: 61-64

Stottlemyer, R., Travis, B., and Toczydlowski, D. 1995. Nitrogen mineralization in boreal forest stands of Isle Royale, northern Michigan. Water Air Soil Poll. 82:191-202.

Stottlemyer, R. and Toczydlowski, D. 1999. Nitrogen mineralization in a mature boreal forest, Isle Royale, Michigan. J. Environ. Qual. 28: 709-720.

Van Cleve, K., and Alexander, V. 1981. Nitrogen cycling in tundra and boreal ecosystems. In Clark FE, Rosswall T, eds. Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies and Management Impacts. Volume 33. Stockholm: Ecol. Bull. p 375-404.

Van Miegroet, H., Cole, D.W., and Foster, N.W. 1992. Nitrogen distribution and cycling. In Johnson DW, Lindberg SE, eds. Atmospheric Deposition and Forest Nutrient Cycling. New York, New York: Springer-Verlag. p 179-99.

Van Miegroet, H., and Johnson, D.W. 1993. Nitrate dynamics in forest soils. In Burt TP, Heathwaite AL, Trudgill ST, eds. Nitrate: Processes, Patterns and Management. Chichester, England: John Wiley and Sons. p 25-97.

Veliz, M. 1999. Relationship of nutrient and mayfly (Ephemeroptera) abundance and diet to periphyton biomass in boreal streams. Department of Biological Sciences. University of Alberta. M.Sc. Thesis.

Vitousek, P.M. 1981. Clear-cutting and the nitrogen cycle. In Clark FE, Rosswall T, Eds. Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies and Management Impacts. Stockholm: Ecol. Bull. p 631-42.

Vitousek, P.M., Gosz, J.R., Grier, C.C., Melillo, J.M., and Reiners, W.A. 1982. A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems. Ecol. Mono. 52(2): 155-77.

Walley, F.L., Van Kessel, C., and Pennock, D.J. 1996. Landscape-scale variability of N mineralization in forest soils. Soil Biol. Biochem. 28(3): 383-91.

# Chapter 2. Net Nitrogen Mineralization and Nitrification in Aspen-Dominated and Aspen-Conifer Stands in the Mixedwood Boreal Forest

## 2.0 Introduction

Nitrogen (N) has been an intensively studied soil nutrient as it is most often the limiting element controlling forest production (Vitousek et al. 1982; Tamm 1991). Only a small fraction of total soil N occurs as ammonium ($NH_4^-$-N) and nitrate ($NO_3^-$-N) ions, the forms of inorganic N produced by microbial mineralization and nitrification processes and most available to higher plants. Interest in the rates of these microbial processes has increased since studies have shown that watershed disturbance can elevate net N mineralization and nitrification rates and, in certain cases, cause N to leach from the plant-rooting zone to groundwater, lakes and streams (Vitousek 1981; Vitousek et al. 1982; Krause 1982). Terrestrial loss of N may further limit forest productivity, and movement of N into adjacent water bodies may increase primary productivity and create water quality problems (Van Miegroet and Johnson 1993; Veliz 1999).

Forest disturbance through timber harvesting effects on soil N transformations has focused primarily on temperate forests in the United States or eastern Canada (Likens et al. 1970; Vitousek et al. 1982; Hendrickson et al. 1985, 1989), or boreal forests in eastern Canada and northern Europe (Krause 1982; Rosen and Lundmark-Thelin 1987; Persson and Wiren 1995; Kubin 1998). Timber harvesting has been shown to temporarily reduce plant uptake of water and N, elevate soil temperature, increase the frequency of wetting and drying cycles, and either increase or decrease soil pH (Boring et al. 1981; Frazer et al. 1990; Adams et al. 1991; Schmidt et al. 1996; Berg et al. 1997; Berden et al. 1997). These changes may increase production of $NH_4^-$-N by N mineralizing bacteria, and in the presence of nitrifying bacteria in aerobic conditions, $NH_4^-$-N may be converted to the mobile $NO_3^-$-N anion that may leach from the plant-rooting zone (Vitousek et al. 1982). In recently developed boreal soils where short, cool growing seasons inhibit decomposition, post-disturbance $NH_4^-$-N immobilization can be high, and due to lack of substrate, nitrification rates also remain low (Vitousek et al. 1982; Van Miegroet et al. 1992). However, in high elevation aspen-dominated forests in northern New Mexico, USA, and in the Mixedwood Boreal forest in Saskatchewan, Canada, studies indicate that tree removal is associated with elevated concentrations of soil $NO_3^-$-N (Vitousek et al. 1982; Walley et al. 1996). Similarly, in the Mixedwood Boreal forest in Alberta, Canada, clear-cutting followed by herbicide application has been associated with higher soil $NH_4^-$-N and $NO_3^-$-N compared to control plots (Maynard 1997). Hence, these studies show that relatively cold-climate aspen forests may respond to watershed disturbance. What remains unknown is how disturbance affects *in situ* N mineralization and nitrification rates and how changes may affect N leaching from the terrestrial environment.

In this study *in situ* net N mineralization and nitrification rates were measured in three undisturbed upland forest stands in Alberta's Mixedwood Boreal forest that differ with respect to vegetation (aspen-dominated vs. aspen/conifer-mixed) and soil texture (sand vs. loam). Net N transformations were expected to be higher in aspen-dominated stands than in aspen/conifer-mixed stands due to the recalcitrant nature of coniferous litter (Finzi et al. 1998). Rates were also expected to be higher in loam soil rather than sandy soil because higher net N mineralization rates have been measured in fine textured soil compared to coarse soil (Reich et al. 1997). Secondly, harvested areas in the three forest stands were compared to the uncut areas to assess differences in soil moisture, temperature, pH, C:N, and the relationships of these soil properties to N transformations. Reciprocal core transplants were conducted to assess if N transformation rates for soils incubated in cut areas are higher than for soils in uncut areas, regardless of whether the soils originated from uncut or cut areas, based on the expectation that soil temperatures are higher in cut than uncut areas (Frazer et al. 1990; Berg et al. 1997). Finally, recent studies indicate that over-winter net N transformations are underestimated when incubation periods are several months long. Winter net N mineralization and nitrification may influence available $NH_4^-$-N and $NO_3^-$-N that are particularly susceptible to leaching during spring snowmelt. Hence, to asses the importance of over-winter N transformations, *in situ* net N transformations were measured during winter for varying incubation periods in uncut and cut areas.

## 2.1 Materials and Methods

### 2.1.1 Study Sites Description

Research was conducted from May 1997 to May 1998 in three upland forest stands in north-central Alberta with adjacent uncut (>70-yr old) and cut (1-yr old) areas. The stands are located in the drainage basins of two north-central Alberta lakes, Moose Lake (55°8'30"N, 111°45'45"W) and Deep Lake (55°25'00"N, 113°42'30"W), that form part of a multidisciplinary project called Terrestrial and Riparian Organisms Lakes and Streams (TROLS) that is investigating the role of buffer strips in the Boreal Mixedwood. Long-term annual precipitation for the Moose and Deep lakes study areas is 469 and 481 mm, respectively, with approximately 90 to 100 mm falling as snow between November and March. Respective long-term mean annual January and July air temperatures are −16.5 and 16.0°C. During this study, 1997 precipitation was 464 mm for Moose Lake, and 449 mm for Deep Lake. Mean January and July 1997 temperatures were −21 and 17°C, respectively, for the two regions. There is no TN deposition data for the study area, however, approximately 200 km south at Narrow Lake (54°35'N, 113°37'W) TN deposition between 1983-1986 was ≈4.24 kg $ha^{-1}$ $y^{-1}$ (Shaw et al. 1989).

The three stands differ with respect to dominant vegetation and soil type: aspen-dominated (ASP), aspen/conifer-mixed (MIX), sand (SD) and loam (LM). The stands will be referred to using these descriptive vegetation and soil properties, i.e. 1) ASP-SD, 2) ASP-LM, and 3) MIX-LM. Timber harvesting was conducted during winter 1996-1997 when the ground was frozen, and snow cover minimized mechanical soil disturbance. Within an uncut and cut area of each of the stands, two replicate 200-$m^2$ study plots were established 30 m from the lakeshore. Replicate plots were approximately 40 m apart, and adjacent uncut and cut areas were 80 to 200 m apart. ASP-SD was located in the Moose Lake catchment within the forest management area (FMA) of Alberta-Pacific Forest Industry Inc., and ASP-LM and MIX-LM are in the Deep Lake catchment within the FMA of Weyerhaeuser Canada Ltd. Slave Lake Division.

Forest composition determined for the uncut plots is summarized in Table 2.1. Air photos of the stands prior to harvesting indicate vegetation composition between the paired uncut and cut areas was similar. During the study period the stands were permitted to regenerate naturally. Within the uncut plots of the three stands, understories were predominately open with heterogeneous shrub growth. Ground cover in cut plots was dominated by slash material (44%), woody plants (33%, predominately *P. balsamifera*), herbaceous growth (17%), and small amounts of grass. Aspen and poplar regeneration in ASP-SD and ASP-LM was substantial during the 1997 growing season. By late September 1997, sucker heights ranged from 30 to 150 cm.

Soil and hillslope characteristics are summarized in Table 2.2. In each study plot, a single soil pit (1.5 m depth) was dug for soil classification purposes. Detailed soil profile descriptions are located in Appendix A, Tables A1 to A3.

### 2.1.2 Field Sampling

Growing season (May 15 to October 9, 1997) *in situ* net N mineralization and nitrification in the three stands were estimated with the buried bag method over seven consecutive, 28-d incubation periods (Eno 1960). Three additional *in situ* incubations were conducted in MIX-LM in 1998 from May 3 to June 3, June 6 to July 3, and July 22 to August 15 as part of a study investigating gross N transformations, and inter-annual net N transformations in the MIX-LM stand (Chapter 3). In each study plot on every sampling date, 7 pairs of cores were collected as Crepin and Johnson (1993) report that 5 to 10 replicate samples are needed for a reliable estimate of soil properties for study plots < 0.5 ha in size. However, loss and/or destruction of incubated cores occasionally occurred, thus, the number of samples ranged between 5 and 7. Soil cores were taken with a 5.5-cm diameter stainless steel bulb corer at three soil depths. The LFH and surface 10-cm of mineral soil were sampled between May and October 1997. The 10- to 20-cm depth of mineral soil was sampled between June and August 1997.

Soil temperature was measured on each sampling date in the middle of each of the three sampled soil layers with a hand-held thermocouple thermometer and copper-constantin thermocouples positioned randomly in three locations in each of the study plots. Beginning in June 1997, dataloggers (HoboTemp, Onset Instruments) also recorded temperature at the LFH /mineral soil interface every 2.5 h in one uncut and one cut plot within each forest stand. The datalogger in the cut plot of ASP-LM was lost, however complete temperature records were obtained for the other two stands.

To assess the extent that temperature differences affect net N mineralization and nitrification compared to intrinsic soil properties, a reciprocal buried bag experiment was conducted in which 7 intact cores from each cut plot were transplanted into adjacent uncut plots, and cores from uncut plots were transplanted into adjacent cut sites. This reciprocal buried bag experiment was conducted for three, 28-d incubation periods (June, July and August 1997).

Winter net N mineralization and net nitrification rates were measured for the LFH horizon in one uncut and one cut plot of each forest stand. Bags left to incubate in the ground became frozen and unretrievable after 28 d. Hence, over-winter rate measurements consisted of three incubation periods that were begun on October 5, 1997, December 10, 1997 and March 18, 1998, and terminated on May 2, 1998. These incubations of 208, 142, and 44 d assess if incubation length affects winter net rates. Soil samples were collected by cutting 15 x 15-cm pieces of LFH material with an axe. Although at least 7 samples were incubated on each date, loss and/or destruction of bags occurred during the incubations, therefore, the number of retrieved bags ranged from 7 to 12 for ASP-SD, 3 to 14 for ASP-LM, and 0 to 4 for MIX-LM. Samples were transported on ice to the laboratory and subsampled with 2 M KCl within 24 h. Winter soil temperatures within the LFH horizon were measured with dataloggers. The datalogger in the cut plot of MIX-LM was lost, however, complete temperature records were obtained for the two aspen stands.

### 2.1.3 Laboratory Methods

Soil extractions were begun in the field to minimize the effects of soil processing time on inorganic N concentrations (Van Miegroet 1995). Cores were hand-mixed within their bags until visually homogenized, and subsampled by placing approximately 2-g fresh weight LFH material or 5-g fresh weight mineral soil into a preweighed plastic Nalgene bottle containing 50 mL of 2 M KCl. The soil-KCl mixtures and the remaining soil were transported on ice to the laboratory, and processed within 24 to 48 h.

Inorganic N was extracted by shaking soil-KCl mixtures for 1 h on a rotary shaker, and filtering gravimetrically through prewashed Whatman No. 42 filter papers. Extracts were immediately frozen until analyzed with a Technicon AutoAnalyzer (Technicon 1973a, b). Quality control on the Technicon AutoAnalyzer was maintained by running control standards every 10 samples. Net N mineralization for a study plot during an incubation period was estimated from the average difference between the amounts of $NH_4^-$-N and $NO_3^-$-N present in all available cores at the beginning and end of each incubation period (Hart et al. 1994). Percent mineralization was calculated as the proportion of total N that was mineralized during the growing season. Similarly, net nitrification was estimated by the average difference between initial and final $NO_3^-$-N content, and percent nitrification was calculated as the proportion of soil $NH_4^-$-N that was nitrified during the growing season.

Gravimetric soil water content was determined for every core by drying a subsample of hand-mixed soil at 105°C for at least 24 h, and is reported on a wet weight basis. A glass electrode was used to measure pH for the LFH horizon and surface 10-cm mineral soil in 10:1 and 2:1 water-soil mixtures, respectively (Carter 1993). Soil bulk density ($D_b$) measurements were determined for soil cores obtained in May (ASP-SD, ASP-LM, MIX-LM), June (ASP-SD), September (ASP-SD, ASP-LM, MIX-LM), and October 1997 (ASP-SD, ASP-LM, MIX-LM). Average $D_b$ for each plot was used to convert soil N concentrations from a per gram basis to areal basis. Total C and TN for the LFH and surface 10-cm mineral soil were determined with an isotope ratio mass spectrometer (V.G. Isogas, Middlewich, Cheshire, England) for samples collected in July 1997. Exchangeable cations were determined on composite samples of 7 soil cores from each study plot collected in September 1997. Exchangeable cations, TC and TN analyses were performed in the Department of Renewable Resources at the University of Alberta.

### 2.1.4 Statistical Methods

The distance between replicate plots required for complete independence of soil properties ranges from 12 to 40 m in old fields (Robertson 1987; Goovaerts and Chiang 1993). In this study, autocorrelation was assessed with the semi-variance statistic ($\gamma$) on net N mineralization data for July 1997 (Robertson 1987). Autocorrelation was as high or lower for cores collected within 5 to 12 m of one another in a study plot ($\gamma$ (5-12 m) = 1628-23482) compared to cores collected about 40 m apart in replicate study plots ($\gamma$ (40m)=3963-48208), cores collected 80 to 200 m apart from one another in paired uncut and cut areas ($\gamma$ (80m)=7352-15134, $\gamma$ (200m) = 5779-43824), and cores collected more than 100 km apart in the two aspen-dominated stands ($\gamma$ (100km) = 29947). Hence, the semi-variance statistics indicate that classical statistical analyses can be employed because replicate plots and treatments are not spatially dependent.

Spatial, temporal and harvesting treatment differences for rates and soil properties among the study plots were assessed primarily with descriptive statistics. Growing season total net N mineralization and nitrification for individual plots were calculated from the sum of the mean amount of N mineralized and nitrified for incubation periods between May and October 1997. Growing season standard errors (*SE*) were calculated by first order error propagation of variances of mean monthly incubations (Meyer 1975).

To support the descriptive statistics, differences in growing season daily net N mineralization, nitrification, extractable $NH_4^-$-N, extractable $NO_3^-$-N and soil moisture between uncut and cut plots and among forest stands were assessed with repeated measures nested analyses of variance (ANOVA). When an interaction between stand and harvest treatment was detected, differences between uncut and cut plots were analyzed on an individual stand basis with Fisher's test combining probabilities from *t*-test performed on monthly incubations during the growing season (Sokal and Rohlf 1998). Differences in soil C:N, pH and $D_b$ between uncut and cut plots and among stands were assessed with ANOVA and the Games-Howell *post-hoc* test (Day and Quinn 1989). Levene's test was used to assess homogeneity of variances. If variances between the groups were heterogeneous, significance levels of *t*-tests were calculated without assuming equal variances (Zar 1984). Furthermore, the three soil depths sampled were analyzed separately as it is well-established that rates on a soil mass basis decrease with depth, and that soils should be subdivided into homogeneous classes to reliably assess environmental factors (Binkley and Hart 1989; Crepin and Johnson, 1993). Relationships between net N mineralization and nitrification, and selected soil characteristics (i.e. soil moisture, temperature, percent C, percent N, and soil TC/TN) were assessed for individual uncut and cut plots with regression analysis. For the reciprocal transplant experiment, differences in monthly net N mineralization and nitrification rates between transplanted and control cores were assessed with *t*-tests. All statistical tests were performed with SPSS Version 8.0 statistical software.

## 2.2 Results

### 2.2.1 Soil C:N, Bulk Density and pH

When data from uncut and cut plots from all three stands were analyzed together, excluding soil C:N which was detectably higher in the LFH horizon of MIX-LM compared to the two ASP stands ($F_{2,72} = 5.28$, $P = 0.007$), interactions between the forest stands and harvesting treatment factors were significant for C:N, pH and $D_b$. In general, however, the range of means was relatively small, and all three stands had mean C:N less than 30 for both the LFH horizon and surface 10-cm mineral soil (Table 2-2).

On an individual stand basis, differences in soil characteristics between uncut and cut plots were detected in the LFH horizon of ASP-SD and MIX-LM for both pH and $D_b$, with pH being higher in the uncut plots and $D_b$ being higher in the cut plots ($P < 0.05$). The same patterns were observed in the surface 10-cm mineral soil of ASP-SD, with the addition of higher C:N in cut than uncut plots. Within the loam soil stands, higher $D_b$ in the surface 10-cm mineral soil in the cut plots of ASP-LM was the only significant difference between uncut and cut plots.

### 2.2.2 Growing Season Soil Moisture and Temperature

Among the three stands, monthly mean soil moisture during the growing season tended to have a wider range in cut than uncut plots. Mean growing season soil moisture in the uncut plots ranged from 68 to 318% in the LFH horizon, and from 9 to 77% in the surface 10-cm mineral soil. In contrast, moisture in the cut plots ranged from 50 to 359% in the LFH horizon, and from 9 to 82% in surface 10-cm mineral soil. Otherwise, there were no detectable differences in soil moisture between uncut and cut plots for either the LFH ($F_{1,52} = 0.02$, $P = 0.9$) or surface 10-cm mineral soil ($F_{1,52} = 0.28$, $P = 0.6$). Among the three stands, growing season soil moisture in the loam stands was typically twice as high as in the sand stand for both the LFH ($F_{2,52} = 158.4$, $P < 0.001$) and surface 10-cm mineral soil ($F_{2,55} = 65.1$, $P < 0.001$).

On an individual stand basis, differences in growing season mean monthly soil moisture between uncut and cut plots were often greater than one *SE*, however, except for the LFH horizon of ASP-LM and the mineral soil of MIX-LM, cut plots were not consistently wetter than uncut plots (Fig. 2.1). Between May and October, mean monthly soil moisture in ASP-LM cut plots was 261% compared to 207% in the uncut plots. However, this effect was driven by one of two replicate cut plots located in a topographic low with a high water table that had 344% soil moisture compared to 229% for the other cut plot. Similarly, the higher soil moisture detected in the cut mineral soil of MIX-LM was driven by one cut plot that had 45% moisture compared to 34% in the other cut plot.

Mean monthly growing season soil temperatures tended to be higher in cut than in uncut plots for all three stands, particularly when soils were thawing in late May, and when temperatures peaked in mid July or early August (Fig. 2.2). The greatest temperature differences between uncut and cut plots were observed in the LFH horizon of MIX-LM where the cut plot was 2 to 5°C warmer than the uncut from late May to mid-July, and remained 1 to 2°C warmer for the duration of the growing season. Otherwise, differences between uncut and cut plots were generally less than 2°C. ASP-SD uncut and cut plots tended to be about 2°C warmer than the two loam soil stands for all soil depths measured. With each incremental decrease in soil sampling depth, temperatures in uncut and cut plots decreased by 2 to 3°C. The thermocouple thermometer tended to measure larger differences between uncut and cut plots compared to the average daily measurements recorded with dataloggers because spot measurements with the thermocouples were generally done at the warmest part of the day. Otherwise, seasonal patterns were consistent between the two devices.

### 2.2.3 Extractable Soil $NH_4^+$-N and $NO_3^-$-N

Extractable $NH_4^+$-N in representative soil cores differed among the three forest stands over the course of the study in the surface 10-cm mineral soil ($F_{2,31} = 6.62$, $P = 0.004$) but a difference among the stands was not detectable in the LFH horizon (Fig. 2.3). In ASP-SD and MIX-LM, extractable $NH_4^+$-N was highest on the first sampling date in May 1997, and gradually decreased throughout the growing season. This seasonal trend occurred in the LFH horizon and surface mineral soil, although extractable $NH_4^+$-N was an order of magnitude lower in the mineral soil. In contrast, extractable $NH_4^+$-N in ASP-LM uncut and cut plots was lowest in spring and peaked in mid-summer. Over winter extractable $NH_4^+$-N tended to increase slightly, however, except for ASP-LM, which showed a high peak in December, winter concentrations remained low compared to 1997 growing season peaks. For MIX-LM where extractable $NH_4^+$-N was also measured in May 1998, high extractable $NH_4^+$-N observed in May 1997 was not observed in 1998. However, seasonal trends between years were the same in that extractable $NH_4^+$-N declined gradually between May and October.

Although seasonal patterns among the three stands differed, all had higher extractable $NH_4^+$-N in the cut compared to uncut plots in the LFH horizon, and differences were greatest when concentrations peaked (ASP-SD: $\ln \Sigma P = 32.46$, $P < 0.001$; ASP-LM: $\ln \Sigma P = 28.58$, $0.01 < P < 0.001$; MIX-LM: $\ln \Sigma P = 48.47$, $P < 0.001$). In the surface 10-cm mineral soil, only MIX-LM had greater extractable $NH_4^+$-N in the cut plots ($\ln \Sigma P = 68.62$, $P < 0.001$), and this difference was particularly high in May 1997 when concentrations in the cut were 30 times greater than in uncut plots. High extractable $NH_4^+$-N in the cut MIX-LM plots in May rapidly decreased by June, coinciding with high net N immobilization in the May to June 1997 incubation.

Extractable soil $NO_3^-$-N was at least an order of magnitude lower and less variable than $NH_4^+$-N, but differences in soil $NO_3^-$-N among the three stands were detected for the LFH horizon ($F_{2,32} = 25.16$, $P < 0.001$), and there was a stand x harvesting treatment interaction in the surface 10-cm mineral soil ($F_{2,31} = 4.96$, $P = 0.01$) (Fig. 2.4). Compared to the two aspen-dominated stands, extractable $NO_3^-$-N in cut plots in MIX-LM was as much as 6 times higher than that in the two ASP stands. Extractable $NO_3^-$-N from a cut MIX-LM plot was particularly high in May 1998 when the highest concentrations in this study were observed. A sharp increase in soil $NO_3^-$-N was observed between March and May 1998, when soil $NO_3^-$-N increased approximately 7-fold over peak growing season concentrations.

No differences in extractable $NO_3^-$-N between uncut and cut plots were detected in ASP-LM, but the LFH horizon of MIX-LM ($\ln \Sigma P = 27.18$, $0.01 < P < 0.001$), and the surface 10-cm mineral soil of MIX-LM (ln $\Sigma P = 24.41$, $0.05 < P$ .01) and ASP-SD (ln $\Sigma P = 21.81$, $0.05 < P < 0.01$) had higher extractable $NO_3^-$-N in cut that uncut plots. Furthermore, in contrast to the ASP stands where extractable $NO_3^-$-N in uncut and cut plots beyond mid-summer remained low and showed little spatial variability, extractable $NO_3^-$-N in cut plots of MIX-LM was consistently higher than uncut plots during the entire growing season for both soil layers, and there was considerable spatial variability for extractable $NO_3^-$-N in both uncut and cut plots.

