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# Nutrient cycling in the forest floor and mineral soil of the boreal forest

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# Nutrient Cycling in the Forest Floor and Mineral Soil of the Boreal Forest

by

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# ABSTRACT

Soil temperatures and moistures were monitored in two Alberta field sites from May 1997 to September 1998. Nitrogen (N) mineralization rates were measured using ion exchange membranes in the field from June 1997 to May 1998. In association with this monitoring N mineralization rates were measured in the laboratory to compare ion exchange membranes, exchange resin bags and 0.01 M $CaCl_2$ extraction under varied physical and chemical soil conditions. Results indicated that both ion exchange membranes and exchange resin bags were accurate in predicting the amount of N as compared to the 0.01 M $CaCl_2$ extraction. This laboratory study was also used to calibrate the ion exchange membranes, thereby allowing the field data to be reported on a volumetric basis. The field data provided insight into temporal changes in available N at the sites investigated.

In addition, intact organic horizon cores (LFH) and homogenized Ae cores from Alberta and Quebec were incubated under various conditions between 231 and 313 days. Every 14 - 28 days, each core was leached with 0.01 M $CaCl_2$ for mineral N determination. To accommodate variability in soil N content and site history, results were normalized to a soil N basis. Results indicated net N mineralization is horizon specific not site specific; net N mineralization over long times was weakly related to lower soil temperatures; and differences in moisture tension did not create differences in specific net N mineralization. A protocol is proposed to estimate N mineralization from soils across Canada for use by present and future forest managers.

Another study traced the fate of N in forest ecosystems. This involved the application of a $^{15}N$ isotope onto moss and grass layers of two Alberta field sites. The objective was to determine if the N cycle is short-circuited by the moss and/or grass layer, thus leaving the larger vegetation nitrogen deficient. Results indicated that a larger proportion of $^{15}N$ is found in the vegetation than in the organic or mineral soil. This study also provided information on plant nutrient uptake before senescence.

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# INTRODUCTION

Between 1986 and 1994, the forest sector in Alberta received over $4 billion of new investment and is now Alberta's third largest primary economic sector (Alberta Environmental Protection 1996). This raises the question whether the current harvesting levels are sustainable. The Sustainable Forest Management Network (SFM) was established in 1995 focusing on preserving the ecological variability and biodiversity of Canada's boreal forest while maintaining the nation's forest-based economy. The network's purpose is to ensure that Canada's boreal forest is effectively managed, its biological diversity preserved, and its resources sustained for future generations. This project was within the Ecological Basis of Sustainable Forest Management theme, the goal of which was to examine natural ecosystem processes and the impact of human activities on them. There were three groups of sites for this project: natural sites in Alberta; disturbed sites in Alberta; and disturbed sites in Quebec. The main focus of this project was on the natural sites in Alberta with some overlap with the disturbed sites in Quebec.

Natural sites were located at Lac La Biche and Whitecourt, Alberta. These sites represented different temperature regimes within the boreal forest and had 3 plots situated along a slope representing upper, middle and lower slope-positions. Both field monitoring and laboratory investigations were completed with these sites. Soil samples from Lac Spencer and Nicabau, Quebec represented disturbed sites. These sites were a component of Dr. A. Munson's study from Laval University. Lac Spencer was burned 50 - 70 years ago while Nicabau was cut 50 - 70 years ago. A full description of the sites, as well as the soil chemical and physical properties is provided in Offord 1999 (chapter 2).

The majority of this project focused on quantifying N mineralization rates from samples of organic and mineral horizons from these sites incubated at varying temperature and moisture conditions. Two other components of this project involved the quantification of available N using ion exchange membrane probes and whether or not the N cycle is short-circuited by the moss or grass layers of forest soils.

Nitrogen (N) cycling is a vital component in the sustainability of long-lived forest systems (Raison and Stottlemyer, 1991). The N cycle is regulated by complex interrelationships among plant uptake of available soil N, the transfer of N from plant litter to soil organic matter (SOM) and the conversion of organic N to $NH_4^+$ by soil microorganisms (Clark 1977; Zak et al. 1986). In temperate forests, N generally limits productivity when water is not limiting (Keenan et al. 1995). Raison and Stottlemyer (1991) stated N availability affects tree productivity by altering the rate of tree canopy development, photosynthetic properties, needle water potentials, and carbon (C) allocation patterns.