### 2.2.4 Growing Season Total Net N Mineralization and Nitrification

Growing season total net N mineralization and nitrification measured on a soil weight basis were within one *SE* of each other among the three uncut plots of the forest stands for either the LFH or surface 10-cm mineral soil (Tables 2-3 and 2-4). Also, the range for mean percent mineralization of TN for the uncut plots tended to be relatively small, and the magnitude of the values was low. In contrast, percent nitrification of $NH_4^-$-N in the uncut plots tended to be greater than percent mineralization, and excluding MIX-LM plots with net $NO_3^-$-N immobilization, larger ranges for percent nitrification show that net nitrification within and among the three stands had greater spatial variability than N mineralization.

Unlike the uncut plots of the three stands, the range of total growing season net N mineralization and nitrification tended to be broader among the three stands for both the LFH and surface 10-cm mineral soil (Tables 2-3 and 2-4). The largest differences were observed between the MIX-LM stand and the two ASP stands. Growing season total net N immobilization was observed in the cut plots of MIX-LM while the ASP stands had net N mineralization. Growing season net nitrification in the LFH horizon of MIX-LM cut plots also differed from the ASP cut plots, however, in this case, net nitrification rates in MIX-LM LFH and surface 10-cm mineral soils were at least 78% and 48% higher, respectively.

When data from the three stands were combined, differences between uncut and cut plots were confounded by interaction between stand and harvest treatment ($0.001 < P < 0.05$). However, when stands were examined individually, a difference between uncut and cut plots in MIX-LM was detected for net N mineralization and nitrification in the

LFH and surface 10-cm mineral soil layers (Tables 2-3 and 2-4). The MIX-LM cut plots had high net N immobilization, while net N mineralization was observed in uncut plots. The MIX-LM cut plots also had high net nitrification compared to low or negative net nitrification in the uncut plots. In the ASP stands, except for the surface 10-cm mineral soil of ASP-SD, no differences between harvesting treatments were detected in the aspen-dominated stands, however, percent mineralization of TN in the aspen-dominated stands tended to be higher in the cut plots.

Few relationships between growing season net N mineralization and physical soil properties were found. In the LFH horizon, net mineralization was weakly correlated with soil C ($r^2 = 0.4$, $P = 0.03$) and mean growing season temperature ($r^2 = 0.3$, $P = 0.06$). In the mineral horizon, growing season net N mineralization was weakly related to mean growing season moisture ($r^2 = 0.3$, $P = 0.07$). Growing season net nitrification did not vary with any of the measured soil properties.

### 2.2.5 Seasonal Patterns of Daily Net N Mineralization and Nitrification

Growing season patterns of daily net N mineralization rates measured during 28-d incubations tended to differ between the ASP and MIX plots. Maximum daily net N mineralization rates in ASP plots were observed between May and July 1997, while minima were observed between mid to late summer after soil temperatures peaked (Fig. 2.5). In contrast, in MIX-LM net N immobilization or low N mineralization occurred in spring, and maximum rates were observed between June and August 1997. With respect to net nitrification, except for the cut plots in MIX-LM, rates in all three stands approached 0 $\mu g\ NO_3^- \text{-} N\ g^{-1}\ d^{-1}$ during the entire growing season for both the LFH and mineral soils (Fig. 2.6).

On an individual stand basis, higher net N mineralization was detected in cut than uncut plots for individual monthly incubations in all three stands. In the ASP stands, these differences coincided with peak mid-summer N mineralization rates in the cut plots. In contrast, differences in net N mineralization between uncut and cut plots in MIX-LM occurred in late spring during the May to June incubation, and late in the growing season between August and October. With respect to net nitrification rates, except for one case in ASP-LM where higher rates were observed in uncut compared to cut plots, no differences between uncut and cut plots were detected in the ASP stands. In contrast in MIX-LM, net nitrification in soils from cut plots were consistently higher than uncut plots, both in the LFH and in the surface 10-cm mineral soil.

Compared to rates measured in 1997 (Fig. 2.5), daily net N mineralization and nitrification rates in MIX-LM in 1998 tended to be lower for both the LFH and surface mineral soil (Chapter 3). For example, in the LFH horizon, 1998 mean daily net N mineralization rates measured with monthly *in situ* incubations between May 3 and August 15 (excluding the period between July 3-22, 1998) ranged from –0.07 ± 0.36 and 1.59 ± 0.60 µg N $g^{-1}$ $d^{-1}$ in the uncut plots, while rates in the cut ranged from –0.68 ± 0.50 and 1.74 ± 0.40 µg N $g^{-1}$ $d^{-1}$. Between 1997 and 1998, net nitrification in the uncut plots was barely detectable for both years. In contrast a change was observed for net nitrification in the cut plots. The relatively high rates observed in the cut plots of MIX-LM in 1997 between June and August (LFH: 0.82 ± 0.44 to 2.19 ± 0.77 µg $NO_3^-$-N $g^{-1}$ $d^{-1}$) were not observed in 1998 when rates ranged between 0.01 ± 0.10 and 1.12 ± 0.44 µg $NO_3^-$-N $g^{-1}$ $d^{-1}$.

Relationships between monthly net rates and monthly mean soil temperature, moisture and extractable $NH_4^+$-N were weak ($r^2 < 0.16$) when the three forest stands and the uncut and cut plots were combined, nor did they improve when the stands were analyzed separately with the uncut and cut plots combined. However, when the uncut and cut plots were analyzed separately on an individual stand basis, relationships with monthly net rates were detected for the three soil properties, although relationships were not consistent among stands. Mean monthly net N mineralization in the surface 10-cm mineral soil of MIX-LM cut plots was related to soil temperature ($r^2 = 0.62$, $P = 0.02$) and moisture ($r^2 = 0.55$, $P = 0.01$), and mean monthly net nitrification was related to soil temperature ($r^2 = 0.53$, $P = 0.04$) and extractable soil $NH_4^+$-N ($r^2 = 0.41$, $P = 0.05$). In ASP-SD, net nitrification in uncut LFH soil varied with extractable soil $NH_4^+$-N ($r^2 = 0.57$, $P = 0.01$), whereas in the cut plots it was weakly related to moisture ($r^2 = 0.39$, $P = 0.05$). In ASP-LM, net N mineralization in the LFH horizon was related to moisture ($r^2 = 0.46$, $P = 0.04$).

### 2.2.6 Reciprocal Transplant Experiment

Net N mineralization rates decreased and increased, respectively, when soil cores were transplanted from cut to uncut plots, and from uncut to cut plots (Fig. 2.7). Compared to untransplanted cores, cores transplanted from cut to uncut plots during the July to August incubation had lower net N mineralization rates for the LFH horizon of the two loam soil stands and in the surface 10-cm soil of ASP-SD and MIX-LM. Transplanting from uncut to cut plots also resulted in an increase in net N mineralization for surface 0 to 10-cm mineral soil cores from ASP-LM during the July to August incubation, although the same transplant caused a decrease in net N mineralization in MIX-LM.

Although not statistically detectable, trends in changes to net N mineralization with transplanting indicate that cores incubated in cut plots had higher rates than counterparts in uncut plots. In the LFH horizons of the three forest stands combined, 5 out of 7 cases where cores were transplanted from cut to uncut plots tended to have lower net N mineralization rates, while the remaining 2 cases had relatively no change with transplanting. In the surface 10-cm mineral soil, cores transplanted from cut to uncut plots tended to have lower net N mineralization in 3 of 8 cases, while 4 remained relatively unchanged and 1 tended to increase. When LFH horizon cores were transplanted from uncut to cut plots, 4 out of 8 cases tended to have higher rates in cut plots, while in the remaining 4 cases no change was registered. In the surface 10-cm mineral soil, 2 out of 7 cases tended to increase with transplanting from uncut to cut areas while the remaining 5 showed no relative change.

Changes were less apparent for net nitrification due to very low rates measured in both uncut and cut plots (Fig. 2.8). The only detectable difference occurred in the surface 10-cm mineral soil of ASP-LM where net nitrification decreased when cores were moved from uncut to cut plots. Otherwise, few trends with transplanting were observed and rates tended to be similar among control and transplanted cores.

### 2.2.7 Winter Soil Moisture and Temperature

Soil moisture in both uncut and cut plots increased by 20 to 25% between October and December 1997, and remained relatively constant from December 1997 until March 1998 (Fig. 2.1). However, during winter sample collection, some unavoidable incorporation of snow into the samples occurred, hence, reported values are slight overestimates of actual moisture in the soils prior to sampling but this should not affect cut vs. uncut comparisons.

Daily mean soil temperatures at the LFH/mineral soil interface fell below 0°C from mid-November until late March for the uncut and cut plots of the three stands (Fig. 2.9). The coldest temperature recorded, -13°C, occurred in early December 1997 in the uncut plot of MIX-LM. The coldest temperature in ASP-SD, -9°C in the cut plot, also occurred in early December 1997, whereas in ASP-LM the peak low, -6°C, occurred in early January 1998 and was observed in both uncut and cut plots. The uncut MIX-LM plot also had the greatest temperature fluctuations, from -13°C to +1°C and back to -13°C, between late November and December 1997. During this same period, the uncut plots in ASP-SD and ASP-LM fluctuated between +4 and -4°C.

In the aspen stands, the greatest temperature differences between uncut and cut plots were observed in ASP-SD where cut plots were 2 to 5°C cooler in December, and 1 to 2°C warmer in spring than uncut plots. Temperatures in the uncut and cut plots in ASP-LM were virtually identical throughout the winter study. Although a comparison between uncut and cut plots in MIX-LM was not possible due to loss of the datalogger in the cut plot, the uncut plot in MIX-LM registered minimum temperatures 4°C cooler than minimum temperatures in the cut ASP-SD plot.

### 2.2.8 Winter Net N Mineralization and Nitrification

Net N mineralization and nitrification tended to increase as the duration of over-winter incubation periods decreased from 208 to 142 to 44 d (Fig. 2.10). This decreasing trend was particularly prominent in the loam soil cut plots where net N mineralization and nitrification more than doubled with each consecutive decrease in incubation duration. High net N mineralization and nitrification measured in the cut plots of MIX-LM during the March to May 1998 incubation coincided with sharp increases in extractable soil $NH_4^+$-N and $NO_3^-$-N during this period. Due to the apparent influence of incubation duration on net rates during winter, only the rates measured during the March to May 1998 incubation are shown in Fig. 2.5 and 2.6. Rates measured during this late winter incubation represent a significant contribution to annual net N mineralization and nitrification. Winter net N mineralization in uncut plots as a percentage of annual net N mineralization was 10% for ASP-SD, 9% for ASP-LM and 0% for MIX-LM. In cut plots these values increased to 18% for ASP-SD, 38% for ASP-LM and >100% for MIX-LM. Excluding ASP-SD, the same trends were observed for net nitrification in ASP-LM and MIX-LM where maximum winter nitrification as a percentage of the annual total was > 1% in uncut plots, and 19% and 40% in respective cut plots. Growing season net nitrification in ASP-SD was barely detectable, hence, although winter rates were also low, the winter contribution for both uncut and cut plots was 66% and 53%, respectively, of the annual total.

## 2.3 Discussion

### 2.3.1 Growing Season Net N Mineralization and Nitrification in Uncut Plots

In both 1997 and 1998, estimates of growing season totals for net N mineralization in the LFH horizon of uncut study plots were within the range measured for other forest ecosystems with similar vegetation and/or climate. For example, Stump and Binkley (1996) measured *in situ* net N mineralization between 8 to 52 kg N $ha^{-1}$ $yr^{-1}$ in ten trembling aspen stands in the Colorado Rocky Mountains. Rates from my study were also similar to laboratory estimates of net N mineralization for LFH soil from a Norway spruce stand in southern Sweden (23 kg N $ha^{-1}$ $yr^{-1}$) even though atmospheric N deposition in Sweden was higher than in northern Alberta (10 to 31 kg N $ha^{-1}$ $yr^{-1}$, Persson and Wiren 1995). In contrast, rates in this study were about 5 times higher than those measured in the Boreal Shield in LFH/mineral soil composite cores from pine/black spruce-treed soil islands (4 to 6 kg N $ha^{-1}$ $yr^{-1}$, Lamontagne 1998), and in LFH soil from pine/black spruce/aspen-mixed stands (1 to 9 kg N $ha^{-1}$ $yr^{-1}$, Westbrook 2000). Within the surface 10-cm mineral soil, growing season net N mineralization was similar to that measured in deciduous/conifer-mixed stands in northern Michigan (11 kg N $ha^{-1}$ $yr^{-1}$, Stottlemyer et al. 1995), and in Norway spruce stands in southern Sweden

(5 kg N $ha^{-1}$ $yr^{-1}$). Hence, comparisons with the literature suggest that net N mineralization rates in the Boreal Mixedwood are similar to forests with similar climates, in combination with similar species composition. Lower N mineralization rates in the two Canadian Shield studies may be due to the higher conifer component that would generate a more recalcitrant forest litter.

Fewer studies on *in situ* net nitrification exist with which to make comparisons, however, growing season net nitrification in the Boreal Mixedwood tends to be among the lowest reported. Net nitrification, barely detectable in the uncut LFH horizon in this study, was similar to the low or negative rates measured on the Boreal Shield by Lamontagne (1998) (0.01 to 0.45 kg $NO_3^-$-N $ha^{-1}$ $yr^{-1}$) and Westbrook (2000) (-0.16 to -0.01 kg $NO_3^-$-N $ha^{-1}$ $yr^{-1}$). Stottlemyer et al. (1995) measured comparably low rates in surface mineral soil from boreal trembling aspen/white birch forests in northern Michigan (0.9 kg $NO_3^-$-N $ha^{-1}$ $yr^{-1}$).

While net N mineralization and nitrification considered suppressed by the recalcitrant nature of coniferous litter, differences in litter quality were not observed between stands with different conifer content in this study (Stump and Binkley 1993). Instead, percent soil N content, percent mineralization of N and net rates of N mineralization and nitrification were similar among the uncut plots of the aspen-dominated and the aspen/conifer-mixed stand. Although growing season net N immobilization was observed in the uncut plots of the aspen/conifer-mixed stand, this was driven by high N immobilization during a single incubation in early spring, and did not reflect net N mineralization activity during the rest of the summer. Similar net N mineralization in deciduous-dominated and conifer-mixed stands has also been reported by Devito et al. (1999) in central Ontario, and Mladenoff (1987) in upper Michigan. Incorporation of considerable deciduous vegetation in the conifer-mixed stands can improve litter quality, thereby equalizing net N mineralization rates between forest stands of varying composition (Hart et al. 1997; Devito et al. 1999). Furthermore, in aspen forests, strong translocation of N prior to leaf senescence, and relatively high concentrations of phenolic compounds and tannins compared to other deciduous species, generate poor quality litter that may explain similar rates registered in the two vegetation types in this study (Lousier and Parkinson 1976; Cragg et al. 1977; Pastor and Bockheim 1984; Clein and Schimel 1995).

It was also predicted that greater soil moisture, while maintaining adequate soil pore aeration, would promote higher rates of net N mineralization and nitrification. Therefore, net rates in loamtextured soil were expected to be higher than sandy soil because the higher water holding capacity of the former would provide a more favorable microbial environment. Instead, although averages for growing season soil moisture in the LFH and mineral soils of the loam soil aspen stand were 10 to 20% higher than in the sandy soil aspen stand, differences in growing season net mineralization and nitrification were not observed. The differences in soil moisture may not have been sufficient to affect microbial N transformation processes. Soil moisture in both the loam soil and sandy soil stands during 1997 was relatively high because between 1995 and 1997, 478. 598 and 471 mm of precipitation were recorded compared to the long-term average of 465 ± 12 mm.

However, soil moisture had an apparent effect on interannual differences in net N mineralization and nitrification. In contrast to the wet years between 1995 and 1997, precipitation in 1998 was 308 mm. Consequently, mean growing season soil moisture was 20 to 47% lower in uncut and cut plots of the aspen/conifer-mixed stand. This reduced soil moisture was reflected in lower net N mineralization and higher net nitrification estimates in 1998. Between early May and late mid-August 1998, net N mineralization in uncut and cut plots in the LFH ranged from –63 to 99 μg $NH_4^-$-N $g^{-1}$ compared to –184 to 113 μg $NH_4^-$-N $g^{-1}$ in 1997. In contrast, net nitrification in 1998 ranged from –0.43 to 98 μg $NO_3^-$-N $g^{-1}$, whereas rates ranged from –3.64 to 65 μg $NO_3^-$-N $g^{-1}$ in 1997. Lower soil moisture in 1998 appears to have limited microbial decomposition processes, thereby curtailing net N mineralization, while increasing dissolved oxygen availability and promoting net nitrification.

### 2.3.2 Contrasts Between N Transformations in Uncut and Cut Plots

As shown in other forests disturbed by harvesting (Boring et al. 1981; Frazer et al. 1990; Adams et al. 1991), cut plots in this study tended to have slightly higher soil temperature and moisture than uncut plots, although the differences were small. Elevated soil temperatures in harvested stands have been attributed to increased ground insolation. However, uncut plots in this study had relatively open mid-summer canopies (canopy cover 0.74 ± 0.02, Lambert 1998), while cut areas had thick shrub growth and rapid aspen regeneration, thereby minimizing differences in ground insolation between uncut and cut. Furthermore, the Boreal Mixedwood is characterized by short, cool growing seasons. In combination, these factors resulted in temperature differences between uncut and cut plots that were generally about 2°C or less.

With respect to soil moisture, post-harvest increases in other studies have been attributed to reduced interception and evapotranspiration (Adams et al. 1991; Berden et al. 1997). However, high soil moisture was maintained during the 1997 growing season in both uncut (LFH: 191%, Mineral: 32%) and cut plots (LFH: 194%, Mineral: 31%) due to above average precipitation. Furthermore, regenerating aspen have been shown to evapotranspire as much as 75% of that evapotranspired by mature stands in temperate regions, thereby resulting in rapid recovery of evapotranspiration rates following harvesting (Johnston 1970).

Differences were noted for growing season net N mineralization and nitrification in the aspen/conifer-mixed stand, and for mid-summer monthly incubations in the aspen stands (Table 2-3, 2-4, Fig. 2.3). These differences were consistent with trends observed in the reciprocal buried bag experiment where soils in cut plots had higher mean rates than uncut plots. High net N immobilization during the May to June 1997 incubation in the aspen/conifer-mixed stand contributed to a detectable difference in growing season total net N mineralization between uncut and cut plots. During this spring incubation period, extractable $NH_4^+$-N decreased dramatically, and, for the remainder of the growing season, net N mineralization and extractable $NH_4^+$-N remained relatively constant. These patterns suggests that initial net N immobilization in the spring resulted from microbial decomposition of slash material with relatively high C:N (Aber 1978; Vitousek et al. 1982; Persson and Wiren 1995; Northup et al. 1995; Finzi et al. 1998). As the growing season progressed, the litter material may have attained a sufficiently low C:N that, in combination with similar moisture and temperature between uncut and cut plots, equilibrated gross N mineralization and immobilization processes so that low net N mineralization, similar to that observed in the uncut plots, was measured in the cut plots

(Rosen and Lundmark-Thelin 1987). The absence of high net N immobilization in the dry spring of 1998 also suggests that immobilization of N in the wetter spring of 1997 was due to decomposition of fresh slash material. That the two aspen stands did not register net N immobilization in the either wet or dry spring suggests that slash material in these stands was less recalcitrant than in the aspen/conifer mixed stand. This is reflected in the slightly lower C:N content of the LFH horizon in the aspen stands compared to the aspen/conifer-mixed stand (Table 2.2). Hence, a short period of net N immobilization as observed in the aspen/conifer-mixed stand was precluded in the aspen-dominated stands.

The higher mid-summer net mineralization rates in the cut aspen-dominated areas compared to the uncut areas are apparently not directly related to soil temperature or moisture. The cut plots were not consistently wetter in mid-summer, and soil temperatures were only 1 to 2°C warmer at most. However, results from the reciprocal core transplant experiment suggest that these small temperature differences may be sufficient to generate changes in net N transformations. Lukewille and Wright (1997) also found that relatively small increases in soil temperature (3 to 5°C), just slightly higher than differences observed between uncut and cut plots in this experiment, could increase $NH_4^-$-N and $NO_3^-$-N concentrations in runoff in a large-scale catchment manipulation of a boreal forest in Norway. Sensitivity to small changes in temperature suggest that future increases in mean growing season temperatures in the Boreal Mixedwood due to global climate warming may result in greater temperature differences and changes to N transformations between undisturbed and disturbed stands.

Sustained high net nitrification rates in the cut plots of the aspen/conifer-mixed stand during the 1997 growing season suggest that while vegetation demands for $NH_4^-$-N were low because of slow plant regeneration, nitrifier populations grew and/or became more active (Lundgren 1982). These results concur with Maynard (1997) who looked at soil N pools following herbicide (Hexazinone) application in clear-cut areas in the Boreal Mixedwood, and found that plots receiving herbicide had higher extractable $NH_4^-$-N and $NO_3^-$-N than control plots or plots with low levels of herbicide application. Higher extractable $NO_3^-$-N concentrations in 4-yr-old cut plots compared to uncut controls have also been reported for Boreal Mixedwood stands the Prince Albert Model Forest in

Saskatchewan, Canada by Walley et al. (1996) despite the fact that soil C:N was higher in the young forest. In my study, 1998 net nitrification rates and extractable soil $NO_3^-$-N in cut plots also tended to be higher than in uncut plots (Chapter 3), hence, the amount of time required for recovery from disturbance in the Boreal Mixedwood is at least 2 years.

The dramatic difference in net nitrification between the aspen-dominated stands and the aspen/conifer-mixed stand may result from more $NH_4^-$-N being available to nitrifiers in the latter where tree regeneration was slower, and therefore plant demands for $NH_4^-$-N were lower. Nitrifiers may be outcompeted in soils where demands for $NH_4^-$-N by vegetation is strong, as it is in aspen stands (Clein and Schimel 1995). Because aspen suckers typically regenerate quickly after timber harvesting, plant $NH_4^-$-N demands remain high, and increases in $NH_4^-$-N availability to nitrifiers is unlikely. In contrast, increased net nitrification may occur in cut aspen/conifer-mixed stands where vegetation regeneration is relatively slower, as was observed in this study. High net nitrification rates coincided with increases in extractable $NO_3^-$-N in MIX-LM in the latter part of the summer (Fig. 2.4) when plant uptake of N was decreasing. Soil $NO_3^-$-N that is not immobilized may percolate beneath the plant-rooting zone, and therefore, higher $NO_3^-$-N at the end of the summer were particularly susceptible to leaching from the plant rooting zone.

### 2.3.3 Winter Net N Mineralization and Nitrification

Our study supports growing evidence in the literature that measurable microbial activity can occur during winter, and that the duration of over-winter incubations affects the rates of these processes (Clein and Schimel 1995; Brooks et al. 1996; Hobbie and Chapin 1996; Devito et al. 1999). Clein and Shimel (1995) have shown that microbes can remain active at least to –5°C, existing in either water films or water-filled pores. Brooks et al. (1996) also measured net N mineralization in frozen soil under alpine snowpacks in Colorado between March and May (before snowmelt), and found rates similar to those in the cut plots in this study (35 to 105 mg $m^{-2}$ $d^{-1}$). Winter net N mineralization and nitrification as a percentage of annual production in the uncut plots tended to be slightly lower than values reported by Devito et al. (1999) for undisturbed maple and hemlock stands in Ontario (mineralization: 26-46%, nitrification: 11-57%). Percentages in the cut plots in this study were similar to their range.

Freezing of water films and/or eventual depletion of available substrates in unfrozen water films or pores could curtail microbial activity over extended periods of time, and explain why net N mineralization and nitrification did not increase with incubation duration. In a similar manner, decreases in growing season net rates with increases in incubation duration have been attributed to the depletion of mineralizable N to soil microbes and immobilization of inorganic N by decomposition of severed roots, and (Adams et al. 1989; Binkley and Hart 1989). Mean percent N mineralization (4%) and nitrification (0%) calculated for the uncut plots of the three stands over 208 and 142 d are consistent with values reported in studies where 6 month winter incubations represented less than 5% of annual mineralization (Hill and Shackleton 1989; Boone 1992; Lamontagne 1998). Studies with long over-winter incubations may be underestimating actual N transformations.

The reason why winter net N mineralization and nitrification rates in the cut plots were higher than in uncut plots is unclear. Soil temperature records for the two aspen were similar both uncut and cut plots, and it is unlikely that the slightly colder temperatures in the cut plots stimulated mineralization and nitrification activity (Fig. 2.9). Furthermore, the occurrence of freeze-thaw cycles do not explain the observed differences because relatively large temperature fluctuations occurred in both uncut (see Fig. 2.9, MIX-LM) and cut plots (see Fig. 2.9, ASP-SD). The higher rates in cut plots may reflect greater availability of soluble substrate N originating from the decomposition of abundant slash material by soil microorganisms. Increased skeletonization of aspen leaves under snow in cut plots compared to uncut plots has been attributed to increased feeding activity by soil invertebrates in cut plots (Bird et al. 1987). Further research on the processing of N in frozen soils is required for a more complete understanding of the factors controlling microbial activity during winter.

## 2.4 Conclusions

This study provides new information on *in situ* soil N transformations for three upland forest stands typical of a geographically large forest region in Canada that is under intensive harvesting pressure. While net N transformations did not differ between uncut and cut plots of aspen-dominated stands, cut plots of an aspen/conifer-mixed stand had high rates of net nitrification during the growing season following disturbance. Net nitrification in the aspen/conifer-mixed stand remained high into the fall and winter, thus, soil $NO_3^-$-N has the potential to increase at a time when plant uptake of N is decreasing or not occurring. Measurable rates of net mineralization and nitrification occurred during winter in all three forest stands, particularly in the cut plots, suggesting that both aspen-dominated and mixed stands have the potential to lose N with spring snowmelt when N may leach from the plant-rooting zone before plant uptake becomes significant.

Differences in rates between uncut and cut plots could not be clearly accounted for by differences in soil moisture, soil C:N, pH, texture or extractable $NH_4^+$-N. Instead, small differences in soil temperature between uncut and cut plots combined with the extent of plant regeneration among the stands may affect rates of N mineralization, nitrification, and subsequent N leaching. In comparison to the aspen-dominated stands where re-growth of suckers was very rapid, plant regeneration in cut plots of the aspen/conifer-mixed stand was slow. Hence, it is possible that the availability of $NH_4^+$-N to nitrifiers was higher in cut plots of the aspen/conifer stand, which promoted higher nitrifier populations and/or activity. Subsequently, leaching of N would also most likely occur in harvested areas with slow plant regeneration. Hence it is recommend that harvesting practices in the region minimize soil disturbances that compromise rapid plant regeneration. Future research should include: (1) Comparing N mineralization and nitrification rates in combination with spatial and temporal changes of soil microbes; (2) Assessing N mineralization and nitrification rates and soil pore water N concentrations in stands with poor regeneration and areas where herbicides are used; (3) Determining the potential for N movement from terrestrial to aquatic ecosystems during spring snowmelt and summer storms; (4) Evaluating disturbance impacts to other forest types that comprise the Boreal Mixedwood ecozone.

## 2.5 Literature Cited

Aber, J.D., Botkin, D.B., and Melillo, J.M. 1978. Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. Can. J. For. Res. 8: 306-315.

Adams, M.A., Polglase, P.J., Attiwill, P.M. and Weston, C.J. 1989. *In situ* studies of nitrogen mineralization and uptake in forest soils; some comments on methodology. Soil Biol Biochem 21: 423-429.

Adams, P.W., Flint, A.L., Fredriksen, R.L. 1991. Long-term patterns in soil moisture and revegetation after a clearcut of a Douglas-fir forest in Orgeon. For. Ecol. Manage. 41: 249-263.

Alberta Environmental Protection. 1996. The status of Alberta's timber supply. Albeta Govt. Publ. NO T/325, Edmonton, AB.

Berden, M., Nilsson, S.I., and Nyman, P. 1997. Ion leaching before and after clear-cutting in a Norway Spruce stand – Effects of long-term application of ammonium nitrate and superphosphate. Water Air Soil Poll. 93: 1-26.

Berg, M.P., Verhoef, H.A., Bolger, T., Anderson, J.M., Beese, F., Couteaux, M.M., Ineson, P., McCarthy, F., Palka, L., Raubuch, M., Splatt, P. and Willison, T. 1997. Effects of air pollutant-temperature interactions on mineral-N dynamics and cation leaching in replicate forest soil transplantation experiments. Biogeochemistry 39: 295-326.

Binkley, D., and Hart, S.C. 1989. The components of nitrogen availability assessments in forest soils. *In* Advances in Soil Science Volume 10. B.A. Stewart. Ed. Springer-Verlag, New York.

Bird, G.A., Rachar, D.B., Chatarpaul, L. 1987. Increased skeletonization of leaf litter under snow following timber harvest. Ecology 68: 221-223.

Boone, R.D. 1992. Influence of sampling date and substrate on nitrogen mineralization: comparison of laboratory-incubation and buried-bag methods for two Massachusetts forest soils. Can. J. For. Res. 22: 1895-1900.

Boring, L.R., Monk, C.D., and Swank, W.T. 1981. Early regeneration of a clear-cut southern Appalachian forest. Ecology 62: 1244-1253.

Brooks, P.D., Williams, M.W., and Schmidt, S.K. 1996. Microbial activity under alpine snowpacks, Niwot Ridge, Colorado. Biogeochemistry 43: 1-15.

Canada Soil Survey Committee. 1987. The Canadian system of soil classification 2nd ed. Agriculture Canada. Ottawa. ON Publ. 1646. 164pp.

Carter, M.R. 1993. Soil sampling and methods of analysis. Canadian Society of Soil Science. Lewis Publishers. Toronto, ON.

Clein, J.S. and Schimel, J.P. 1995. Microbial activity of tundra and taiga soils at sub-zero temperatures. Soil Biol. Biochem. 27: 1231-1234.

Crepin, J. and Johnson, R.L. 1993. Soil sampling for environmental assessment. *In* Soil Sampling and Methods of Analysis. M.R. Carter. Ed. Canadian Society of Soil Science. Lewis Publishers. Toronto, ON.

Cragg, J.B., Carter, A., Leischner, C., Peterson, E.B., and Sykes, G.N. 1977. Litter fall and chemical cycling in an aspen (*Populus tremuloides*) woodland ecosystem in the Canadian Rockies. Pedobiologia 17: 428-443.

Day, R.W. and Quinn, G.P. 1989. Comparisons of treatments after an analysis of variance in ecology. Ecol. Mono. 59: 433-463.

Devito, K.J., Westbrook, C.J., and Schiff, S.L.1999. Nitrogen mineralization and nitrification in upland and peatland forest soils in two Canadian Shield catchments. Can. J. For. Res.

Eno, C.H. 1960. Nitrate production in the field by incubating the soil in polyethylene bags. Soil Sci. Soc. Am. Proc. 24: 277-279.

Finzi, A.C., Van Breemen, N, and Canham, C.D. 1998. Canopy tree-soil interactions within temperate forests: species effects on soil carbon and nitrogen. Ecol. Appl. 8: 440-446.

Frazer, D.W., McColl, J.G., and Powers, R.F. 1990. Soil nitrogen mineralization in a clearcutting chronosequence in a northern California conifer forest. Soil Sci. Soc. Am. J. 54: 1145-1152.

Goovaerts, P., and Chiang, C.N. 1993. Temporal persistence of spatial patterns for mineralizable nitrogen and selected soil properties. Soil Sci. Soc. Am. J. 57: 372-381.

Hart, S.C., Stark, J.M., Davidson, E.A., and Firestone, M.K. 1994. Nitrogen mineralization, immobilization, and nitrification. *In* Methods of soil analysis, part 2. Microbiological and biochemical properties. Soil Science Society of America. Madison, US.A. pp. 985-1018.

Hart, S.C., Binkley, D. and Perry, D.A. 1997. Influence of red alder on soil nitrogen transformations in two conifer forests of contrasting productivity. Soil Biol Biochem. 29: 1111-1123.

Hendrickson, O.Q., Chatarpaul, L. and Robinson, J.B. 1985. Effects of two methods of timber harvesting on microbial processes in forest soil. Soil Sci. Soc. Am. J. 49: 739-746.

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.

Hill, A.R. and Shackleton, M. 1989. Soil N mineralization and nitrification in relation to nitrogen solution chemistry in a small forested watershed. Biogeochemistry 8:167-184.

Hobbie, S.E. and Chapin, III, F.S. 1996. Winter regulation of tundra litter carbon and nitrogen dynamics. Biogeochem. 35:327-338.

Johnston, R.S. 1970. Evapotranspiration from bare, herbaceous, and aspen plots: a check on a former study. Water Resour. Res. 7: 324-327.

Krause, H.H. 1982. Nitrate formation and movement before and after clear-cutting of a monitored watershed in central New Brunswick, Canada. Can. J. For. Res. 12:922-30.

Kubin, E. 1998. Leaching of nitrate nitrogen into the groundwater after clear felling and site preparation. Boreal Environment Research. 3: 3-8.

Lambert, J.D. 1998. Ovenbirds (*Seiurus aurocapillus*) in riparian buffer strips: short-term response to upland timber harvest in Alberta's boreal mixed-wood forest. Department of Biological Sciences. University of Alberta. M.Sc. Thesis.

Lamontagne, S. 1998. Nitrogen mineralization in upland Precambrian Shield catchments: contrasting the role of lichen-covered bedrock and forested areas. Biogeochemistry 41: 53-69.

Likens, G.E., Bormann, F.H., Johnson, N.M., Fisher, D.W. and Pierce, R.S. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Mono. 40: 23-47.

Lousier, J.D. and Parkinson, D. 1976. Litter decomposition in a cool temperate deciduous forest. Can. J. Bot. 54: 419-436.

Lukewille, A. and Wright, R.F. 1997. Experimental increased soil temperature causes release of nitrogen at a boreal forest catchment in southern Norway. Global Change Biology 3:13-21.

Lundgren, B. 1982. Bacteria in a pine forest soil as affected by clear-cutting. Soil Biol. Biochem. 14: 537-542.

Maynard, D.G. 1997. Soil nutrient dynamics in a boreal mixedwood cutover following the application of hexazinone. Ecol. Appl. 7: 416-430.

Meyer, S.L. 1975. Data analysis for scientists and engineers. John Wiley and Sons, New York, N.Y.

Mladenoff, D.J. 1987. Dynamics of nitrogen mineralization and nitrification in hemlock and hardwood treefall gaps. Ecology 68: 1171-1180.

Northup, R.R., Dahlgren, R.A., and Yu, Z. 1995. Intraspecific variation of conifer phenolic concentration on a marine terrace soil acidity gradient: a new interpretation. Plant and Soil 171: 255-262.

Pastor, J. and Bockheim, J.G. 1984. Distribution and cycling of nutrients in an aspen-mixed-hardwood-spodosol ecosystem in northern Wisconsin. Ecology 65: 339-353.

Persson, T. and Wiren, A. 1995. Nitrogen mineralization and potential nitrification at different depths in acid forest soils. Plant and Soil 168-169: 55-65.

Reich, P.B., Grigal, D.F., Aber, J.D. and Gower, S.T. 1997. Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. Ecology 78: 335-347.

Robertson, G.P. 1987. Geostatistics in ecology: Interpolating with known variance. Ecology 68: 744-748.

Rosen, K., and Lundmark-Thelin, A. 1987. Increased nitrogen leaching under piles of slash – a consequence of modern forest harvesting techniques. Scand. J. For. Res. 2:21-29.

Rowe. J.S. 1972. Forest regions of Canada. Publication Number 1300, Department of the Environment, Canadian Forestry Service, Ottawa, Ontario, Canada.

Schmidt, M.G., Macdonald, S.E. and Rothwell, R.L. 1996. Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. Can. J. For. Res. 531-540.

Shaw, R.D., Trimbee, A.M., Minty, A., Fricker, H., and Prepas, E.E. 1989. Atmospheric deposition of phosphorus and nitrogen in central Alberta with emphasis on Narrow Lake. Water Air Soil Poll. 43: 119-134.

Stottlemyer, R., Travis, B. and Toczydlowski, D. 1995. Nitrogen mineralization in boreal forest stands of Isle Royale, northern Michigan. Water Soil Air Poll. 82: 191-202.

Stump, L.M. and Binkley, D. 1993. Relationships between litter quality and nitrogen availability in Rocky Mountain forests. Can. J. For. Res. 23: 492-502.

Tamm, C.O. 1991. Nitrogen in terrestrial ecosystems: questions of productivity, vegetational changes, and ecosystem stability. Ecological Studies v. 81. Springer-Verlag, Berlin, Germany. 115 pp.

Technicon. 1973a. Ammonia in water and wastewater. Industrial method 696-82W. Technicon Industrial Systems, Tarrytown, NY.

Technicon. 1973b. Nitrate and nitrite in water and seawater. Industrial method 100-70W. Technicon Industrial Systems, Tarrytown, NY.

Van Miegroet, H., Cole, D.W. and Foster, N.W. 1992. Nitrogen distribution and cycling. *In* Atmospheric deposition and forest nutrient cycling. New York, N.Y. Springer-Verlag. pp. 179-199.

Van Miegroet, H. and Johnson, D.W. 1993. Nitrate dynamics in forest soils. *In* Terrestrial nitrogen cycles: processes, patterns and management. John Wiley and Sons. Chichester, England. pp. 25-97.

Van Miegroet, H. 1995. Inorganic nitrogen determined by laboratory and field extractions of two forest soils. Soil Sci. Soc. Am. J. 59: 549-553.

Veliz, M. 1999. Relationship of nutrient and mayfly (Ephemeroptera) abundance and diet to periphyton biomass in boreal streams. Department of Biological Sciences. University of Alberta. M.Sc. Thesis.

Vitousek, P.M. 1981. Clear-cutting and the nitrogen cycle. *In* Terrestrial nitrogen cycles: processes, ecosystem strategies and management impacts. Volume 33. Stockholm: Ecol. Bull. pp. 631-642.

Vitousek, P.M., Gosz, J.R., Grier, C.C., Melillo, J.M., and Reiners, W.A. 1982. A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems. Ecol. Mono. 52: 155-177.

Walley, F.L., Van Kessel, C., and Pennock, D.J. 1996. Landscape-scale variability of N mineralization in forest soils. Soil Biol. Biochem. 28:383-391.

Westbrook, C. 2000. Nitrogen dynamics in upland and peatland Boreal Shield soils. M.Sc. Thesis. University of Alberta.

Zar, 1984. Biostatistical analysis 2$^{nd}$ Ed. Prentice Hall. Englewood Cliffs, New Jersey, USA.

Table 2-1. Vegetation characteristics of uncut plots in three forest stands. Data presented are mean stem counts for each study plot. Trees were defined as individuals taller than 5 m in height.

| | ASP – SD | ASP – LM | MIX-LM |
|---|---|---|---|
| Tree density (stems m$^{-2}$) | 0.07 | 0.09 | 0.13 |
| Phytosociology (%) | | | |
| *Populus tremuloides* | 81 | 77 | 62 |
| *Populus balsamifera* | 15 | 23 | 0 |
| *Betula papyrifera* | 0 | 0 | 16 |
| *Picea glauca* | 0 | 0 | 16 |
| *Abies balsamifera* | 0 | 0 | 6 |
| *Salix sp.* | 4 | 0 | 0 |

Table 2-2. Soil properties of the LFH and 0 to 10-cm mineral soil depths in uncut and cut plots of three forest stands. Values are means (± 1 SE) for two study plots. Soil Great Groups were determined from a single pit in each study plot.

| | | | ASP - SD | | ASP - LM | | MIX - LM | |
|---|---|---|---|---|---|---|---|---|
| Harvesting Treatment | | | Uncut | Cut | Uncut | Cut | Uncut | Cut |
| Soil Great Group | | Plot 1 | Gray Luvisol | Eutric Brunisol | Dark Gray Luvisol | Gleyed Gray Luvisol | Gray Luvisol | Gray Luvisol |
| | | Plot 2 | Gray Luvisol | Eutric Brunisol | Dark Gray Luvisol | Orthic Gray Luvisol | Gray Luvisol | Gleyed Luvisol |
| Soil Texture | | Plot 1 | loamy sand | loamy sand | loam | silt loam | loam | loam to sandy loam |
| | | Plot 2 | loamy sand | sand | loam | loam | loam | clay to clay loam |
| LFH Thickness (cm) | | Plot 1 | 7.3 (0.5) | 6.9 (0.3) | 5.7 (0.4) | 3.6 (0.2) | 5.8 (0.3) | 7.3 (0.5) |
| | | Plot 2 | 7.4 (0.3) | 6.4 (0.4) | 6.2 (0.5) | 2.9 (0.2) | 6.0 (0.3) | 8.7 (0.4) |
| Ae Thickness (cm) | | Plot 1 | 0-10 | 0-10 | 0-5 | 0-25 | 0-8 | 0-7 |
| | | Plot 2 | 0-35 | 0-15 | 0-5 | 0-9 | 0-7 | 0-3 |
| Soil pH (n=14) | | LFH | 6.45 (0.05) | 5.92 (0.09) | 5.99 (0.11) | 5.84 (0.12) | 6.04 (0.18) | 5.92 (0.09) |
| | | 0-10cm | 5.80 (0.18) | 4.93 (0.11) | 6.12 (0.08) | 6.36 (0.15) | 5.54 (0.17) | 5.79 (0.16) |
| Total Carbon:Total Nitrogen (n=14) | | LFH | 23.2 (0.9) | 24.9 (1.0) | 24.3 (1.3) | 23.9 (2.2) | 28.8 (1.3) | 27.2 (1.1) |
| | | 0-10cm | 17.9 (0.5) | 21.1 (1.1) | 14.0 (0.5) | 12.6 (0.6) | 15.5 (0.7) | 15.3 (0.5) |
| Bulk Density (g $cm^{-3}$) (n=44-63) | | LFH | 0.10 (0.01) | 0.19 (0.01) | 0.15 (0.01) | 0.14 (0.01) | 0.15 (0.00) | 0.19 (0.01) |
| | | 0-10cm | 0.80 (0.02) | 1.06 (0.02) | 1.09 (0.02) | 1.20 (0.03) | 1.19 (0.03) | 1.18 (0.03) |
| Exchangeable Cations (meq $100g^{-1}$ soil) (n=14) | Ca | LFH | 51.4 (4.5) | 28.6 (0.1) | 66.6 (1.3) | 70.9 (3.5) | 63.5 (8.2) | 81.0 (12.8) |
| | | 0-10cm | 10.7 (2.5) | 2.8 (0.1) | 21.2 (0.9) | 20.9 (7.3) | 10.8 (1.8) | 16.7 (1.9) |
| | Mg | LFH | 9.7 (0.6) | 5.5 (0.6) | 13.5 (0.2) | 11.4 (1.5) | 11.3 (1.0) | 9.5 (2.3) |
| | | 0-10cm | 1.4 (0.2) | 0.5 (0.0) | 5.3 (1.4) | 2.6 (0.7) | 3.4 (0.4) | 3.5 (0.5) |
| | K | LFH | 2.7 (0.1) | 2.1 (0.2) | 3.2 (0.1) | 3.4 (0.1) | 3.3 (0.3) | 2.9 (0.3) |
| | | 0-10cm | 0.7 (0.1) | 0.3 (0.0) | 1.8 (0.2) | 1.1 (0.2) | 0.6 (0.2) | 1.4 (0.2) |
| | Na | LFH | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) |
| | | 0-10cm | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) | 0.1 (0.0) |
| Grade (%) | | Plot 1 | 25 | 20 | 21 | 4 | 20 | 10 |
| | | Plot 2 | 21 | 16 | 17 | 12 | 10 | 10 |

Table 2-3. Growing season (May 15 to Oct. 9, 1997) net N mineralization and percent mineralization of soil N for the LFH and 0 to 10 cm mineral soil in three forest stands. Data are sums (±1 *SE*) for monthly incubations for each plot in each forest stand. *SE* was determined by first order error propagation of variances of mean monthly incubations. Contrasts between uncut and cut plots for the growing season for each forest stand were examined with Fisher's combined probabilities test with *P* values from *t*-tests performed on data from each monthly incubation period (*, **, *** indicate $P < 0.05$, 0.01 and 0.001, respectively; $df = 10$).

|  | Net N Mineralization Growing Season Total ($\mu g\ N\ g^{-1}$ dwt) |  |  |  |  |
|---|---|---|---|---|---|
| Forest Stand | Uncut |  | Cut |  | Fisher's Test |
| **LFH** | Plot 1 | Plot 2 | Plot 1 | Plot 2 | $-2\ \Sigma \ln P$ |
| ASP-SD | 84 (66) | 233 (65) | 212 (107) | 312 (236) | 17.2 |
| ASP-LM | 248 (73) | 188 (62) | 289 (120) | 247 (132) | 15.8 |
| MIX-LM | 138 (50) | 110 (55) | -59 (90) | -171 (164) | 27.2** |
| **Mineral (0-10 cm)** |  |  |  |  |  |
| ASP-SD | 16 (8) | 3 (6) | 26 (10) | 9 (6) | 14.1 |
| ASP-LM | 11 (3) | 7 (4) | 27 (6) | -1 (14) | 9.2 |
| MIX-LM | 6 (2) | 5 (2) | -31 (16) | -49 (22) | 46.1*** |

|  | Growing Season Total (kg ha$^{-1}$) |  |  |  | % Mineralization of N |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | Uncut |  | Cut |  | Uncut |  | Cut |  |
| **LFH** | Plot 1 | Plot 2 | Plot 1 | Plot 2 | Plot 1 | Plot 2 | Plot 1 | Plot 2 |
| ASP-SD | 4 (3) | 19 (5) | 12 (6) | 41 (31) | 0.61 | 1.63 | 1.71 | 3.03 |
| ASP-LM | 25 (7) | 32 (10) | 32 (13) | 37 (19) | 1.49 | 1.05 | 2.33 | 1.56 |
| MIX-LM | 23 (8) | 15 (7) | -14 (22) | -30 (28) | 0.97 | 0.66 | -0.34 | -1.08 |
| **Mineral (0-10 cm)** |  |  |  |  |  |  |  |  |
| ASP-SD | 13 (7) | 3 (4) | 28 (10) | 10 (6) | 1.23 | 0.17 | 1.65 | 1.05 |
| ASP-LM | 12 (3) | 7 (4) | 32 (7) | -1 (17) | 0.28 | 0.22 | 2.44 | -0.05 |
| MIX-LM | 7 (2) | 6 (3) | -41 (21) | -54 (24) | 0.34 | 0.36 | -1.81 | -1.54 |

Table 2-4. Growing season (May 15 to Oct. 9, 1997) net nitrification and percent nitrification of $NH_4^+$-N for the LFH and 0 to 10 cm mineral soil in three forest stands. Data are sums (±1 *SE*) for monthly incubations for each plot in each forest stand. *SE* was determined by first order error propagation of variances of mean monthly incubations. Contrasts between uncut and cut plots for the growing season for each forest stand were examined with Fisher's combined probabilities test with *P* values from *t*-tests performed on data from each monthly incubation period (*, **, *** indicate $P < 0.05$, 0.01 and 0.001, respectively; *df* = 10).