Nitrogen fixation and N deposition throughout the biosphere replenish losses of N from the N cycle. However, N deficiency is common in forest ecosystems (Johnson 1992). Possible losses from the N cycle include denitrification, volatilization, leaching, runoff, export in bodies of consumers, nitrification and immobilization; however, these losses are not significant enough to be the cause of the N depravation in forest stands (Preston et al. 1990). Documentation of montane tropical rainforests, boreal forests and peatlands has lead to speculation that Bryophytes, lichens and possibly grasses, short circuit the N cycle because they play a significant role in the uptake, retention and redistribution of N within a forest ecosystem (Coxson 1991; Li and Vitt 1997). The moss layer acts as a filtering agent by slowing downward movement of N into the soil, where most of the vascular plant roots are located (Weber and Van Cleve 1984). If the annual nutrient accumulation by mosses exceeds uptake by trees, the moss layer may represent an effective bottleneck in the N cycle of the stand (Weber and Van Cleve 1981).

Soil moisture influences soil organic N mineralization (Stanford and Epstein, 1974). The amount of N available for mineralization is in turn a function of the amount of organic C stored in the soil. The C content or amount of SOM is regulated by climatic conditions, and by chemical factors of the litter which affect activity of soil microorganisms. The two most important limiting factors to growth in boreal forests are low N availability and low air temperatures (Makipaa, 1995). The plant availability of N within a growing season may be more dependent on the temperature sensitivity of mineralization than the quantities of N in the mineralizable fraction of SOM (Ellert and Bettany, 1992). N availability often increases with an increase in temperature due to an increase in decomposition of SOM (Cole, 1995; Makipaa, 1995). Amount of SOM usually increases with decreasing mean annual temperature.

In situ measurement of available N in forest soils can be monitored using exchange resin bags (ERB) (Binkley and Matson 1983), or the recently developed ion exchange membrane probes (IEM) (Subler et al. 1995). ERB are time consuming, expensive to assemble (Binkley and Matson 1983); results may be confounded by soil disturbance created during placement of ERB in soil (Subler et al. 1995); and the effort required to place ERB properly may limit their effectiveness by altering the flow of water and nutrients through or around the bag (Subler et al. 1995). IEM have the advantage of being easier to install than ERB, allow more samples to be taken with the same effort, and reduce the overall cost per sample (Western Ag Innovations 1997).

Disturbance caused by forestry operations or wildfires creates changes in the forest ecosystem. This disturbance could increase or decrease the soil N mineralization rate by changing the soil temperature and / or moisture regime. Basic understanding of the natural N mineralization of soils across boreal forests are required if predictions of soil N mineralization from forest soils after disturbances such as clear cutting or wildfires are to be made in relation to their soil temperature moisture regimes. It is anticipated that the results from this project will provide a more fundamental understanding of controls on N dynamics of natural sites thereby yielding tools for prediction of N dynamics under a variety of disturbances. Specific questions we asked:

1. Does the specific net rate of N mineralization vary in samples from along a catenary sequence at each site and between sites?
2. Does the specific net rate of N mineralization vary among samples of different horizons?
3. Does the specific net rate of N mineralization differ among samples incubated at different soil temperatures?
4. Does the specific net rate of N mineralization differ among samples incubated at different soil moisture tensions?
5. Does the specific net rate of N mineralization differ among samples from different moisture and temperature regimes or from soils with different disturbance regimes?
6. Are N ions removed from exchange resin under immobilizing conditions?
7. Is N sorption onto exchange resin reduced as soil ped size increases?
8. Is N sorption onto exchange resin reduced as leaching intensity increases?
9. Does the mosses and/or grass layer short-circuit the N cycle?

# SUMMARY OF DATA ANALYSIS

## The Pattern of Soil N Mineralization from Three Slope Positions Incubated at a Single Temperature

The objective of this study was to characterize patterns of net N mineralization in organic and mineral soil horizons from three slope positions along a catena from sites at Lac La Biche and Whitecourt. We hoped to answer the question: does the specific net rate of N mineralization vary in samples from along a catena at each site and between sites? We expected the specific net rate of N mineralization to be lower in the mineral horizons due to greater degrees of humification. Consequently, the patterns of N mineralization were expected to vary among horizons. It was also expected that the rate of N mineralization would decrease as incubation time increased (Winkler et al. 1995). We hypothesized that the specific net rate of N mineralization would not differ among slope positions.