| | Net Nitrification<br>Growing Season Total (μg N $g^{-1}$ dwt) | | | | |
|---|---|---|---|---|---|
| Forest Stand | Uncut | | Cut | | Fisher's Test |
| **LFH** | Plot 1 | Plot 2 | Plot 1 | Plot 2 | -2 Σ ln P |
| ASP-SD | 1.7 (3.3) | 6.0 (1.8) | 8.0 (8.6) | 3.0 (5.8) | 11.5 |
| ASP-LM | 57 (76) | 6.5 (6.3) | 28 (61) | 34 (32) | 16.2 |
| MIX-LM | -1.6 (3.2) | -5.9 (8.0) | 155 (114) | 133 (97) | 41.3*** |
| **Mineral (0-10 cm)** | | | | | |
| ASP-SD | -0.2 (1.0) | 0.6 (0.9) | 7.3 (16) | 0.2 (0.6) | 10.9 |
| ASP-LM | 1.5 (1.2) | 0.7 (0.8) | 0.6 (1.8) | -0.2 (2.6) | 20.7* |
| MIX-LM | 0.4 (1.1) | -0.2 (0.7) | 8.5 (7.1) | 5.4 (3.1) | 37.2*** |

| | Growing Season Total (kg $ha^{-1}$) | | | | % Nitrification of $NH_4^+$-N | | | |
|---|---|---|---|---|---|---|---|---|
| | Uncut | | Cut | | Uncut | | Cut | |
| **LFH** | Plot 1 | Plot 2 | Plot 1 | Plot 2 | Plot 1 | Plot 2 | Plot 1 | Plot 2 |
| ASP-SD | 0.1 (0.2) | 0.5 (0.2) | 0.4 (0.5) | 0.4 (0.8) | 2 | 3 | 4 | 0.9 |
| ASP-LM | 5.8 (7.7) | 1.1 (1.1) | 3.1 (6.8) | 5.0 (4.8) | 23 | 3 | 10 | 14 |
| MIX-LM | -0.3 (0.5) | -0.8 (1.1) | 37 (27) | 23 (17) | -1 | -5 | >100 | >100 |
| **Mineral (0-10 cm)** | | | | | | | | |
| ASP-SD | -0.2 (0.9) | 0.4 (0.7) | 7.7 (16) | 0.3 (0.6) | -1 | 17 | 28 | 2 |
| ASP-LM | 1.6 (1.3) | 0.7 (0.9) | 0.7 (2.2) | -0.3 (3.1) | 13 | 10 | 2 | 29 |
| MIX-LM | 0.5 (1.3) | -0.3 (0.9) | 11 (9) | 5.9 (3.3) | 7 | -4 | >100 | >100 |

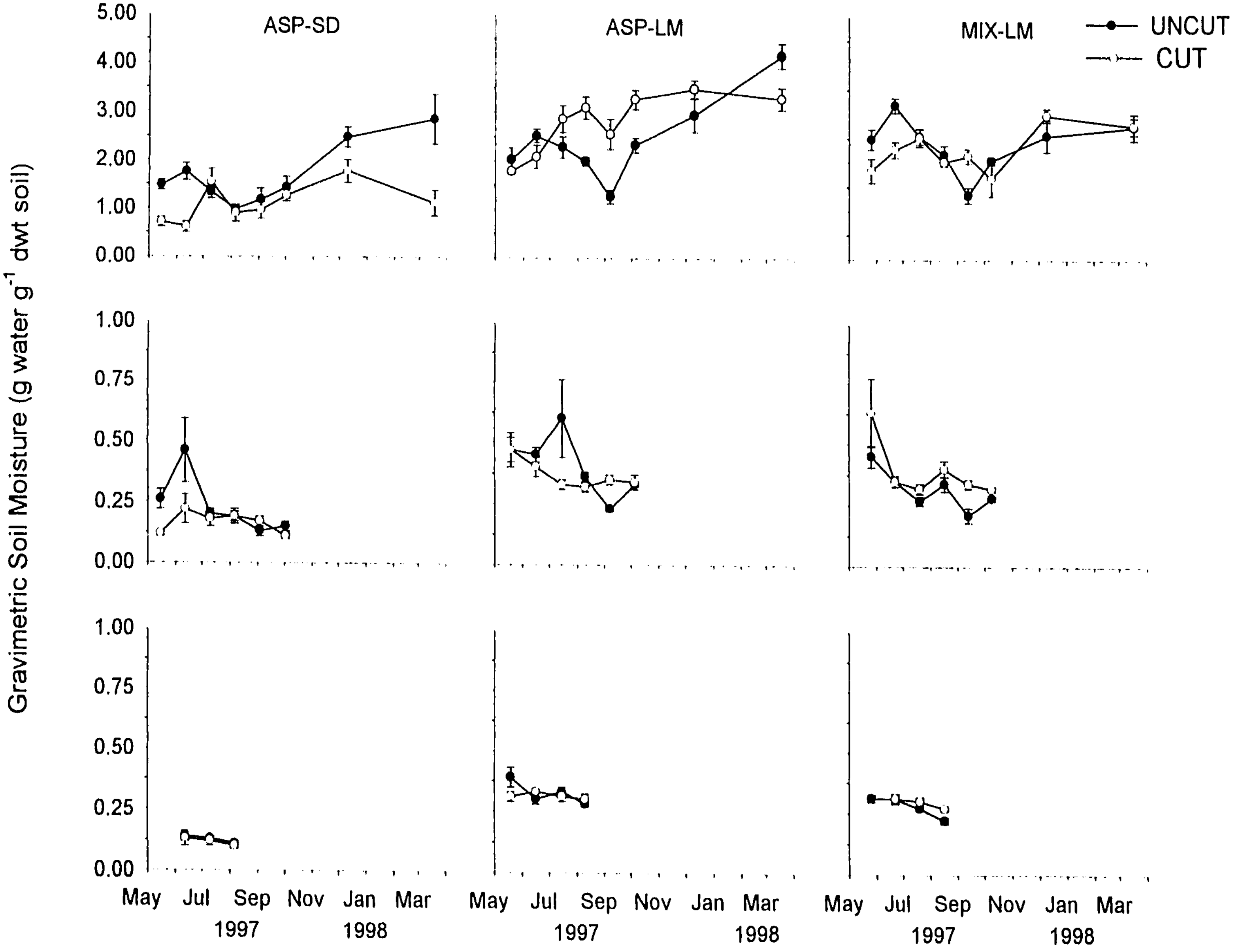

Fig. 2.1. Soil moisture (gravimetric) of three soil layers in three forest stands. Symbols represent means (± 1 *SE*) for soil cores from two study plots (n = 14).

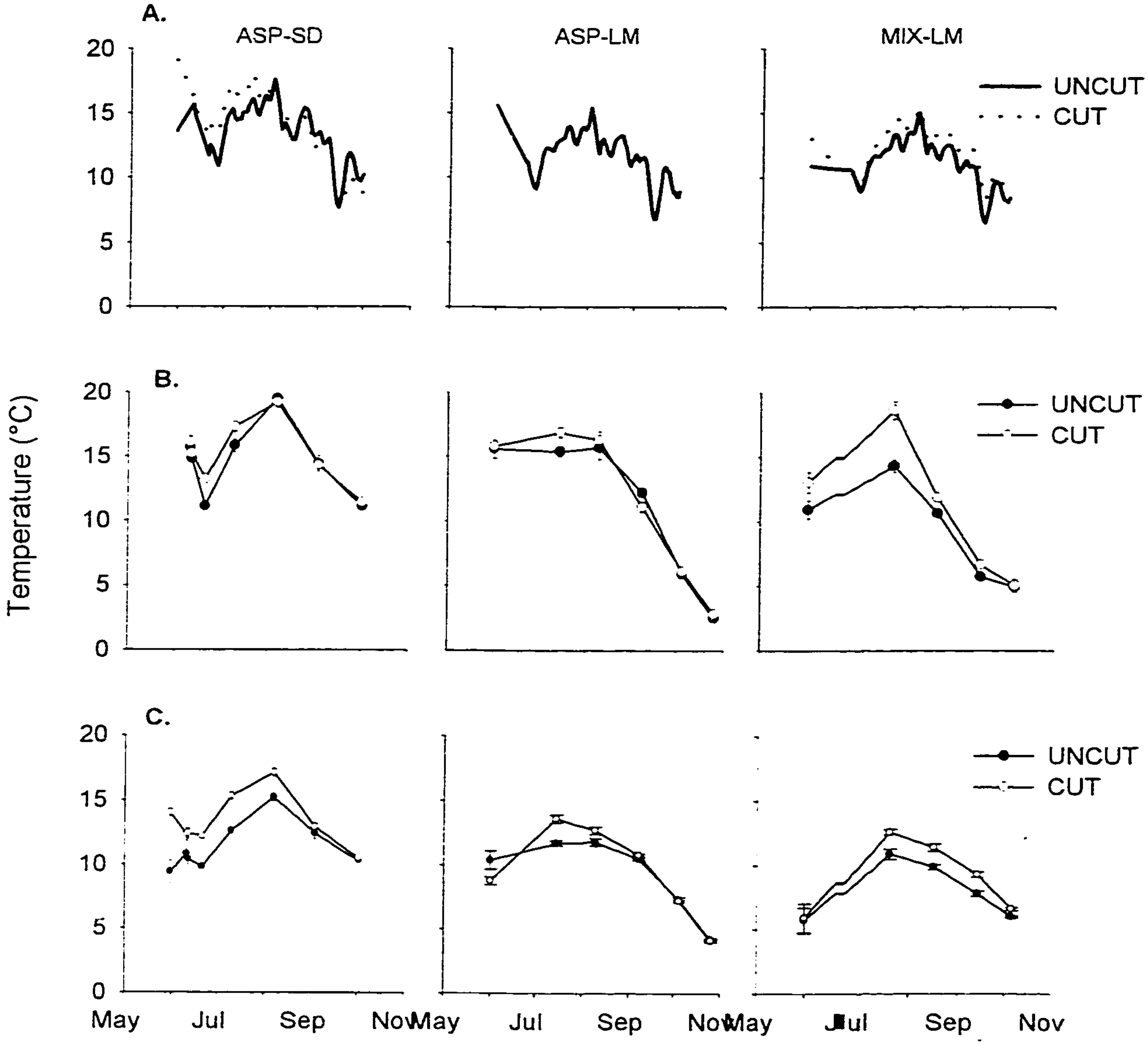

Fig. 2.2. Soil temperatures at various depths for three forest stands. A. shows mean daily temperatures at the LFH/mineral soil interface monitored with dataloggers. The datalogger in the cut area of ASP-LM was lost. B. and C. show average mid–day temperatures (n = 3) recorded with thermocouples at the centre of the LFH and 0 to 10 cm mineral soil depths, respectively.

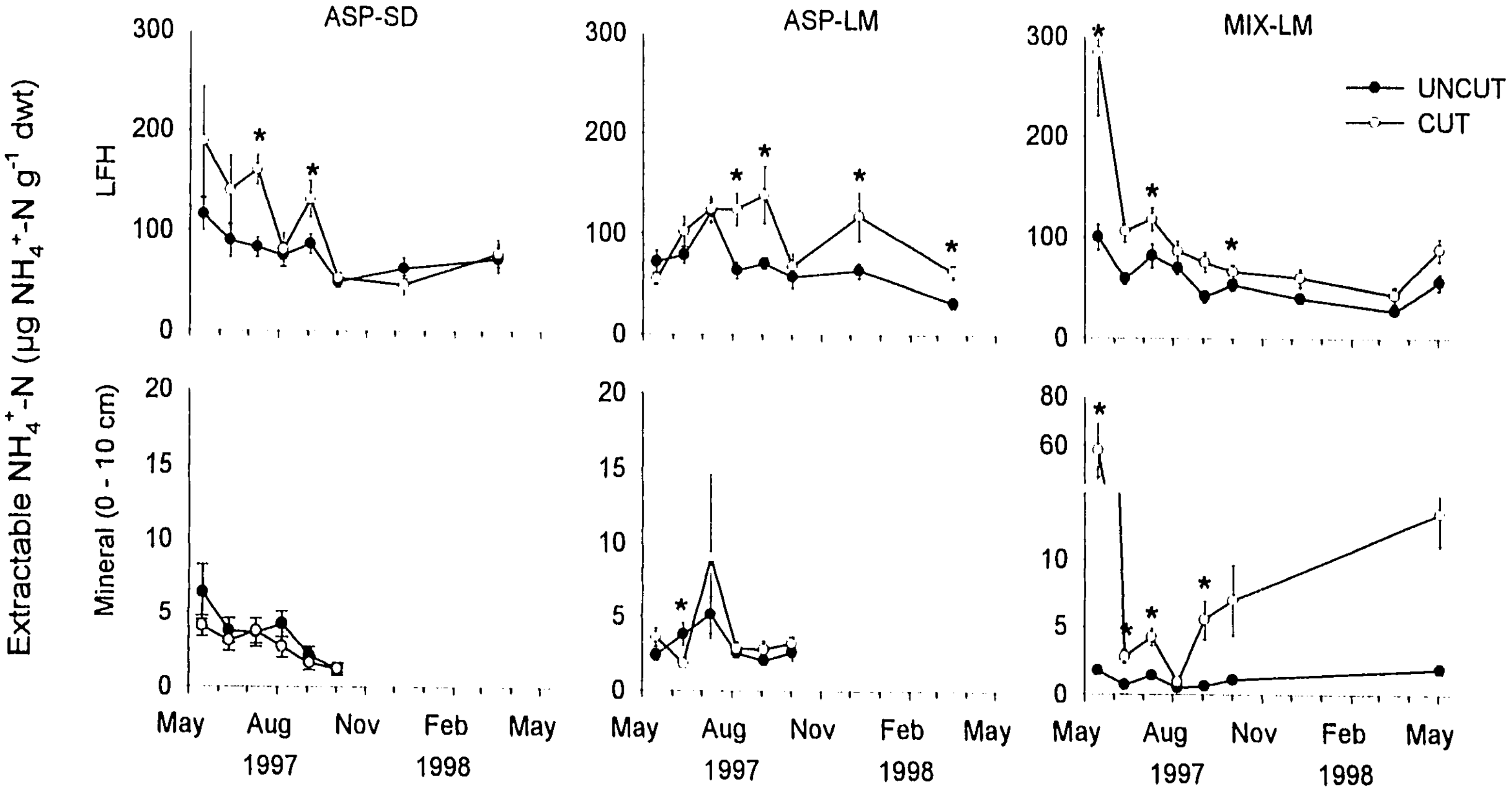

Fig. 2.3. Extractable soil $NH_4^+$-N at two soil depths for three forest stands. Symbols represent monthly averages (± 1 *SE*). An asterisk indicates a significant difference between uncut and cut plots within a forest stand during an incubation within a forest stand ($P < 0.05$).

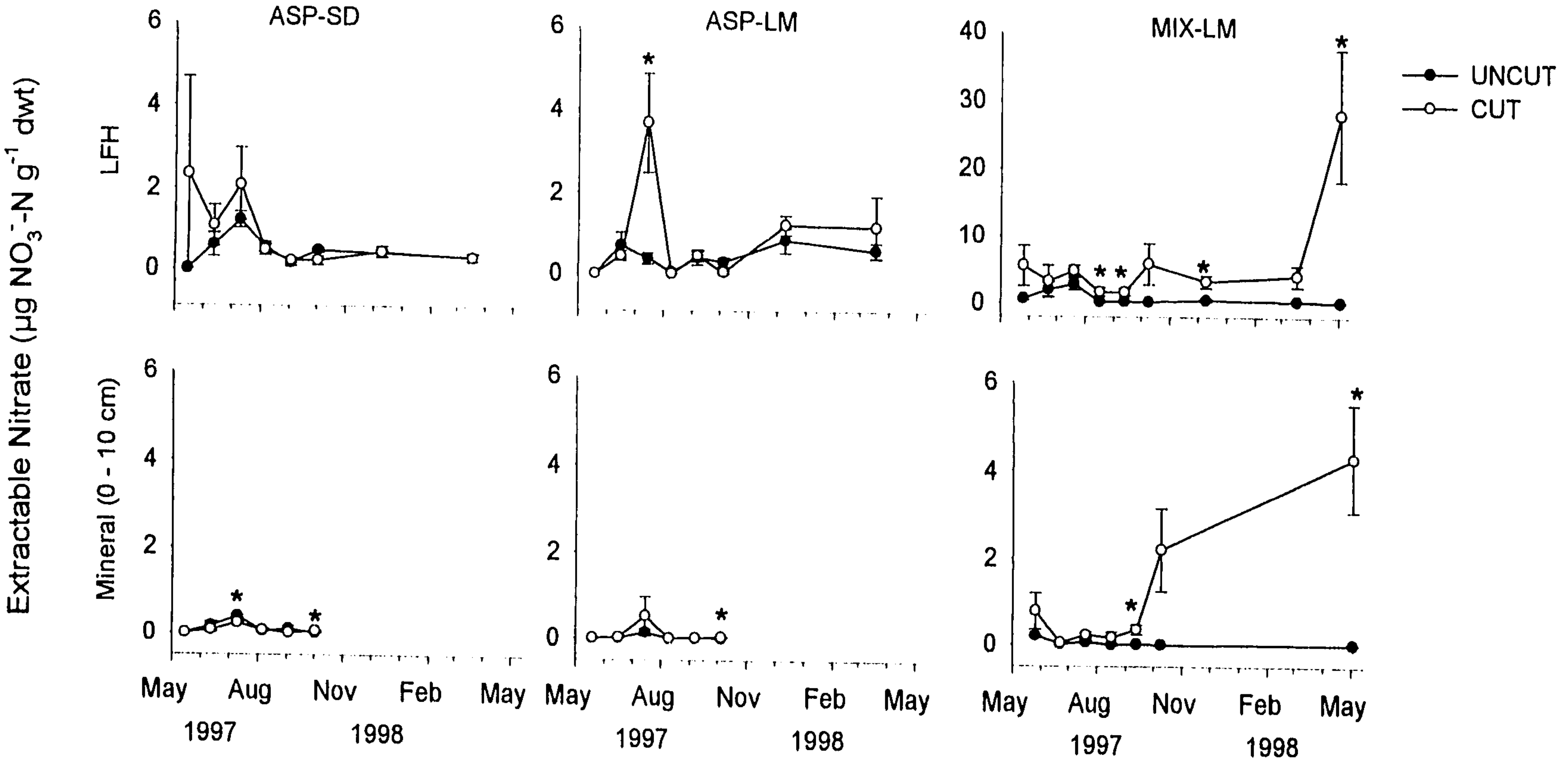

Fig. 2.4. Extractable soil $NO_3^-$-N at two soil depths for three forest stands. Symbols represent monthly averages (± 1 *SE*). An asterisk indicates a significant difference between uncut and cut plots during an incubation within a forest stand ($P < 0.05$). Note scale for MIX-LM LFH horizon is different.

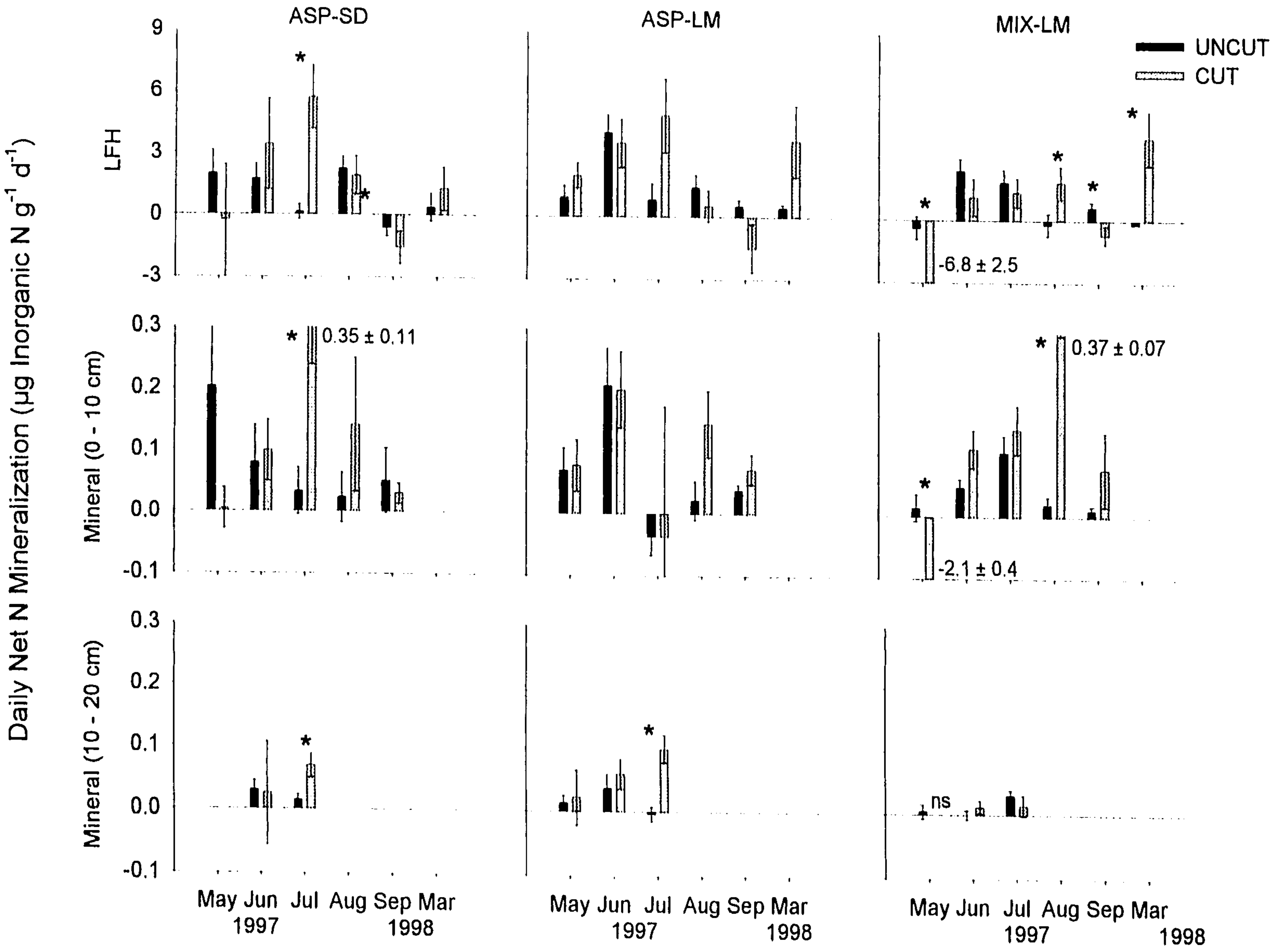

Fig. 2.5. Daily net N mineralization in three soil layers for three forest stands. Bars represent averages (± 1*SE*) measured over 28-d *in situ* incubation periods. The March 1998 incubation was 44 d long. An asterisk indicates a significant difference exists between uncut and cut plots within an incubation period ($P < 0.05$). "ns" indicates a site was not sampled due to frozen soils.

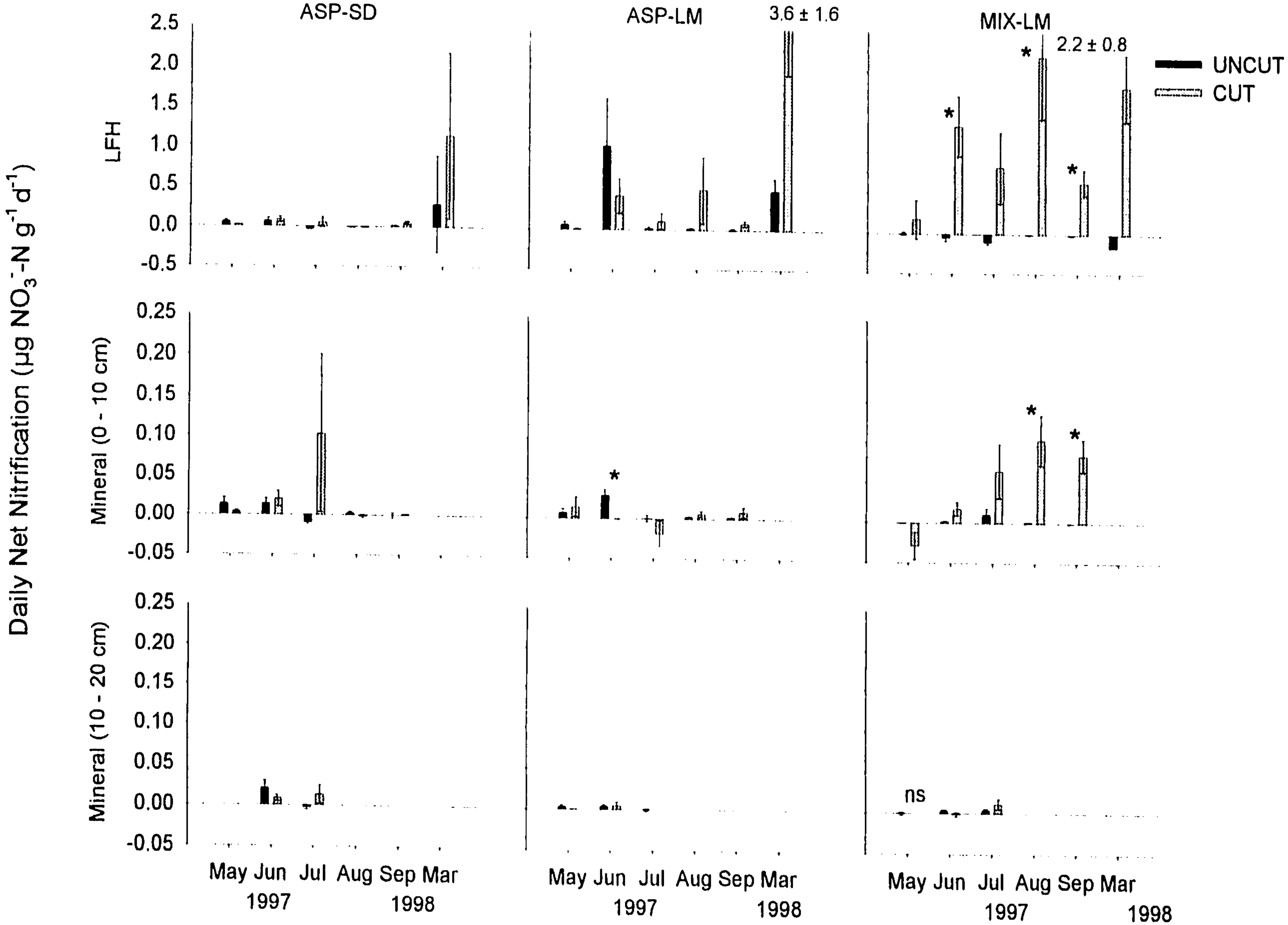

Fig. 2.6. Daily net nitrification in three soil layers for three forest stands. Bars represent averages (± 1*SE*) measured over 28-d *in situ* incubation periods. The March 1998 incubation was 44 d long. An asterisk indicates a significant difference exists between uncut and cut plots within an incubation period ($P < 0.05$) "ns" indicates a site was not sampled due to frozen soils.

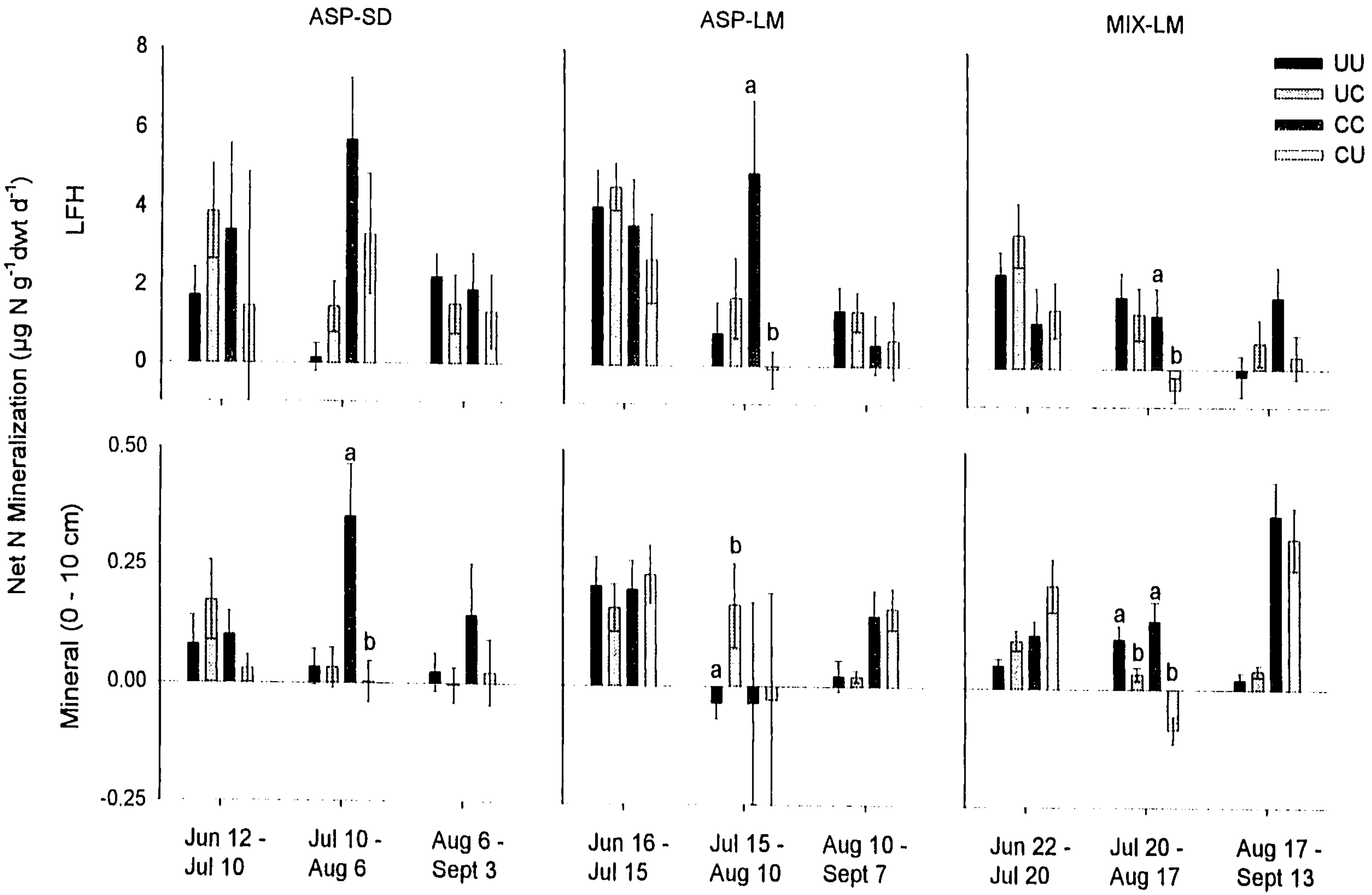

Fig. 2.7. Daily net N mineralization for control and transplanted soils from two soil layers of three forest stands. Bars represent averages (± 1 *SE*) for 28-d *in situ* incubations. UU and CC represent cores from uncut and cut plots, respectively, that were incubated within their original sites. UC and CU represent cores from uncut and cut plots, respectively, that were transplanted. "a" and "b" over adjacent bars indicate a significant difference between control and transplanted cores ($P < 0.05$).

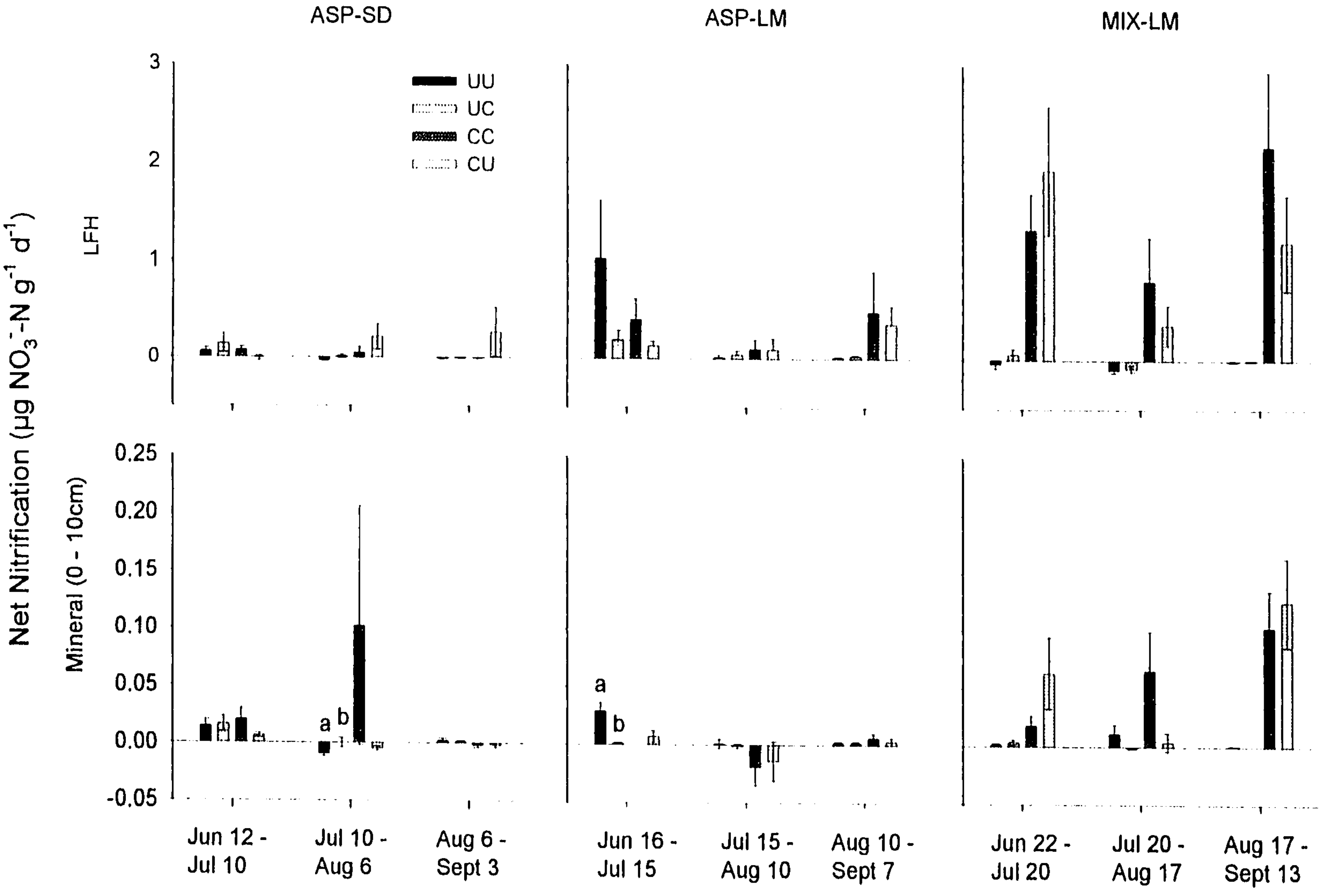

Fig. 2.8. Daily net nitrification for control and transplanted cores from two soil layers of three forest stands. Bars represent averages (± 1 *SE*) for 28-d *in situ* incubations. UU and CC represent cores from uncut and cut plots, respectively, that were incubated within their original sites. UC and CU represent cores from uncut and cut plots that were transplanted. "a" and "b" over adjacent bars indicate a significant difference between control and transplanted cores ($P < 0.05$).

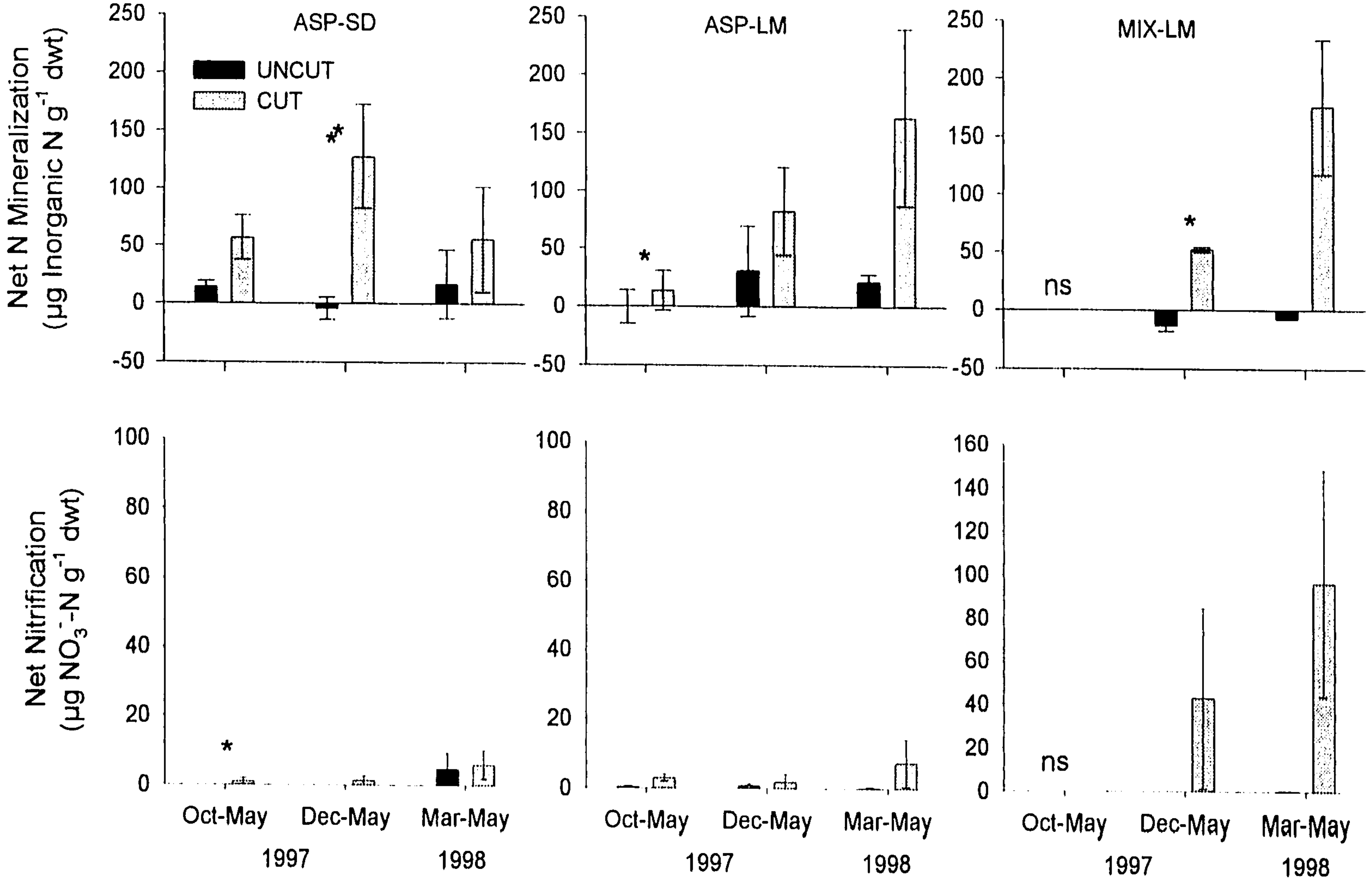

Fig. 2-10. Winter net N transformations in the LFH horizon of three forest stands. Bars represent averages (± 1*SE*). Bars without errors indicate n = 1 due to sample loss or damage. "ns" indicates that no samples exist for a particular site. Significant differences between uncut and uncut plots within an incubation are shown with an asterisk ($P < 0.05$). The Oct to May, Dec to May, and March to May incubation periods were 208, 142, and 44 days long, respectively. Note scale difference for MIX-LM.

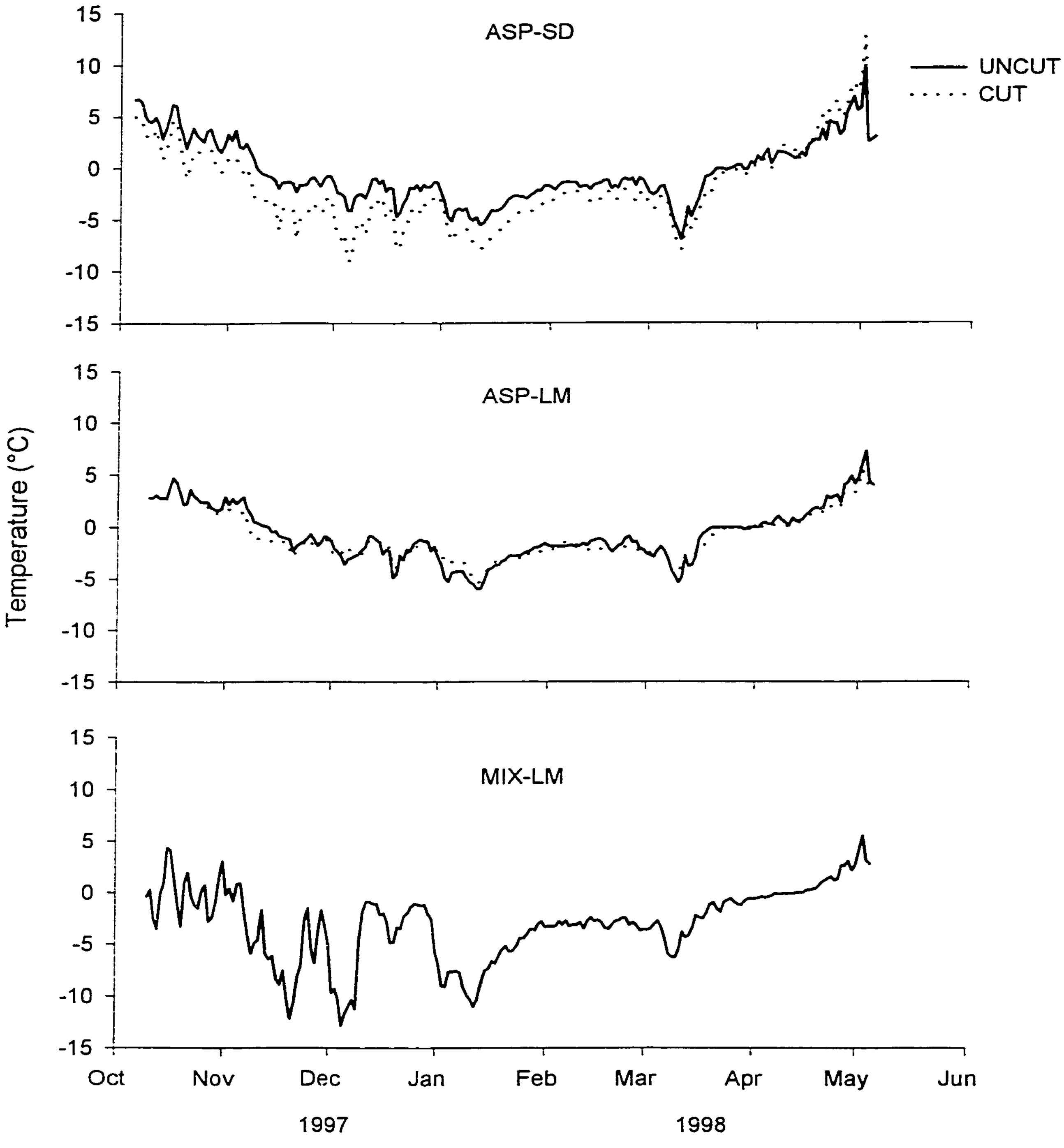

Fig. 2.9. Winter mean daily soil temperature measured at the LFH/mineral soil interface with dataloggers. The datalogger in the cut plot of MIX-LM was lost.

# Chapter 3. Gross Mineralization and Nitrification in an Aspen/Conifer-Mixed Stand in the Mixedwood Boreal Forest

## 3.0 Introduction

Numerous studies investigating the impacts of forest harvesting have shown that disturbance can alter net rates of N mineralization and nitrification (Vitousek et al. 1982; Hendrickson et al. 1985; Chapter 2). However, recent studies in forest soils have shown that net and gross rates are often not correlated, and that net rates may underestimate N turnover when production and immobilization of small inorganic N pools is rapid (Davidson et al. 1992; Stark and Hart 1997; Neill et al. 1999; Stottlemyer and Toczydlowski 1999). Net rates, the sum of ammonium ($NH_4^+$-N) and nitrate ($NO_3^-$-N) production and immobilization processes, reflect plant available N but they do not tease apart inorganic N production from immobilization processes that are important for predicting the potential for N leaching in disturbed forest ecosystems. In forests where net rates appear relatively unchanged after disturbance, it is possible that rapid microbial N immobilization co-occurring with increased gross $NH_4^+$-N and $NO_3^-$-N production result in little change in extractable soil pools of inorganic N. When net rates appear stimulated by disturbance, information on gross rates would reveal to what degree changes result from altered gross production or gross immobilization. Because soil disturbance can affect production and immobilization processes to varying degrees, a more complete picture of N transformations in forest soils is required.

Currently, there is limited information on gross N transformation rates in disturbed ecosystems, and results have been inconsistent. For example, in the Sierra Nevada Mountains, Davidson et al. (1992) worked in a 10-yr-old mixed-conifer plantation and a mature conifer-mixed forest and found that gross N mineralization was 2 to 3 times higher in the mature forest than in the young one, while gross nitrification rates were similar in both forests. In contrast, a more recent study by Pedersen et al. (1999) in a similar Sierra Nevada forest found that gross N mineralization rates did not differ in mineral soil among a 3-yr-old clear-cut, a 14-yr-old mixed-conifer plantation and a mature stand, whereas gross nitrification rates were highest in the young clear-cut, intermediate in the plantation, and lowest in the mature forest. These two studies suggest that factors regulating gross N transformations in forest soils vary spatially and temporally, hence, results from one forest ecosystem are unlikely to be applicable to others with different climate and physiographic regimes, and that research in a variety of forest ecosystems in warranted.

In the Mixedwood Boreal forest in Alberta, Canada (classification by Rowe 1972), 60% of productive forestland has been allocated to timber harvesting (Alberta Environment Protection 1996), yet there is limited information on soil N transformations in these N-poor forest soils. In 1997 I compared net N transformations between a 1-yr old clear-cut area and an uncut control in an aspen/conifer-mixed stand, and found net N immobilization during the growing season in the cut and low net N mineralization in the uncut area. In contrast, growing season net nitrification was relatively high in the cut compared to the uncut area. Lacking information on gross rates, it was unknown if lower net N mineralization in the cut treatment resulted from lower gross inorganic N production or higher immobilization. Similarly, whether higher net nitrification was due to elevated gross $NO_3^-$-N production or lower gross immobilization was unknown. Gross nitrification not coupled to $NO_3^-$-N immobilization could result in leachable pools of $NO_3^-$-N and N loss from the terrestrial ecosystem. Soil N is the limiting nutrient controlling productivity in the Boreal Mixedwood forest. Therefore, information on gross N transformations in undisturbed and disturbed stands is needed to predict the potential for N leaching, and the consequences to future forest productivity and water quality in adjacent surface waters.

The objective of this study was to quantify gross and net N mineralization and nitrification rates for soils in an upland aspen/conifer-mixed stand in north-central Alberta with adjacent mature and cut (2-yr old) areas. Laboratory incubations of intact soil cores were conducted to test the hypothesis that microbial immobilization of $NH_4^+$-N and $NO_3^-$-N balances gross production of these species resulting in low net rates that underestimate actual soil N turnover and the potential for N leaching. It was also expected that gross inorganic N production rates would be higher in disturbed compared to undisturbed forest soils, but that higher immobilization in former would result in no differences in net rates between uncut and cut areas. Rates were measured for varying duration to assess the influence of incubation length on measurements of net and gross N transformations. To facilitate extrapolation of the laboratory study to field conditions, *in situ* measurements of net N mineralization and nitrification were made concurrently with lab incubations.

## 3.1 Materials and Methods

### 3.1.1 Study Site Description

Research was conducted from May to August 1998 in an upland aspen/conifer-mixed stand in north-central Alberta (55°25'00"N, 113°42'30"W) with adjacent mature (>70-yr old) and cut (2-yr old) areas. Soils properties are summarized in Table 3-1. Forest composition based on stem count for the uncut area is 62% *Populus tremuloides*, 16% *Betula papyrifera*, and 16% *Picea glauca*. The disturbed and undisturbed study areas are 150 m apart, and air photos of the stands prior to harvesting indicate vegetation composition between the two areas was similar. Logging was conducted over-winter in 1996-97.

Long-term (25 yr) annual precipitation is 481 mm with approximately 90 to 100 mm falling as snow between November and March. Long-term mean annual January and July air temperatures are -16.5 and 16.0°C, respectively. During 1998, precipitation was 320 mm, and mean January and July temperatures were −18.9 and 17.4°C, respectively. There is no TN deposition data for the study area, however, approximately 200 km south at Narrow Lake (54°35'N, 113°37'W), TN deposition between 1983-1986 was ≈4.24 kg $ha^{-1}$ $y^{-1}$ (Shaw et al. 1989).