### *Calculation of specific rate (mg N g$^{-1}$ soil N)*

Normally, N mineralization is expressed as $\mu$g g soil$^{-1}$. This takes into account the mass of soil used and organic matter quality. Differences in soil total N may influence rates of N mineralization independently of organic matter quality. Therefore, N mineralized was expressed as a specific net N ($NH_4^+$-N + $NO_3^-$-N) mineralization with units of mg N mineralized g$^{-1}$ soil N at each sample time. Specific net mineralization normalizes the data to a N basis not to a soil mass basis. The concept behind specific net mineralization can be explained by two examples:

| **Organic Horizon** | **Mineral Horizon** |
|---|---|
| Nt = 0.021 g N $g^{-1}$ soil | Nt = 0.002g N $g^{-1}$ soil |
| Ms = 100 g soil | Ms = 100 g soil |
| Nm = 15 mg N | Nm = 3 mg N |
| $\frac{15 mgN}{100 gsoil} * \frac{gsoil}{0.021 gN}$ | $\frac{3 mgN}{100 gsoil} * \frac{gsoil}{0.002 gN}$ |
| Specific net rate = 7.1 mg N $g^{-1}$ soil N | Specific net rate = 15 mg N $g^{-1}$ soil N |

where Nt is the total amount of N (g $kg^{-1}$); Ms is the mass of soil (g); and Nm is the amount of N mineralized.

This example indicates that the mineral horizon mineralized proportionally more N than the organic horizon, even though the amount mineralized from the organic horizon is five times more than from the mineral horizon. This approach allows data to be compared from different sites and horizons because it is normalized to the total amount of N contained within each sample. Therefore varying N content can be treated separately, allowing interpretation about the nature of the N and of the soil environment.

### *Statistical Analysis*

A variety of models (exponential Eq [1], logistic Eq [2] and modified Gompertz (Ellert and Bettany, 1992) Eq [3]), were fitted to incremental mineralization data for each site using a non-linear (NLIN) procedure from the SAS statistical program package (SAS Institute Inc., 1998). These models were used to predict mineralization potential ($N_o$), decay rate (k) or other equation parameters (h or x). For the most part the modified Gompertz model fit the data best.

$$N_i = N_o e^{-kt}\left(e^{ki} - 1\right) \qquad [1]$$

$$N_i = N_o \left[ \frac{1}{1 + \left(\frac{N_o}{x} - 1\right) e^{-kt}} - \frac{1}{1 + \left(\frac{N_0}{x} - 1\right) e^{-k(t-i)}} \right] \qquad [2]$$

$$N_i = N_o e^{-h\left[1 - e^{k(t-i)}\right]} - N_o e^{h\left(1 - e^{kt}\right)} \qquad [3]$$

Because equation parameters: h, k and $N_o$ are correlated with each other, derived variables that include 2 or 3 of the parameters are more appropriate for comparing among soils or sites. Therefore, time to inflection point Eq. [4] ($T_{ni}$; d), containing k and $\alpha_o$, and maximum rate of N mineralization Eq [5] ($R_m$; mg N $g^{-1}$ soil N $d^{-1}$), containing $N_{o,}$ k and $\alpha_o$, were calculated and used for comparative purposes.

$$T_{ni} = \frac{1}{k}\ln\left(\frac{k}{\alpha_o}\right) \qquad [4]$$

$$R_m = N_o k\left[e^{\left(\frac{\alpha_o}{k}\right)-1}\right] \qquad [5]$$

In summary, the specific net rate of N mineralization was not significantly different between sites or slope positions. Complete investigation of this hypothesis is found in Offord 1999 (chapter 3).

### The Pattern of Soil N Mineralization at Increasing Soil Temperature and Moisture Tension

This component of the project involved two separate experiments with the objectives to document the course of N accumulation from forest soil horizons incubated at (1) five temperatures and (2) four moisture tensions. The first hypothesis was that samples incubated at higher temperatures would have a higher maximum specific net N mineralization than those samples incubated at lower temperatures. Ellert and Bettany (1992), Kirschbaum (1995), and Winkler et al. (1996) hypothesized that N mineralization, organic matter decomposition and soil respiration rates, is temperature dependent. We interpreted our data in the context of the hypotheses set out by these authors. The second experiment hypothesized that N mineralization was moisture dependent and would increase as moisture tension decreased, and would reach a maximum before saturation where N mineralization would then decrease. Incremental mineralization data were then fitted to a variety of models and the time to inflection point and maximum rate of N mineralization were calculated (see above).

The specific net rate of N mineralization from samples of Ae horizons exceeded the specific net rate from samples of organic horizons. The specific net N mineralization from the organic and Ae horizons were horizon-specific not site-specific. Differences in maximum specific net rate of N mineralization and time to inflection for organic horizons incubated at different temperatures, suggested that net N mineralization rates were altered by temperature, however the cumulative amount of net N that can be mineralized was not. The cumulative specific net N mineralization from organic and Ae horizons was similar among moisture tensions. Maximum specific net rates of N mineralization from samples of Ae horizons incubated at all moisture tensions were higher than from samples of organic horizons. Complete documentation of these results are presented in Offord 1999 (chapter 3 and 4), and Offord and McGill (In press).