### 3.1.2 Laboratory Gross N Mineralization and Nitrification Measurements

Soil cores for laboratory measurements of gross N mineralization and nitrification rates were collected between May 8-10, 1998. Seven adjacent 2.5 x 2.5-m study plots were established in the uncut and cut treatments of the aspen/conifer-mixed stand. From each of the 7 uncut study plots, 5 pairs of intact LFH horizon and 5 pairs of intact mineral soil cores were collected. From each of the 7 cut study plots, 3 pairs of intact LFH horizon and mineral soil cores were collected. One core from each pair was allocated to measurements of gross N mineralization, and the other was used for gross nitrification measurements. Four to five days after field sampling, gross rates were measured with the $^{15}N$ isotope-dilution technique (Hart et al. 1994a) on 3 of the 5 pairs of soil cores from the uncut plots, and on all 3 pairs of cores collected from the cut plots for both the LFH and mineral soil depths. One of the 3 pairs of cores was used to determine "time 0" enrichment and recovery of the $^{15}N$ label. The second and third pairs of cores from each of the plots were used to measure gross N mineralization and nitrification after a 24 and 72 h, respectively. Two incubation lengths were used to assess if incubation duration affects measurements of gross rates. Gross N transformations on the remaining 2 pairs of cores collected from each of the 7 uncut plots were measured after a 1-wk delay period to assess if rates measured within 4 to 5 d of collection were inflated due to collection disturbance compared to cores incubated undisturbed for an additional 7-d stabilization period.

Intact soil cores were collected by driving 10-cm long PVC cylinders (5.0 cm internal diameter) into the soil as described by Hart et al. (1994a). Barring interference from rocks and large tree roots, cores were collected as close together as possible from the centre of the study plots. The open ends of the cylinders were sealed with plastic caps, and the cores were placed in a cooler and transported to the laboratory within 72 h. In the laboratory, soil cores were incubated in the dark at 20°C and 99% relative humidity within the PVC tubes. Cores used to estimate gross N mineralization, the production of $NH_4^+$-N from organic N, were injected with 10 mL of 30 mg $(^{15}NH_4)_2SO_4$ $L^{-1}$, while cores for estimates of gross nitrification, the production of $NO_3^-$-N from $NH_4^+$-N or organic N, were injected with 10 mL of 30 mg $K^{15}NO_3$ $L^{-1}$. Both solutions were enriched with 98% $^{15}N$ (Aldrich Chemicals). The solutions were added to each core by making 10 evenly spaced injections with a spinal needle (Quiken tip, 18 gauge, 10-cm length, Fisher Instruments) attached to a 1-mL plastic syringe. The 10, 1-mL injections added either 67.11 µg $^{15}NH_4^+$-N or 44.10 µg $^{15}NO_3^-$-N to each core, and took approximately 15 minutes per core to complete.

Upon injecting the time 0, 24 and 72 h cores from a single plot and soil depth with either $^{15}NH_4^+$-N or $^{15}NO_3^-$-N, the time 0 core was extracted to determine initial $^{15}N$ label enrichment and recovery. For all individual cores, extracts of inorganic N were prepared by removing the soil from the PVC tubes, and hand-mixing in a polyethylene bag until visually homogenized. Homogenized soil was subsampled by placing 12 g of LFH material or 24 g of mineral soil into a preweighed Nalgene container with 120 mL of 2 M KCL. Soil-KCl mixtures were shaken for 1 h on a rotary shaker, and then filtered gravimetrically through Whatman No. 42 filters that were prewashed with deionized water. Extracts were immediately frozen for later analyses. Pools of $^{14-15}NH_4^+$-N and $^{14-15}NO_3^-$-N were analyzed with a Technicon AutoAnalyzer (Technicon 1973a, b). The nitrogen diffusion method of Brooks et al. (1989) was used to prepare the KCl extracts for $^{15}N$ analyses. For extracts where inorganic N was less than 60 µg of N in a 60 mL aliquot, a spike of $(NH_4)_2SO_4$ or $KNO_3$ "carrier" solution of 100 mg $L^{-1}$ was added to increase the N content of the aliquot to at least 60 µg $L^{-1}$. Background $^{15}N$ enrichment of the carrier solutions was measured to be 0.3652 for $NH_4^+$ and 0.3709 for $NO_3^-$. The glass fiber filter N traps were analyzed on a SIRA 10 isotope ratio mass spectrometer (V.G. Isogas, Middlewich, Cheshire, England) in the Department of Renewable Resources, University of Alberta.

Gross N mineralization, nitrification, $NH_4^+$-N consumption, $NO_3^-$-N consumption and $^{15}N$ recovery were calculated with the equations of Hart et al. (1994a). All rates are expressed on a dry soil weight basis. To calculate gross $NH_4^+$-N immobilization, gross nitrification is subtracted from gross $NH_4^+$-N consumption, while gross $NO_3^-$-N immobilization is equivalent to gross $NO_3^-$-N consumption (Hart et al. 1994b). Although the $^{15}N$ isotope dilution technique may overestimate gross immobilization rates because a process substrate is added in the measurement, similar effects should be observed in soils from uncut and cut plots, thus facilitating comparisons of gross immobilization rates. Mean residence times (MRTs) of extractable $NH_4^+$-N pools were calculated by dividing the concentration of extractable soil $NH_4^+$-N (µg $NH_4^+$-N $g^{-1}$) by the gross N mineralization rate (µg $NH_4^+$-N $g^{-1}$ $d^{-1}$). Mean residence times of extractable soil $NO_3^-$-N were calculated in the same way by substituting extractable soil $NO_3^-$-N concentrations and gross nitrification rates. Extractable soil $NH_4^+$-N and $NO_3^-$-N concentrations used in these calculations were obtained from initial (time 0) cores used in the laboratory incubations for measurements of net rates (see below).

Gravimetric soil water content was determined for every core by drying a subsample of hand-mixed soil at 105°C for at least 24 h, and is reported on a wet soil weight basis (wwt). A glass electrode was used to measure pH for the LFH and mineral soil in 10:1 and 2:1 water-soil mixtures, respectively (Carter 1993). Bulk density for the study areas was determined for cores obtained for an earlier 1997 study measuring net rates at the same location. Total carbon and TN were determined on C/N analyzer (Carlo-Erba Strumentazione, Italy) coupled to an isotope ratio mass spectrometer (V.G. Isogas, Middlewich, Cheshire, England) in the Department of Renewable Resources at the University of Alberta.

### 3.1.3 Laboratory and *In Situ* Net N Mineralization and Nitrification Measurements

The polyethylene bag method of Eno (1960) was used to estimate net N mineralization and nitrification in laboratory incubations of soil cores collected between May 8-10, 1998 from each of the 7 uncut and 7 cut study plots. Four intact LFH and mineral soil cores were collected from each of the uncut plots, and 2 intact LFH and mineral soil cores were collected from the cut plots with a 5.5-cm diameter stainless steal bulb corer. Soil cores were placed in a cooler with minimal disturbance and transported to the laboratory within 72 h. One LFH and one mineral soil core from each study plot was used to determine initial extractable pools of soil $NH_4^+$-N and $NO_3^-$-N for laboratory incubated cores. A second and third set of LFH and mineral soil cores from each of the 7 uncut plots were extracted after 1- and 2-wk incubations. The remaining set of cores from each of the 7 uncut and 7 cut plots were extracted after 4-wk incubation periods. Incubations of 1-, 2- and 4-wk durations in the uncut plots were used to assess the effects of incubation length on measurements of net rates. Cores were incubated in the dark at 20°C and 99% relative humidity within the polyethylene bags. After 48 h in the incubator, initial pools of $NH_4^+$-N and $NO_3^-$-N for laboratory measurements of net rates were measured by extracting 1 LFH and 1 mineral core from each of the 7 uncut and cut plots as described in the methods for gross rates measurements. Pools of $NH_4^+$-N and $NO_3^-$-N were analyzed with a Technicon AutoAnalyzer (Technicon 1973a, b). Net N mineralized during an incubation period was estimated from the average difference between the amounts of $NH_4^-$-N present in all available cores from a harvesting treatment at the beginning and end of each incubation period. Net nitrification was estimated by the average difference between initial and final $NO_3^-$-N content. All rates are expressed on a dry soil weight basis.

In addition, in each of the 7 uncut and 7 cut plots, the buried bag method was used to measure *in situ* net N mineralization and nitrification for 4 wk incubations begun on May 8, June 6 and July 22, 1998. In each study plot on each sampling date, 1 pair of intact LFH cores and 1 pair of mineral soil cores were collected. One core from each pair was used to determine initial soil pools of $NH_4^-$-N and $NO_3^-$-N, while the other was replaced into the hole it was obtained from and incubated *in situ* for approximately 28 d. Extractions of inorganic N pools were commenced in the field as described in Chapter 2, and extracts were analyzed as described above.

### 3.1.4 Statistical Methods

Means comparisons of net and gross rates between uncut and cut treatments were done with *t*-tests. Differences among rates measured over various incubation periods within a harvesting treatment were assessed with a general linear model ANOVA. The Games-Howell *post-hoc* test was used to evaluate pairwise comparisons among measurements. Levene's test was used to evaluate homogeneity of variances. If variances among groups were heterogeneous, ANOVAs and *t*-tests were calculated for data with heterogeneous variances (Zar 1984). Differences in soil moisture between uncut and cut plots were assessed with descriptive statistics. All tests were performed with SPSS version 8.0. Statistical differences were at $P \leq 0.05$.

## 3.2 Results

### 3.2.1 Soil Temperature and Moisture

Small differences between uncut and cut treatments were observed for *in situ* soil temperature and moisture. Soil temperatures tended to be 1 to 2°C warmer in cut compared to uncut plots. Soil moisture in the former tended to be 26 to 50% higher than moisture in the latter (Fig. 3.1).

### 3.2.2 Nitrogen Mineralization

Gross N mineralization and $NH_4^+$-N immobilization were consistently higher in cut than uncut plots for cores incubated for 72 h (Table 3-2). For LFH and mineral soil cores incubated for 72 h, mean gross mineralization and $NH_4^+$-N immobilization rates in the cut plots were at least 37% and 43% higher, respectively, than in uncut plots. Higher rates in cut than uncut plots did not translate into differences in MRTs of extractable $NH_4^+$-N, nor were differences in MRTs of extractable $NH_4^+$-N pools detected for any other incubations (Table 3-3).

Net N mineralization rates and extractable soil $NH_4^+$-N pools rarely differed between uncut and cut plots (Table 3-2). The *in situ* incubation begun on June 6, 1998, where net N mineralization was higher in the uncut treatment ($t = -4.03$, $P = 0.002$), was the only case where a difference in net N mineralization between uncut and cut plots was detected. Differences in soil pools of extractable $NH_4^+$-N between uncut and cut plots were only detected early in May 1998. During this time pools in cut plots were higher than uncut plots for LFH cores incubated *in situ*, and for mineral soil cores incubated *in situ* and in the laboratory.

Comparisons of net N mineralization rates measured for the laboratory and the *in situ* incubations indicate that while these measurements differed from one another, no trends were observed with respect to where cores were incubated, or with soil temperature. Rates measured *in situ* between July and August, when soil temperatures were highest and closest to laboratory temperatures, did not reflect laboratory-measured net rates more closely than rates measured in earlier *in situ* incubations when soil temperatures were cooler. Also, among the *in situ* incubations, rates did not progressively increase with increasing soil temperatures during the growing season.

As a proportion of gross rates, net rates were consistently low for both uncut and cut areas. For the LFH soil cores, net N immobilization was observed in the laboratory incubations, while mean gross rates for these cores were comparatively high and positive. For the *in situ* incubated LFH cores where positive net N mineralization was measured, mean net rates represented less than 2% of gross N mineralization over 24 h. For the mineral soil cores, laboratory net N mineralization represented less than 3% of gross N mineralization for cores from the uncut plots, while in the cut plots, laboratory net rates were about 13% of gross rates. For *in situ* incubated mineral soil cores, mean net N mineralization represented at most 2.4% of gross N mineralization in soils from the uncut plots, while no cases of mean net N mineralization were measured in soils from cut plots.

Initial (time 0) recovery of injected $^{15}NH_4^+$-N was lower for soil cores from the uncut compared to cut plots for both the LFH and mineral soil layers (Table 3-3). While there was complete recovery of $^{15}NH_4^+$-N from LFH and mineral soil cores from the cut plots, recovery from the uncut plots was just under 40% for LFH horizon, and 50% for the mineral soil.

### 3.2.3 Nitrification

Mean gross nitrification, $NO_3^-$-N immobilization and net nitrification rates were very low or not detectable in the uncut and cut plots, and differences between the uncut and cut were rare (Table 3-4). Except for a single *in situ* incubation begun on May 3, 1998, where higher net nitrification was measured in cut than uncut plots, no differences in gross or net rates between uncut and cut plots were detected. However, net and gross $NO_3^-$-N transformations were more spatially variable in cut than uncut plots, and this was particularly true for gross rates which varied by one to two orders of magnitude in the cut compared to the uncut plots (Table 3-4). Gross nitrification for LFH soil cores measured over 24 h ranged from -1.5 to 1.0 μg $NO_3^-$-N $g^{-1}d^{-1}$ for the uncut plots, and from -74 to 113 μg $NO_3^-$-N $g^{-1}$ $d^{-1}$ for the cut plots. Similarly, gross $NO_3^-$-N immobilization ranged from 1.1 to 2.5 μg $NO_3^-$-N $g^{-1}$ $d^{-1}$ in the uncut plots, and from -78 to 51 μg $NO_3^-$-N $g^{-1}$ $d^{-1}$

in the cut plots. These trends were also observed in the mineral soil and for the 72-h incubations.

Extractable soil $NO_3^-$-N pools were also higher by two orders of magnitude in cut than uncut plots for May *in situ* and laboratory incubations of LFH and mineral soil cores (Table 3-3). However, by the beginning of June 1998, $NO_3^-$-N pools in the cut plots had declined by more than 50%, and differences between uncut and cut were no longer significant, but $NO_3^-$-N pools tended to remain higher in cut than uncut plots for the remainder of the study.

Too few estimates of MRT for $NO_3^-$-N existed from which to evaluate differences between uncut and cut plots (Table 3-3). Mean residence times for $NO_3^-$-N were not calculated for individual plots that had gross nitrification and/or extractable $NO_3^-$-N concentrations below detection. The number of plots with useable numbers was reduced to between 0 and 5. However, MRTs for plots for which $NO_3^-$-N turnover could be calculated indicate that turnover tends to be faster in uncut rather than cut plots.

Rapid immobilization of injected $^{15}NO_3^-$-N was observed in soil cores from uncut compared to those from cut plots, particularly for LFH cores (Table 3-3). Initial (time 0) recovery of $^{15}NO_3^-$-N from LFH cores from uncut plots was half that recovered from cores from cut plots. After 24 and 72 h, recovery in LFH cores from uncut plots was at least 60% lower than cores from cut plots. For mineral soil cores, initial $^{15}NO_3^-$-N recovery was actually higher in uncut than cut plots, however both types had relatively high recovery. After 24 h there was no recoverable $^{15}NO_3^-$-N in mineral soil cores from the uncut plots while recovery in cut plots was 51%. For cores incubated 72 h, recovery of $^{15}NO_3^-$-N was not different between uncut and cut plots.

### 3.2.4 Effects of Incubation Duration

Increasing the incubation period from 24 to 72 h decreased gross N mineralization rates in LFH cores from uncut ($t = 4.0$, $P = 0.003$) and cut plots ($t = 2.9$, $P = 0.03$). Goss $NH_4^+$-N immobilization in mineral soil cores from cut plots also decreased ($t = 2.7$, $P = 0.02$). Gross $NO_3^-$-N immobilization in LFH ($t = 4.8$, $P = 0.004$) and mineral soil cores ($t = 5.3$, $P = 0.003$) from uncut plots were also lower for the 72-h incubations. Lower gross rates measured over 72 h translated into higher MRTs for soil $NH_4^+$-N pools in the LFH cores in the cut ($t = -3.6$, $P = 0.01$) and uncut plots ($t = -3.0$, $P = 0.01$).

Whether the $^{15}N$ isotope-dilution technique was commenced within 4 to 5 d of collecting the soils or after a 1-wk delay resulted in no detectable differences in initial $^{15}NH_4^+$-N or $^{15}NO_3^-$-N recovery. However, average $^{15}NH_4^+$-N recoveries were 53 and 19% higher for LFH and mineral soil cores, respectively, that were incubated undisturbed for the additional 1 wk. Similarly, $^{15}NO_3^-$-N recovery tended to be 45 and 7% higher for LFH and mineral soil cores incubated undisturbed for 1 wk, respectively.

Except for one case, laboratory incubations measuring net N mineralization and nitrification over 1-, 2-, and 4-wk did not differ with varying incubation duration ($P > 0.8$). Net nitrification in LFH soil was the only case where statistically higher rates were measured over 2 compared to 4 wk, however, in both cases rates were less than 0.05 $\mu g\ NO_3^-\text{-N}\ g^{-1}\ d^{-1}$.

## 3.3 Discussion

### 3.3.1 Nitrogen Mineralization

As has been shown for temperate, tropical, and other boreal forests, net N mineralization rates in the aspen/conifer-mixed stand represented only a small percentage of the total amount of N cycled between the organic and inorganic fractions (Davidson et al. 1992; Neill et al. 1999; Stottlemyer and Toczydlowski 1999). Hence, net rates underestimated actual N mineralization activity in the Boreal Mixedwood. Gross N mineralization rates in the uncut aspen/conifer-mixed stand in this study (LFH: 68 to 81 $\mu g$ $NH_4^-$-N $g^{-1}$ $d^{-1}$) are among the highest reported in the literature. Rates similar to those measured in the uncut LFH horizon were reported for coniferous and deciduous stands in The Netherlands (22 to 79$\mu g$ $NH_4$-N $g^{-}d^{-1}$, Wessel and Tietema 1992; Tietema and Wessel 1992) as well as for an old-growth mixed conifer forest in the Sierra Foothills in California (26.67 to 36.53 $\mu g$ $NH_4^-$-N $g^{-1}$ $d^{-1}$, Davidson et al. 1991, 1992). Rates 66 to 97% lower than those from this study have been measured in undisturbed boreal birch, spruce and alder stands in Isle Royale, Michigan (Stottlemyer and Toczydlowski 1999), although soil cores in the Michigan study contained a small amount of mineral soil with the LFH material that may have reduced mean gross rates in the cores. Gross N mineralization in mineral soil of the aspen/conifer-mixed stand (0.66 to 1.67 $\mu g$ $NH_4^-$-N $g^{-1}$ $d^{-1}$) was similar to rates for a 10-yr old mixed conifer stand in the Sierra Nevada Mountains (1.65 $\mu g$ $NH_4^-$-N $g^{-1}$ $d^{-1}$), but slightly lower than gross mineralization in a >100-yr old mixed conifer stand (5.25 $\mu g$ $NH_4^-$-N $g^{-1}$ $d^{-1}$, Davidson et al. 1992). Mineral soil gross mineralization was about half that measured in the surface 5 cm of soil in a humid tropical forest in Rodonia, Brazil (3.70 $\mu g$ $NH_4^-$-N $g^{-1}$ $d^{-1}$, Neill et al. 1999). Although gross rates were relatively high in this study, mean residence times of $NH_4^-$-N pools were within the range for temperate and tropical forests with smaller extractable $NH_4^-$-N pools (Davidson et al. 1992; Hart et al. 1994b; Neill et al. 1999). Hence, these results differ from the long-held belief that boreal forests cycle N more slowly than temperate or tropical forests (Van Cleve and Alexander 1981).

It has also been suggested that gross N mineralization may be related to site fertility, and northern latitude boreal forests are considered to be relatively infertile (Van

Cleve and Alexander 1981; Nadelhoffer et al. 1985). However, although soil TN in this study indicates that these soils are relatively infertile (0.24 to 0.34 g TN $m^{-2}$), gross N mineralization rates were similar to rates in more fertile soils of young and old growth mixed-conifer forests in the Sierra Nevada Mountains (45 to 200 g TN $m^{-2}$, Davidson et al. 1991, 1992). Furthermore, TN in this study was also lower than that in boreal deciduous and conifer stands in Isle Royale, Michigan (55 g N $m^{-2}$) where gross N mineralization rates were much lower (Stottlemyer and Toczydlowski 1999). Therefore, our results indicate that TN is not a good predictor of how quickly a site can cycle N.

This study suggests that higher gross N mineralization and gross $NH_4^+$-N immobilization may occur in cut compared to uncut areas. The reasons for higher gross N mineralization and $NH_4^+$-N immobilization rates in the cut plots appear to be related to soil moisture. While laboratory incubations kept cores at a constant temperature, and C:N in the uncut and cut plots was similar, moisture in cores from cut plots tended to be about 20% higher than cores from uncut plots, which may have stimulated microbial N mineralization. Hence, increases in soil moisture, which can arise from timber-harvesting disturbance (Adams et al. 1991; Berden et al. 1995), may elevate gross N mineralization without increases in soil temperature or decreases in soil C:N. Although many studies have established soil temperature and C:N as regulating factors of microbial N mineralization activity, the relative influence of moisture, temperature and substrate lability can vary over time (Leiros et al. 1999). During the short 24- and 72-h incubations in this study, moisture appears to have been the factor promoting differences between the uncut and cut soil cores.

To extrapolate gross N mineralization rates measured in the laboratory to field conditions, it is necessary to consider that net N mineralization rates measured in the laboratory in early May 1998 did not differ from rates measured *in situ* between July 22 and August 15, 1998 when soil temperatures were the highest measured in this study, but still about 10°C cooler than lab conditions. Furthermore, soil moisture, which this study suggests may affect gross N mineralization, decreased very little between May and July (Fig. 3.1). Hence, it is possible that the gross N mineralization rates measured in the laboratory incubations in May are similar to gross rates occurring *in situ* between July and

August because net rates and soil moisture between these sets of cores are similar. To assess the moisture hypothesis, *in situ* gross rates should be measured over several incubations during a growing season.

Future research on gross N mineralization and immobilization rates in forest soils should also focus on understanding how substrate availability, soil temperature and moisture combine to control gross N transformations over time and space. In various studies, soil moisture, temperature and forest litter all affect gross N mineralization however, results have been conflicting and inconclusive (Tietema and Wessel 1992; Wessel and Tietema 1992; Neill et al. 1999; Stottlemyer and Toczydlowski 1999). Variation in gross N mineralization rates has also been related to soil microbial biomass N. Davidson et al. (1992) found strong positive correlation between microbial biomass N and gross mineralization in a 10-yr old mixed-conifer forest and a >100-yr old growth mixed-conifer forest in the Sierra Nevada Mountains. Contrary to our findings, they measured higher gross mineralization in the old than in the young forest, while net mineralization was higher in the young stand. Microbial biomass was not estimated in my study, however, future research in the Boreal Mixedwood should evaluate if larger populations of N-mineralizing microbes occur in cut areas which would explain higher gross N mineralization rates in this study's cut plots compared to the uncut plots.

### 3.3.2 Nitrification

Measurements of net and gross nitrification were very low or below detection in this study for both uncut and cut plots. For cores from the uncut plots, the disparity between net and gross rates observed for N mineralization was not observed for nitrification, as both net and gross rates were very low when detected (Table 3-4). For incubations of cores from cut plots where positive net and gross nitrification rates were measured, net rates were between 10 and 28% of gross rates, hence net estimates may underestimate actual nitrification activity in these soils.

The relatively low gross and net nitrification rates in the cut plots in this study differ from results in an earlier 1997 study at this location that measured high *in situ* net nitrification between July and August during the growing season following winter timber harvesting (Chapter 2). Contrary to the long-held belief that nitrification is insignificant in boreal forests, results from the earlier study suggest that gross nitrification in excess of $NO_3^-$-N immobilization can occur in these soils, and that the potential for $NO_3^-$-N loss by leaching may exist. Instead, in this study, low recovery of injected $^{15}NO_3^-$-N from cores from uncut plots, along with net $NO_3^-$-N immobilization observed in laboratory and *in situ* incubations, suggest that these soils have a high capacity for $NO_3^-$-N immobilization. This study, which was limited to one incubation period in the spring, may have failed to register gross nitrification activity if it occurs infrequently or in pulses. Hence, net and gross rates measured over several incubation periods during a growing season, combined with estimates of nitrifier biomass and assessments of the fate of injected $^{15}N$ label, may help assess the temporal and spatial factors that control nitrification and immobilization of $NO_3^-$-N in uncut and cut areas.

Low recovery of injected $^{15}NO_3^-$-N, combined with small and variable soil $NO_3^-$-N pools, resulted in theoretically undefined negative gross nitrification rates when the percent abundance of the $^{15}NO_3^-$-N pools did not decline with time during an incubation. Negative gross nitrification rates resulting from these problems have also been reported by Wessel and Tietema (1992), Tietema and Wessel (1992), and Neill et al. (1999). Davidson et al. (1992) have shown that the $^{15}N$ isotope dilution method is best applied to systems where the inorganic-N pool is relatively small but turns over daily. At the time this study was conducted, immobilization of a large fraction of injected $^{15}N$ label prevented reliable estimates of gross nitrification rates, indicating that at certain times of the growing season, the $^{15}N$ isotope dilution technique is not an effective method of measuring gross rates. However, because results from the earlier 1997 study at this location indicate that at other times these soils may have sufficiently high soil $NO_3^-$-N pools and gross rates to apply the $^{15}N$ isotope dilution technique, more research to assess annual and interannual temporal variability in nitrification activity is needed.

Gross nitrification rates in the uncut and cut plots in this study were very low compared to rates orders of magnitude higher that have been reported for a variety of temperate, tropical and boreal forests. In aspen and mixed conifer stands in New Mexico, Stark and Hart (1997) measured gross nitrification rates of 0.46 ± 0.04 and

$0.62 \pm 0.03$ $\mu$g $NO_3^-$-N $g^{-1}$ $d^{-1}$, respectively. In boreal birch, spruce and alder stands in Michigan, gross nitrification ranged from 0.8 to 3.2 $\mu$g $NO_3^-$-N $g^{-1}$ $d^{-1}$ (Stottlemyer and Toczydlowski 1999). In The Netherlands, Wessel and Tietema (1992) and Tietema and Wessel (1992) measured gross nitrification rates between 0.3 and 16.3 $\mu$g $NO_3^-$-N $g^{-1}$ $d^{-1}$. Measurements of gross nitrification in Boreal Mixedwood stands at various times during the growing season and over several years are needed to determine if gross rates in this forest stand are consistently lower than other forests.

Differences in gross nitrification rates between this study and other forests, and the apparent lack of differences in rates between this study's uncut and cut plots were not related to extractable soil $NH_4^+$-N. Extractable $NH_4^+$-N concentrations were higher in cut than uncut plots, and were similar to or greater than concentrations in aspen and spruce/fir stands in New Mexico (≈500 and 150 mg $NH_4^+$-N $m^{-2}$, Stark and Hart 1997), mixed-conifer stands in the Sierra Foothills (50 – 450 mg $NH_4^+$-N $m^{-2}$, estimated from figure, Davidson et al. 1992), boreal stands in northern Michigan (10 – 230 mg $NH_4^+$-N $m^{-2}$, estimated from figure, Stottlemyer and Toczydlowski 1999), and a tropical rainforest in Brazil (1224 mg $NH_4^+$-N $m^{-2}$, Neill et al. 1999). Hence, as has been shown in other forest ecosystems, availability of $NH_4^+$-N did not limit nitrification (Tietema and Wessel 1992; Pedersen et al. 1999). Future research on the factors that limit gross nitrification at various times during the growing season is warranted to assess time periods when changes in nitrification rates and soil $NO_3^-$-N pools may result in conditions favourable to $NO_3^-$-N leaching from the plant-rooting zone.

### 3.3.3 Effects of Incubation Duration

Increasing the length of the laboratory incubation period from 24 to 72 h resulted in decreased gross N mineralization and $NH_4^+$-N immobilization rates. Since commencing measurements of gross rates within 4 to 5 d after soil core collection or after an additional 1-wk delay period did not affect rates, these decreases in rates with increasing incubation time are related to the length of the incubation, and not to changes in the soil cores over time. In an experiment measuring gross N cycling over 1 and 3 d, Wessel and Tietema (1992) also found that gross mineralization decreased by 23% with increasing incubation duration. When incubations are too long, recycling of the added $^{15}N$ isotope back to the enriched pool can decrease estimates of gross rates because the recycled $^{15}N$ slows down the decrease of $^{15}N$ abundance in the enriched pool (Wessel and Tietema 1992). Therefore, laboratory $^{15}N$ isotope dilution experiments conducted at the environmental conditions used in this study should not exceed 1 d, however, the incubation duration should be optimized with preliminary experimentation for studies conducted at different environmental conditions or in the field.

Varying the length of the incubation period for laboratory net rate measurements attempted to address two concerns: 1) that physical disturbance of cores during the collection process may inflate mineralization and consumption estimates if the incubation period is too short (Lamontagne 1989), and 2) that excessively long incubation periods may exhaust the labile portion of the soil organic matter pools and, therefore, underestimate net rates (Binkley and Hart 1989). In both the LFH and mineral soils there was no indication that physical disturbance influenced net mineralization or nitrification because rates from the 1-wk incubations were not higher than the 2- or 4-wk incubations. The apparent lack of a collection disturbance effect was also supported by the fact that gross N mineralization, nitrification, and immobilization rates did not differ when measured within 4 to 5 d of soil collection or after an additional 1-wk delay period. Furthermore, except for net nitrification in undisturbed LFH soil, differences were not detected among the three incubation lengths, indicating that a 4-wk long incubation does not exhaust the labile N pool. This study concurs with findings by Adams et al. (1989) that show that a 4 wk is a useful incubation duration to allow comparison with the majority of studies in literature, and to permit study of forest sites in relatively remote locations that may be difficult to access.

### 3.4 Conclusions

Consistent with results from other forest ecosystems, this study shows that net measurements of gross N mineralization can underestimate actual cycling of N between organic N and inorganic fractions. Gross N mineralization rates were among the highest reported in the literature although soil TN concentrations were relatively low. During this short study period, cut plots tended to have higher gross N mineralization and $NH_4^+$-N immobilization rates than uncut plots, and gross $NH_4^+$-N immobilization tended to be higher than gross N mineralization.

Difficulties encountered in measuring gross $NO_3^-$-N transformations due to immobilization of the $^{15}N$ label suggest that these soils have a high capacity for $NO_3^-$-N immobilization. However, my 1997 study measured relatively high net nitrification in the cut area in this aspen/conifer-mixed stand, suggesting that gross nitrification in excess of $NO_3^-$-N immobilization can occur at certain times. Hence, future research on N transformations in the Boreal Mixedwood should include measurements of gross rates over several incubation periods, and preferably over several years to assess annual and interannual patterns. This research is warranted because changes to soil N mineralization and soil pools of $NH_4^+$-N may have implications to future forest productivity. Furthermore, changes to nitrification rates may result in conditions favourable to $NO_3^-$-N leaching which may subsequently affect soil acidity, translocation of ions, and the quality of nearby surface waters (Davidson et al. 1992). Research on gross N transformations in the Boreal Mixedwood should also be extended to forest stands with different species composition and disturbance regimes for a greater appreciation of the spatial variability within this ecosystem, and how this ecosystem differs from forests with different climates and physiographies. Studies should include estimates of populations of N-mineralizing bacteria, and tests to determine the relative influence of substrate lability, and soil temperature and moisture on net rates to determine what factors control N transformations in the Boreal Mixedwood forest.

## 3.5 Literature Cited

Adams, M.A., Polglase, P.J., Attiwill, P.M. and Weston, C.J. 1989. *In situ* studies of nitrogen mineralization and uptake in forest soils; some comments on methodology. Soil Biol Biochem 21: 423-429.

Adams, P.W., Flint, A.L., Fredriksen, R.L. 1991. Long-term patterns in soil moisture and revegetation after a clearcut of a Douglas-fir forest in Orgeon. For. Ecol. Manage. 41: 249-263.

Alberta Environmental Protection. 1996. The status of Alberta's timber supply. Alberta Govt. Publ. NO T/325, Edmonton, AB.

Berden, M., Nilsson, S.I., and Nyman, P. 1997. Ion leaching before and after clear-cutting in a Norway Spruce stand – Effects of long-term application of ammonium nitrate and superphosphate. Water Air Soil Poll. 93: 1-26.

Binkley, D., and Hart, S.C. 1989. The components of nitrogen availability assessments in forest soils. *In* Advances in Soil Science Volume 10. B.A. Stewart. Ed. Springer-Verlag, New York.

Brooks, P.D., Stark, J.M., McInteer, B.B., and Preston, T. 1989. Diffusion method to prepare soil extracts for automated nitrogen-15 analysis. Soil Sci Soc Am J. 53: 1707-1711.

Canada Soil Survey Committee. 1987. The Canadian system of soil classification 2nd ed. Agriculture Canada. Ottawa. ON Publ. 1646. 164pp.

Carter, M.R. 1993. Soil sampling and methods of analysis. Canadian Society of Soil Science. Lewis Publishers. Toronto, ON.

Davidson, E.A., Hart, S.C., Shanks, C.A., Firestone, M.K. 1991. Measuring gross nitrogen mineralization, immobilization, and nitrification by 15N isotopic pool dilution in intact soil cores. J Soil Science 42: 335-349.

Davidson, E.A., Hart, S.C., and Firestone, M.K. 1992. Internal cycling of nitrate in soils of a mature coniferous forest. Ecology 73: 1148-1156.

Eno, C.H. 1960. Nitrate production in the field by incubating the soil in polyethylene bags. Soil Sci. Soc. Am. Proc. 24: 277-279.

Hart, S.C., Stark, J.M., Davidson, E.A., and Firestone, M.K. 1994a. Nitrogen mineralization, immobilization, and nitrification. In Methods of soil analysis, part 2. Microbiological and biochemical properties. Soil Science Society of America. Madison, US.A. pp. 985-1018

Hart, S.C., Nason, G.E., Myrold, D.D., and Perry, D.A. 1994b. Dynamics of gross nitrogen transformations in an old-growth forest: the carbon connection. Ecology 75: 880-891.

Hendrickson, O.Q., Chatarpaul, L. and Robinson, J.B. 1985. Effects of two methods of timber harvesting on microbial processes in forest soil. Soil Sci. Soc. Am. J. 49: 739-746.

Lamontagne, S. 1998. Nitrogen mineralization in upland Precambrian Shield catchments: contrasting the role of lichen-covered bedrock and forested areas. Biogeochemistry 41: 53-69

Leiros, M.C., Trasar-Cepeda, C., Seoane, S., and Gil-Sotres, F. 1999. Dependence of mineralization of soil organic matter on temperature and moisture. Soil Biol Biochem. 31: 327-335.

Nadelhoffer, K.J., Aber, J.D., and Melillo, J.M. 1985. Fine roots, net primary production, and soil nitrogen availability: a new hypothesis. Ecology 66: 1377-1390.

Neill, C., Piccolo, M.C., Melillo, J.M., Steudler, P.A., and Cerri, C.C. 1992. Nitrogen dynamics in Amazon forest and pasture soils measured by 15N pool dilution. Soil Biol Biochem 31: 567-572.

Pedersen, H., Dunkin, K.A., Firestone, M.K. 1999. The relative importance of autotrophic and heterotrophic nitrification in a conifer forest soil as measured by $^{15}$N tracer and pool dilution techniques. Biogeochem. 44: 135-150.

Rowe, J.S. 1972. Forest regions of Canada. Publication Number 1300, Department of the Environment, Canadian Forestry Service, Ottawa, Ontario, Canada.

Shaw, R.D., Trimbee, A.M., Minty, A., Fricker, H., and Prepas, E.E. 1989. Atmospheric deposition of phosphorus and nitrogen in central Alberta with emphasis on Narrow Lake. Water, Air and Soil Pollution. 43: 119-134.

Stark, J.M. and Hart, S.C. 1997. High rates of nitrification and nitrate turnover in undisturbed coniferous forests. Nature 385: 61-64

Stottlemyer, R. and Toczydlowski, D. 1999. Nitrogen mineralization in a mature boreal forest, Isle Royale, Michigan. J. Environ. Qual. 28: 709-720.

Technicon. 1973a. Ammonia in water and wastewater. Industrial method 696-82W. Technicon Industrial Systems, Tarrytown, NY.

Technicon. 1973b. Nitrate and nitrite in water and seawater. Industrial method 100-70W. Technicon Industrial Systems, Tarrytown, NY.

Tietema, A. and Wessel, W.W. 1992. Gross nitrogen transformations in the organic layer of acid forest ecosystems subjected to increased atmospheric nitrogen input. Soil Biol Biochem. 24: 943-950.

Van Cleve, K. and Alexander, V. 1981. Nitrogen cycling in tundra and boreal ecosystems. In Terrestrial nitrogen cycles. Ecol. Bull. Stockholm. 33:375-404.

Vitousek, P.M., Gosz, J.R. Grier, C.C., Melillo, J.M. and Reiners, W.A. 1982. A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems. Ecol. Mono. 52: 155-177.

Wessel W.W. and Tietema, A. 1992. Calculating gross N transformation rates of 15N pool dilution experiments with acid forest litter: analytical and numerical approaches. Soil Biol Biochem. 24: 931-942.

Zar, 1984. Biostatistical analysis 2nd Ed. Prentice Hall. Englewood Cliffs, New Jersey, USA.

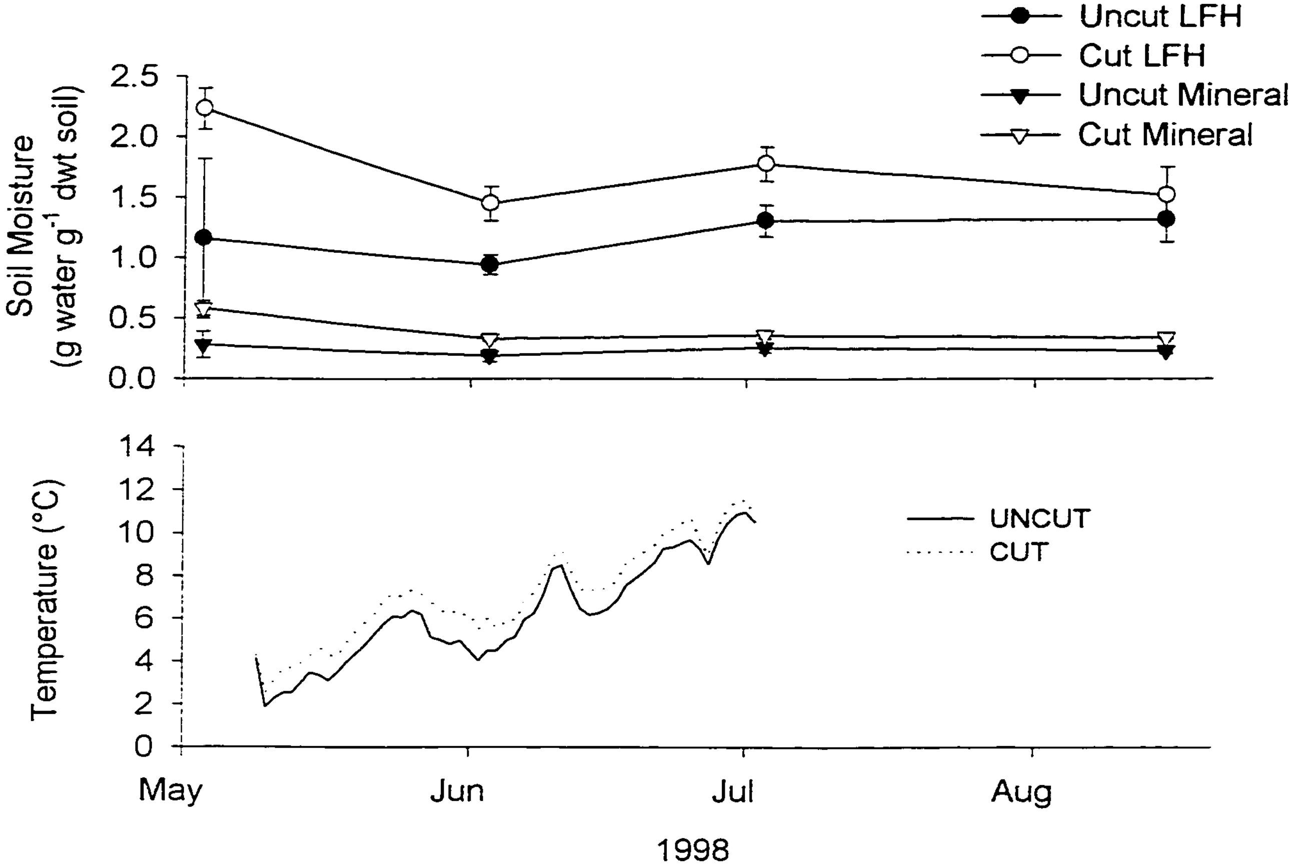

Fig. 3.1 Soil moisture and mean daily temperature in uncut and cut plots. Symbols for soil moisture represent means (± 1 *SE*, n = 7) for LFH horizon or 0 to 10 cm mineral soil cores. When not shown, error bars for soil moisture are smaller than the symbol. Temperature was measured at the LFH/mineral soil interface with dataloggers.

Table 3-1. Soil properties in uncut and cut plots of an aspen/conifer-mixed stand. Data are averages (± 1 *SE*) for cores from seven uncut and seven cut plots. Bulk density was determined for cores collected in a 1997 study at this location.

| Soil Property | Depth | Uncut | Cut |
|---|---|---|---|
| Soil Great Group | | Gray Luvisol | Gleyed Gray Luvisol |
| LFH Thickness | | 6.0 (0.3) | 8.7 (0.4) |
| Ae Thickness | | 0-7 | 0-3 |
| Total N (μg $g^{-1}$ dwt) | LFH | 16.0 (1.4) | 16.4 (1.4) |
| (n=7) | Mineral | 2.3 (0.2) | 2.9 (0.4) |
| C/N | LFH | 28.9 (2.0) | 28.4 (0.7) |
| (n=7) | Mineral | 17.3 (0.7) | 17.3 (0.2) |
| Bulk Density | LFH | 0.15 (<0.00) | 0.19 (0.01) |
| (g $cm^{-3}$) | Mineral | 1.19 (0.03) | 1.18 (0.03) |
| Initial moisture | LFH | 0.46 (0.03) | 0.67 (0.02) |
| (g water $g^{-1}$ wwt) | Mineral | 0.17 (0.01) | 0.32 (0.02) |
| Moisture after $^{15}N$ | LFH | 0.58 (0.05) | 0.65 (0.07) |
| solution injection | Mineral | 0.23 (0.02) | 0.39 (0.03) |

Table 3-2. Gross and net rates of $NH_4^+$-N production, gross $NH_4^+$-N immobilization, and extractable soil $NH_4^+$-N. Values are means (*SE*). For gross rate measurements in the uncut plots, 1-wk delay indicates cores that were incubated undisturbed for 1 wk prior to commencing the $^{15}N$ isotope dilution technique. Differences between uncut and cut plots were assessed with a *t*-test at a significance level of $P < 0.05$. Similar letters within a row indicate that mean values are not significantly different.

| | | Gross $NH_4^+$-N Production ($\mu g\ NH_4^+\text{-N}\ g^{-1}\ dwt\ d^{-1}$) | | | | Gross $NH_4^+$-N Immobilization ($\mu g\ NH_4^+\text{-N}\ g^{-1}\ dwt\ d^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Soil | Incubation Period | Uncut | n | Cut | n | Uncut | n | Cut | n |
| LFH | 24 h | 80.8 (10.3)$^a$ | 6 | 164.5 (33.6)$^a$ | 7 | 85.8 (21.0)$^a$ | 6 | 155.0 (46.7)$^a$ | 7 |
| | 72 h | 24.8 (9.4)$^a$ | 5 | 66.9 (5.6)$^b$ | 7 | 31.5 (9.0)$^a$ | 5 | 72.6 (9.3)$^b$ | 7 |
| | 24 h (1-wk delay) | 68.2 (38.4) | 4 | - | | 120.7 (44.4) | 4 | - | |
| Mineral | 24 h | 1.67 (0.39)$^a$ | 7 | 3.60 (1.10)$^a$ | 7 | 1.45 (0.63)$^a$ | 7 | 4.82 (1.04)$^b$ | 7 |
| | 72 h | 0.66 (0.24)$^a$ | 5 | 1.70 (0.52)$^a$ | 6 | 0.85 (0.42)$^a$ | 5 | 1.67 (0.37)$^a$ | 6 |
| | 24 h (1-wk delay) | 0.94 (1.14) | 4 | - | | 1.85 (0.90) | 4 | - | |

| | | | Net $NH_4^+$-N Production ($\mu g\ NH_4^+\text{-N}\ g^{-1}\ dwt\ d^{-1}$) | | | | Extractable Soil $NH_4^+$-N ($\mu g\ NH_4^+\text{-N}\ g^{-1}\ dwt$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil | Incubation Period | | Uncut | n | Cut | n | Uncut | n | Cut | n |
| LFH | Laboratory Bag Incubation | 1 wk | -6.27 (3.33) | 7 | - | | 100.9 (17.2)$^a$ | 7 | 118.0 (13.4)$^a$ | 7 |
| | | 2 wk | -0.48 (1.58) | 7 | - | | - | | - | |
| | | 4 wk | -2.98 (0.72)$^a$ | 6 | -3.72 (0.47)$^a$ | 7 | - | | - | |
| | *In situ* Bag Incubation | May 3 – June 3 | 0.17 (0.50)$^a$ | 7 | -1.32 (0.48)$^a$ | 7 | 55.41 (8.05)$^a$ | 7 | 87.98 (9.84)$^b$ | 7 |
| | | June 6 – July 3 | -0.08 (0.36)$^a$ | 7 | -0.92 (0.16)$^a$ | 7 | 42.44 (8.00)$^a$ | 7 | 32.37 (3.27)$^a$ | 7 |
| | | July 22 – Aug 15 | 1.53 (0.56)$^a$ | 7 | 1.20 (0.46)$^a$ | 7 | 36.90 (9.24)$^a$ | 7 | 25.09 (3.56)$^a$ | 7 |
| Mineral | Laboratory Bag Incubation | 1 wk | 0.02 (0.09)$^a$ | 7 | - | | 1.97 (0.49)$^a$ | 7 | 6.97 (1.50)$^b$ | 7 |
| | | 2 wk | 0.05 (0.04)$^a$ | 7 | - | | - | | - | |
| | | 4 wk | -0.02 (0.01)$^a$ | 6 | 0.45 (0.45)$^a$ | 7 | - | | - | |
| | *In situ* Bag Incubation | May 3 – June 3 | 0.00 (0.01)$^a$ | 7 | -0.09 (0.09)$^a$ | 7 | 1.89 (0.32)$^a$ | 7 | 14.16 (2.15)$^b$ | 7 |
| | | June 6 – July 3 | 0.04 (0.02)$^a$ | 7 | -0.07 (0.02)$^b$ | 7 | 1.32 (0.24)$^a$ | 7 | 2.46 (0.46)$^a$ | 7 |
| | | July 22 – Aug 15 | -0.04 (0.04)$^a$ | 7 | -0.06 (0.02)$^a$ | 7 | 2.02 (0.27)$^a$ | 7 | 2.98 (0.56)$^a$ | 7 |

Table 3-3. Extractable soil N, mean residence times, and $^{15}N$ isotope recovery for uncut and cut treatments. Time 0 cores were extracted approximately 15 min after injection. In the uncut treatment, 1-wk delay indicates cores that were incubated undisturbed for 1 wk prior to commencing the $^{15}N$ isotope dilution technique. Similar letters within a row indicate that mean values do not differ between uncut and cut treatments (*t*-test, $P > 0.05$). Differences in $NO_3^-$-N mean residence times between uncut and cut treatments were not tested due to small sample sizes.