### Measurement of Mineral N Using Ion Exchange Membranes or Exchange Resin Bags under Various Conditions

This laboratory study was designed to compare IEM, ERB and 0.01 M $CaCl_2$ extraction techniques for measurement of soil mineral N availability under varied physical and chemical soil conditions. The following hypotheses were tested: under immobilizing condition, N ions will be removed from the exchange resin; N sorption onto exchange resins will be reduced as soil ped size increases; and N sorption onto exchange resins will be reduced as leaching intensity increases. The laboratory study was used to calibrate the IEM, thereby allowing the field data to be reported on a volumetric basis. Field data were collected between May 1997 and May 1998 from sites at Lac La Biche and Whitecourt, AB at all slope positions. This data provided insight into temporal changes in available N at the sites investigated.

Both IEM and ERB were accurate in predicting the amount of N as compared to the 0.01 M $CaCl_2$ extraction. As ped size increased, $NH_4^+$ or $NO_3^-$ sorption onto IEM or ERB did not decrease. As leaching intensity increased, the amount of $NH_4^+$ or $NO_3^-$ predicted by using IEM or ERB did not decrease. In fact the IEM and ERB appear to be efficient predictors of the amount of $NH_4^+$ and $NO_3^-$ in soil. There was no evidence suggesting that $NH_4^+$ or $NO_3^-$ ions were removed from the exchange resins under conditions of immobilization. Furthermore the results suggested that the exchange resins retained $NO_3^-$ ions.

Mineralization of $NO_3^-$ from both sites and horizons fluctuated from 0 to 6 $\mu$g $NO_3^-$ $cm^{-3}$ and $NH_4^+$ fluctuated from 0 to 13 $\mu$g $NH_4^+$ $cm^{-3}$ throughout the year. Mineralization of $NH_4^+$ between sites and horizons is similar, both flushing between September to October, which corresponded to high inputs of litter. Further explanation of these results are found in Offord 1999 (chapter 5) and Offord et al. 1998.

### Fate of N in Forested Ecosystems

This study involved the application of a $^{15}N$ isotope onto moss and grass layers at Lac La Biche and Whitecourt. The objective was to determine if the N cycle is short-circuited by the moss and/or grass layers, thus leaving the larger vegetation nitrogen deficient. The results indicated that a larger proportion of $^{15}N$ was found in the vegetation than in the organic or mineral soil throughout the duration of the experiment (late August to late October) (unpublished data).

## MANAGEMENT IMPLICATIONS

Quantification of nutrient cycling processes of forested ecosystems has the potential to identify nutrients most likely to limit site productivity in current or future forests. However N concentrations within forested sites vary considerably. McNabb et al. (1986) concluded that there was considerable variation in the N and C concentrations of surface soil within small forested sites in the Cascade Mountains of Oregon. They determined that this variation could not be accounted for by simple characterization of microsites around a sampling point. Given that there is large variation in N concentration from site to site, we hoped that this research could aid in the prediction of specific net N mineralization rates from sites across Canada.

The Gompertz model predicted parameters $N_o$, k and h. These parameters were used to calculate time to inflection point ($T_{ni}$) and maximum rate of N mineralization at inflection point ($R_m$). It has been suggested that one k value might be valid for all soils (Dendooven et al. 1995). If we limit analysis to the Alberta sites, median k values for both organic and Ae horizons (k = 0.009 $d^{-1}$) and median $N_o$ values for organic (30.93 mg N $g^{-1}$ soil N) and Ae (42.85 mg N $g^{-1}$ soil N) horizons can be selected to represent all soils. Because the proportionality constant, h, varied to a greater extent than the other parameters, the sensitivity of the Gompertz model to varying values of h was tested. Median values for k (0.009 $d^{-1}$) and $N_o$ (42.85 mg N $g^{-1}$ soil N) were held constant as h ranged from 0.19 to 0.99 (dimensionless) (Figs. 1 and 2). As h increased from 0.19 to 0.99 (dimensionless), the time to inflection point increased from 1.1 to 184 days, and the maximum rate of N mineralization increased from 0.17 to 0.38 mg N $g^{-1}$ soil N $d^{-1}$. Therefore, the Gompertz model is sensitive to changes in h.