| | | Extractable $NH_4^+$-N ($\mu g$ $NH_4^+$-N $g^{-1}$ dwt) | | | | $NH_4^+$-N Mean Residence Time (d) | | | | $^{15}NH_4^+$-N Recovery (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Uncut | | Cut | | Uncut | | Cut | | Uncut | | Cut | |
| Soil | Incubation Period | Mean (SE) | n | Mean (*SE*) | n | Mean (SE) | n | Mean (*SE*) | n | Mean (*SE*) | n | Mean (*SE*) | n |
| LFH | 0 | 100.9 (17.2)$^a$ | 7 | 118.0 (13.4)$^a$ | 7 | - | | - | | 38.1 (1.5)$^a$ | 7 | 120 (10.8)$^b$ | 7 |
| | 24 h | - | | - | | 1.30 (0.22)$^a$ | 6 | 0.82 (0.13)$^a$ | 7 | 15.8 (1.5)$^a$ | 6 | 14.7 (2.9)$^a$ | 7 |
| | 72 h | - | | | | 3.77 (0.92)$^a$ | 4 | 1.69 (0.18)$^a$ | 7 | 16.0 (6.1)$^a$ | 5 | 8.1 (2.6)$^a$ | 7 |
| | 0 (1-wk delay) | 57.0 (11.3) | 7 | - | | - | | - | | 80.3 (37.3) | 4 | - | |
| | 24 h (1-wk delay) | - | | - | | 1.70 (0.93) | 3 | - | | 10.8 (1.5) | 4 | - | |
| Mineral | 0 | 1.97 (0.49)$^a$ | 7 | 6.97 (1.5)$^b$ | 7 | - | | - | | 50.1 (3.7)$^a$ | 7 | 116 (14.0)$^b$ | 7 |
| | 24 h | - | | - | | 1.60 (0.49)$^a$ | 7 | 2.02 (0.60)$^a$ | 6 | 16.3 (3.1)$^a$ | 7 | 23.0 (6.8)$^a$ | 7 |
| | 72 h | - | | - | | 3.49 (2.23)$^a$ | 3 | 2.83 (0.56)$^a$ | 5 | 82.5 (22.0)$^a$ | 4 | 26.5 (7.4)$^a$ | 6 |
| | 0 (1-wk delay) | 2.09 (0.69) | 7 | - | | - | | - | | 62.0 (7.0) | 4 | | |
| | 24 h (1-wk delay) | - | | - | | 8.15 (5.11) | 2 | - | | 25.0 (6.2) | 4 | | |

| | | Extractable $NO_3^-$-N ($\mu g$ $NO_3^-$-N $g^{-1}$ dwt) | | | | $NO_3^-$-N Mean Residence Time (d) | | | | $^{15}NO_3^-$-N Recovery (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Uncut | | Cut | | Uncut | | Cut | | Uncut | | Cut | |
| | Incubation Period | Mean (SE) | n | Mean (*SE*) | n | Mean (SE) | n | Mean (*SE*) | n | Mean (*SE*) | n | Mean (*SE*) | n |
| LFH | 0 | 0.21 (0.19)$^a$ | 7 | 42.14 (13.2)$^b$ | 7 | - | | - | | 34.5 (10.9)$^a$ | 6 | 67.9 (7.5)$^b$ | 7 |
| | 24 h | - | | - | | 1.43 | 1 | 1.76 (0.56) | 5 | 7.0 (2.3)$^a$ | 6 | 67.4 (2.8)$^b$ | 7 |
| | 72 h | - | | - | | 45.14 (45.14) | 2 | 30.42 (28.41) | 2 | 5.0 (2.0)$^a$ | 7 | 66.2 (9.5)$^b$ | 6 |
| | 0 (1-wk delay) | 0.24 (0.05) | 7 | - | | - | | - | | 63.0 (8.5) | 5 | - | |
| | 24 h (1-wk delay) | - | | - | | 1.16 (1.16) | 2 | - | | 21.0 (5.1) | 5 | - | |
| Mineral | 0 | 0.02 (0.01)$^a$ | 7 | 3.44 (2.72)$^b$ | 7 | - | | - | | 93.0 (6.4)$^a$ | 5 | 78.0 (9.0)$^a$ | 7 |
| | 24 h | - | | - | | nd | 0 | 0.13 (0.08) | 5 | 0 (0)$^a$ | 6 | 50.9 (6.8)$^b$ | 7 |
| | 72 h | - | | - | | 2.64 | 1 | 0.18 (0.18) | 2 | 1.7 (1.7) | 7 | 13.2 (6.6)$^b$ | 6 |
| | 0 (1-wk delay) | 0.05 (0.04) | 7 | - | | - | | - | | 113 (10.4) | 5 | | |
| | 24 h (1-wk delay) | - | | - | | 0.53 (0.20) | 2 | - | | 42.0 (14.2) | 5 | | |

Table 3-4. Gross and net rates of $NO_3^-$-N production, gross $NO_3^-$-N immobilization, and extractable soil $NO_3^-$-N. Values are means (*SE*). For gross rate measurements in the uncut plots, 1-wk delay indicates cores that were incubated undisturbed for 1 wk prior to commencing the $^{15}N$ isotope dilution technique. Differences between uncut and cut plots were assessed with a *t*-test at a significance level of $P < 0.05$. Similar letters within a row indicate that mean values are not significantly different

| | | Gross $NO_3^-$-N Production ($\mu g$ $NO_3^-$-N $g^{-1}$ dwt $d^{-1}$) | | | | Gross $NO_3^-$-N Immobilization ($\mu g$ $NO_3^-$-N $g^{-1}$ dwt $d^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| Soil | Incubation Period | Uncut | n | Cut | n | Uncut | n | Cut | n |
| LFH | 24 h | -0.26 (0.35)$^a$ | 6 | 11.7 (22.5)$^a$ | 7 | 1.74 (0.25)$^a$ | 6 | -0.87 (16.1)$^a$ | 7 |
| | 72 h | <0.00 (0.03)$^a$ | 7 | -6.07 (5.00)$^a$ | 6 | 0.53 (0.05)$^b$ | 7 | 7.18 (4.80)$^a$ | 6 |
| | 24 h (1-wk delay) | -0.25 (0.29)$^a$ | 5 | - | | 1.85 (0.38)$^a$ | 5 | - | |
| Mineral | 24 h | <0.00 (<0.00)$^a$ | 6 | -1.46 (2.76)$^a$ | 7 | 0.32 (0.05)$^a$ | 6 | 7.58 (4.73)$^a$ | 7 |
| | 72 h | <0.00 (<0.00)$^a$ | 7 | 0.13 (0.11)$^a$ | 6 | 0.08 (0.01)$^b$ | 7 | 0.34 (0.12)$^a$ | 6 |
| | 24 h (1-wk delay) | -0.06 (0.12)$^a$ | 5 | - | | 0.34 (0.13)$^a$ | 5 | - | |

| | | | Net $NO_3^-$-N Production ($\mu g$ $NO_3^-$-N $g^{-1}$ dwt $d^{-1}$) | | | | Extractable Soil $NO_3^-$-N ($\mu g$ $NO_3^-$-N $g^{-1}$ dwt) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Soil | Incubation Period | | Uncut | n | Cut | n | Uncut | n | Cut | n |
| LFH | Laboratory Bag | 1 wk | <0.00 (0.03) | 7 | - | | 0.21 (0.19)$^a$ | 7 | 42.14 (13.2)$^b$ | 7 |
| | Incubation | 2 wk | 0.05 (0.01) | 7 | - | | - | | - | |
| | | 4 wk | -0.03 (0.01)$^a$ | 6 | 3.05 (1.34)$^a$ | 7 | - | | - | |
| | *In situ* Bag | May 3 – June 3 | -0.01 (<0.00)$^a$ | 7 | 1.12 (0.44)$^b$ | 7 | 0.25 (0.06)$^a$ | 7 | 33.15 (9.63)$^b$ | 7 |
| | Incubation | June 6 – July 3 | <0.00 (<0.00)$^a$ | 7 | 0.02 (0.14)$^a$ | 7 | 0.22 (0.08)$^a$ | 7 | 12.50 (5.59)$^a$ | 7 |
| | | July 22 – Aug 15 | <0.00 (<0.00)$^a$ | 7 | 0.47 (0.21)$^a$ | 7 | 0.57 (0.29)$^a$ | 7 | 9.07 (8.67)$^a$ | 7 |
| Mineral | Laboratory Bag | 1 wk | 0.01 (0.01) | 7 | - | | 0.02 (0.01)$^a$ | 7 | 3.44 (2.72)$^b$ | 7 |
| | Incubation | 2 wk | 0.75 (0.49) | 7 | - | | | | | |
| | | 4 wk | <0.00 (<0.00)$^a$ | 6 | -0.02 (0.04)$^a$ | 7 | | | | |
| | *In situ* Bag | May 3 – June 3 | <0.00 (<0.00)$^a$ | 7 | -0.03 (0.09)$^a$ | 7 | 0.01 (0.01)$^a$ | 7 | 5.91 (1.91)$^b$ | 7 |
| | Incubation | June 6 – July 3 | 0.02 (0.01)$^a$ | 7 | 0.03 (0.02)$^a$ | 7 | <0.00 (<0.00)$^a$ | 7 | 1.05 (0.56)$^a$ | 7 |
| | | July 22 – Aug 15 | <0.00 (<0.00)$^a$ | 7 | 0.01 (0.01)$^a$ | 7 | 0.04 (0.02)$^a$ | 7 | 0.77 (0.71)$^a$ | 7 |

# Chapter 4.0 General Discussion

This study provides the first estimates of *in situ* net and potential gross N mineralization and nitrification rates for the Boreal Mixedwood, an extensive forest ecozone in Alberta experiencing harvesting disturbance. It was hypothesized that net rates in either undisturbed or disturbed stands in the Boreal Mixedwood would be relatively low due to low soil total N and cool temperatures. Instead, results from this study suggest that soil microbial N transformations in certain cut stands in the Boreal Mixedwood may be relatively high.

*In situ* growing season net N mineralization rates in the uncut plots of the three Boreal Mixedwood stands in this study were similar to rates reported for forests with similar vegetation composition (Stump and Binkley 1993; Stottlemyer et al. 1995) and to conifer-dominated stands at similar latitudes in Europe (Persson and Wiren 1995). Net N mineralization was 5 times higher than rates measured in Boreal Shield stands in central Ontario (Lamontagne 1998; Westbrook 2000). In contrast, *in situ* net nitrification was barely detectable in the uncut plots, and rates were similar to those measured in Boreal Shield stands by Stottlemyer et al. (1995), Lamontagne (1998), and Westbrook (2000).

Comparisons among the uncut plots within this study showed that growing season net N mineralization did not differ with forest stand composition or soil texture. It was hypothesized that the aspen/conifer-mixed stand would have lower litter quality compared to the aspen-dominated stands due to the presence of recalcitrant coniferous litter. Instead, soil TN and C:N between the two vegetation groups did not differ and there were no detectable differences in net N transformations among the stands. It was also hypothesized that comparisons between the sandy and clay-loam soil aspen-dominated stands would show that net rates are higher in the latter because of more favorable moisture conditions for soil microbes. Instead, above average precipitation between 1995 and 1997 resulted in soil moisture differences of 10 to 20% between the soil types, which were apparently insufficient to effect differences in net N transformations between the stands. However, below average precipitation in 1998 reduced soil moisture by 20 to 47% in the aspen/conifer-mixed stand and this had an apparent effect on net rates. In 1998, net N mineralization was approximately 12% lower while net nitrification was 34% higher. Lower soil moisture in 1998 appears to have limited microbial decomposition while greater aeration increased dissolved oxygen availability and subsequent net nitrification.

Differences in net N mineralization and nitrification rates between uncut and cut plots were detected, although soil moisture and temperature were only slightly higher in cut than uncut plots. Cut plots of the aspen/conifer-mixed stand had higher growing season net N immobilization and net nitrification than uncut plots, while the aspen-dominated stands registered higher net N mineralization in cut than uncut plots during mid-summer incubation periods. In the aspen/conifer-mixed stand, growing season total net N immobilization driven by high N immobilization in spring that may have resulted from microbial decomposition of slash material. High net nitrification in cut plots of the aspen/conifer-mixed stand sustained throughout the growing season suggests that nitrifier populations grew and/or became more active while vegetation demands for $NH_4^+$-N were low because of tree removal. The absence of high spring net N immobilization in the aspen-dominated stands may be attributed by the slightly lower soil C:N in these stands compared to the aspen/conifer-mixed stand. The higher mid-summer net N mineralization rates observed in the cut aspen-dominated plots compared to the uncut plots are more difficult to explain because there were no clear trends with moisture, and soil temperatures were only 1 to 2°C warmer in the cut plots. However, the reciprocal buried bag experiment suggests that temperature differences as small as a few degrees could result in the observed differences in net rates.

Results from this study support growing evidence in the literature indicating that measurable net N mineralization and nitrification can occur during winter, and that the duration of over-winter incubations affect rate measurements. Maximum winter net N mineralization activity as a percentage of annual net N mineralization ranged between 0 and 10% in the uncut plots of the three stands, and between 18 and >100% for the cut plots. The same trends were observed for net nitrification. As was observed in the summer months, differences in soil temperature did not account for differences in rates. It is possible that higher rates in cut plots reflect decomposition of slash material by soil microorganisms (Bird et al. 1987).

The aspen/conifer-mixed stand was selected for further research on gross N transformations in the Boreal Mixedwood. As has been shown for temperate, tropical and other boreal forests, net N mineralization rates in the aspen/conifer-mixed stand represented only a fraction of the total amount of N cycled between the organic and inorganic fractions of soil N (Davidson et al. 1992; Neill et al. 1999; Stottlemyer and Toczydlowski 1999). Furthermore, although studies on gross rates in forest soils are relatively few, gross N mineralization in the Boreal Mixedwood was among the highest reported in the literature even though soil TN was relatively low (Davidson et al. 1991, 1992; Stottlemyer and Toczydlowski 1999). Hence, these results suggest that a site's fertility (TN) may not be a good predictor of how quickly it cycles N as previously thought.

Comparisons of gross N mineralization and $NH_4^+$-N immobilization between soils in cut and uncut plots show that rates in the former tended to higher. Mean gross N mineralization was 46% higher in cut plots, while mean $NH_4^+$-N immobilization was 52% higher. Since laboratory incubations maintained constant temperature and soil C:N was similar between cores from uncut and cut plots, higher soil moisture in cut than in uncut plots appears to account for the higher gross N mineralization and $NH_4^+$-N immobilization rates in the cut plots.

In contrast to gross N mineralization, potential gross nitrification rates in both uncut and cut study plots were among the lowest reported in the literature (Stark and Hart 1997; Stottlemyer and Toczydlowski 1999; Wessel and Tietema 1992; Tietema and Wessel 1992). These results differ from the high *in situ* net nitrification rates measured at the same location in 1997. Extractable soil $NH_4^+$-N cannot account for the low gross nitrification rates because extractable soil $NH_4^+$-N remained relatively constant between 1997 and 1998, and these pools were similar to or greater than pools in other forests ecosystems. Future research on net and gross rates over several incubation periods during a growing season, combined with estimates of microbial biomass, may help assess the temporal and spatial factors controlling nitrification activity in the Boreal Mixedwood.

The Boreal Mixedwood is an extensive ecozone comprised of a variety of physiographic components. This study, concentrated in upland forest stands, investigated soil N transformations during one wet and one dry growing season. To further the information gathered in this project, future research should be directed towards assessing:

(1) the relative importance of moisture, temperature, and substrate C:N over time and space in both undisturbed and disturbed watersheds; (2) the extent of over-winter microbial activity and the factors that regulate winter activity; (3) soil pore water N concentrations in stands with poor regeneration and areas where herbicides are used to determine the potential for N movement from terrestrial to aquatic ecosystems during spring snowmelt and summer storms.

### 4.1. Literature Cited

Bird, G.A., Rachar, D.B., Chatarpaul, L. 1987. Increased skeletonization of leaf litter under snow following timber harvest. Ecology 68: 221-223.

Davidson, E.A., Hart, S.C., Shanks, C.A., Firestone, M.K. 1991. Measuring gross nitrogen mineralization, immobilization, and nitrification by 15N isotopic pool dilution in intact soil cores. J Soil Science 42: 335-349.

Davidson, E.A., Hart, S.C., and Firestone, M.K. 1992. Internal cycling of nitrate in soils of a mature coniferous forest. Ecology 73: 1148-1156.

Lamontagne, S. 1998. Nitrogen mineralization in upland Precambrian Shield catchments: contrasting the role of lichen-covered bedrock and forested areas. Biogeochemistry 41: 53-69.

Neill, C., Piccolo, M.C., Melillo, J.M., Steudler, P.A., and Cerri, C.C. 1992. Nitrogen dynamics in Amazon forest and pasture soils measured by 15N pool dilution. Soil Biol Biochem 31: 567-572.

Persson, T. and Wiren, A. 1995. Nitrogen mineralization and potential nitrification at different depths in acid forest soils. Plant and Soil 168-169: 55-65.

Stark, J.M. and Hart, S.C. 1997. High rates of nitrification and nitrate turnover in undisturbed coniferous forests. Nature 385: 61-64

Stottlemyer, R., Travis, B. and Toczydlowski, D. 1995. Nitrogen mineralization in boreal forest stands of Isle Royale, northern Michigan. Water Soil Air Poll. 82: 191-202.

Stottlemyer, R. and Toczydlowski, D. 1999. Nitrogen mineralization in a mature boreal forest, Isle Royale, Michigan. J. Environ. Qual. 28: 709-720.

Stump, L.M. and Binkley, D. 1993. Relationships between litter quality and nitrogen availability in Rocky Mountain forests. Can. J. For. Res. 23: 492-502.

Tietema, A. and Wessel, W.W. 1992. Gross nitrogen transformations in the organic layer of acid forest ecosystems subjected to increased atmospheric nitrogen input. Soil Biol Biochem. 24: 943-950.

Wessel W.W. and Tietema, A. 1992. Calculating gross N transformation rates of 15N pool dilution experiments with acid forest litter: analytical and numerical approaches. Soil Biol Biochem. 24: 931-942.

Westbrook, C. 2000. Nitrogen dynamics in upland and peatland Boreal Shield soils. Department of Biological Sciences. University of Alberta. M.Sc. Thesis

**Table A1.** ASP-SD soil profile and related properties.

**Uncut 1: Orthic Gray Luvisol on glacial fluvial parent material**

| Profile | LFH | Ae | Bt | BC |
|---|---|---|---|---|
| Depth (cm) | 5 | 0-10 | 10-30 | 30-100+ |
| Colour | | 10YR4/2 moist crushed | 10YR4.5/3 moist exped | 10YR5/5 moist crushed |
| Texture | | loamy sand | sandy loam | loamy sand to sandy loam, clay lenses |
| Structure | | structureless | subangular blocky | structureless |
| Slope 25% | | | | |

| Profile | LFH | Ae | Bt | BC |
|---|---|---|---|---|
| Depth (cm) | 9 | 0-35 | 35-70 | 70-100+ |
| Colour | | 10YR5/3 moist crushed | 10YR4/2 moist exped | 10YR6/4 moist crushed |
| Texture | | loamy sand | loamy sand with clay loam lenses | loamy sand, occasional clay lenses |
| Structure | | platy | subangular blocky | structureless |
| Slope 21% | | | | |

**Cut 1: Orthic Eutric Brunisol on glacial fluvial parent material**

| Profile | LFH | Ae | Bm | BC |
|---|---|---|---|---|
| Depth (cm) | 3 | 0-10 | 10-30 | 30-100+ |
| Colour | | 10YR5/2 moist crushed | 10YR4.5/6 moist | 10YR5/4 moist crushed |
| Texture | | loamy sand | sandy loam | loamy sand |
| Structure | | structureless | structureless | structureless |
| Slope 20% | | | | |

**Cut 2: Orthic Eutric Brunisol on glacial fluvial parent material**

| Profile | LFH | Ae | Bm | BC |
|---|---|---|---|---|
| Depth (cm) | 7 | 0-15 | 15-40 | 40-100 |
| Colour | | 10YR6/3 moist crushed | 10YR5/5 moist crushed | 10YR5/4 moist crushed |
| Texture | | . sand | loamy sand | loamy sand |
| Structure | | structureless | structureless | structureless |
| Slope 16% | | | | |

**Table A2.** ASP-LM soil profile and related properties.

Uncut 1: Orthic Dark Gray Luvisol on till parent material with eroded A

| Profile | LFH | Ahe | Bt | BC |
|---|---|---|---|---|
| Depth (cm) | 6 | 0-5 | 5-55 | 55-65+ |
| Colour |  | 10YR2/2 moist | 10YR4/3 exped moist | 10YR4/3 moist |
| Texture |  | loam | clay | clay |
| Structure |  |  | subangular blocky |  |
| Slope 17% |  |  |  |  |

**Uncut 2: Orthic Dark Gray Luvisol on till parent material with eroded A**

| Profile | LFH | Ah | Ae | Bt | BC |
|---|---|---|---|---|---|
| Depth (cm) | 12 | 0-5 | 5-7 | 7-60 | 60-80+ |
| Colour |  | 10YR2/2 moist | 10YR5/3 moist | 2.5Y4/3 | 2.5Y3/2 |
| Texture |  | loam | loam | clay-loam | clay |
| Structure |  |  |  | subangular blocky |  |
| Slope 21% |  |  |  |  |  |

**Cut 1: Gleyed Gray Luvisol with faint mottles on till parent material**

| Profile | LFH | Aegj | Btgj | BC |
|---|---|---|---|---|
| Depth (cm) | 8 | 0-25 | 25-70 | 70-80+ |
| Colour |  | 10YR4/3 mosit crushed, 5YR5/6 mottle | 10YR4/3 exped moist | 2.5Y4/2 exped moist |
| Texture |  | silt loam | loam-clay, loam with sand lenses | clay |
| Structure |  | platy | subangular blocky |  |
| Slope 4% |  |  |  |  |

**Cut 2: Orthic Gray Luvisol on till parent material**

| Profile | LFH | Ae1 | Ae2 | Bt | BC |
|---|---|---|---|---|---|
| Depth (cm) | 10 | 0-9 | 9-25 | 25-70 | 70-90 |
| Colour |  | 10YR4.5/2 moist crushed | 10YR4/3 moist crushed | 10YR4/3 moist crushed | 2.5Y3/2 moist exped |
| Texture |  | loam | loam | clay loam | clay |
| Structure |  | platy | platy | subangular blocky |  |
| Slope 12% |  |  |  |  |  |

**Table A3.** MIX-LM soil profile and related properties.

**Uncut 1: Orthic Gray Luvisol on till parent material**

| Profile | LFH | Ae | Bt | BC |
|---|---|---|---|---|
| Depth (cm) | 11 | 0-8 | 8-60 | 60-70 |
| Colour | | 10YR4/4 moist | 2.5Y4/3 moist inped | 10YR3/2 moist |
| Texture | | loam | clay | clay |
| Structure | | platy | fine subangular blocky | |
| Slope 20% | | | | |

**Uncut 2: Orthic Gray Luvisol on till parent material**

| Profile | LFH | Ae | Bt | BC |
|---|---|---|---|---|
| Depth (cm) | 9 | 0-7 | 7-60 | 60-75 |
| Colour | | 10YR5/3, moist | 10TY4/3 moist | 10YR4/3 |
| Texture | | loam | clay loam | clay |
| Structure | | platy | subangular blocky | |
| Slope 10% | | | | |

**Cut 1: Orthic Gray Luvisol on till parent material**

| Profile | LFH | Ae1 | Ae2 | Bt | BC |
|---|---|---|---|---|---|
| Depth (cm) | 10 | 0-7 | 7-18 | 18-70 | 70-90 |
| Colour | | 10YR3/2 moist | 10YR5/3 moist | 10YR4/3 moist | 10YR4/2 moist |
| Texture | | loam to sandy loam | loam to sandy loam | clay | clay |
| Structure | | platy | platy | | |
| Slope 10% | | | | | |

**Cut 2: Gleyed Gray Luvisol on till parent material**

| Profile | LFH | Ae | Bt | BCg |
|---|---|---|---|---|
| Depth (cm) | 10 | 0-3 | 3-36 | 36-90 |
| Colour | | 10YR3/3 moist | 10YR4/4 moist | 10YR4/3 moist, 7.5YR5/8 mottle |
| Texture | | clay to clay loam | clay | clay |
| Structure | | | subangular blocky | |
| Slope 10% | | | | |