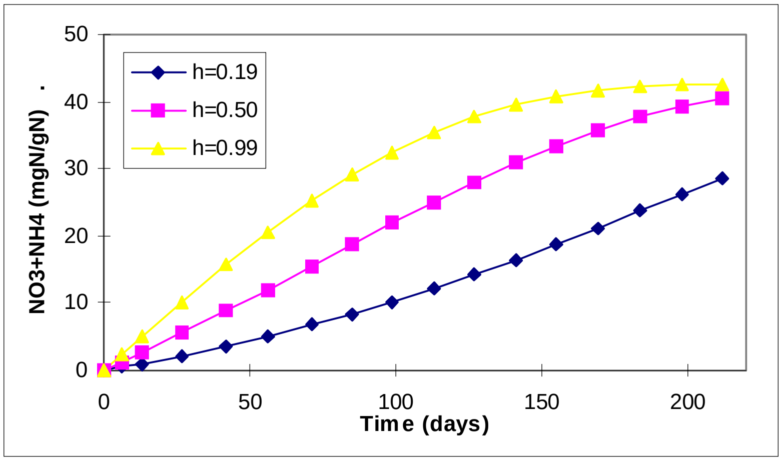

**Figure 1: Cumulative specific net $NH_4^+$+$NO_3^-$ -N mineralization as h varied from 0.19 to 0.99 (dimensionless) during 212 days where $N_o$ = 42.85 mg N $g^{-1}$ soil N and k = 0.009 $d^{-1}$.**

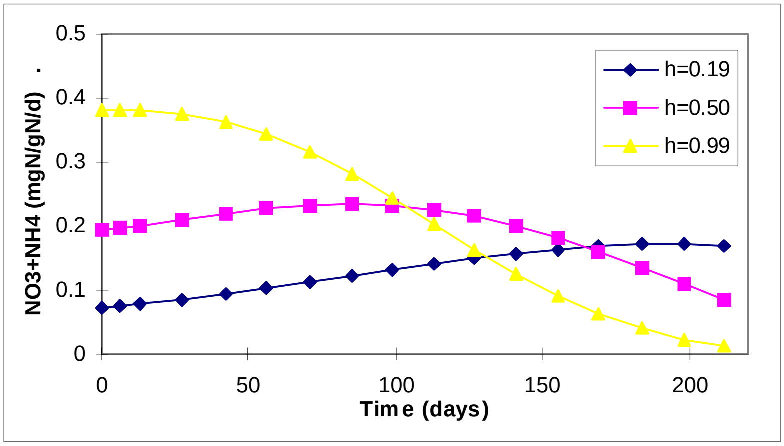

**Figure 2: Incremental specific net $NH_4^+$+$NO_3^-$ -N mineralization as h varied from 0.19 to 0.99 (dimensionless) during 212 days where $N_o$ = 42.85 mg N $g^{-1}$ soil N and k = 0.009 $d^{-1}$.**

However, if median values of k (0.009 $d^{-1}$), and horizon specific h (0.186) and $N_o$ (30.93 mg N $g^{-1}$ N) values are used to predict the cumulative amount of N mineralized over 313 days, the outcome is similar to what was actually measured (Fig. 3 and 4).

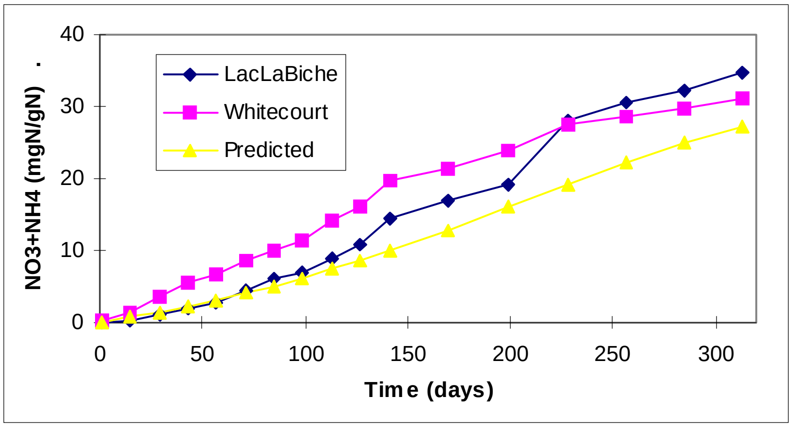

**Figure 3: Predicted and actual cumulative specific net $NH_4^+$+$NO_3^-$ -N mineralization during 313 days from samples of organic horizons incubated at 22°C.**

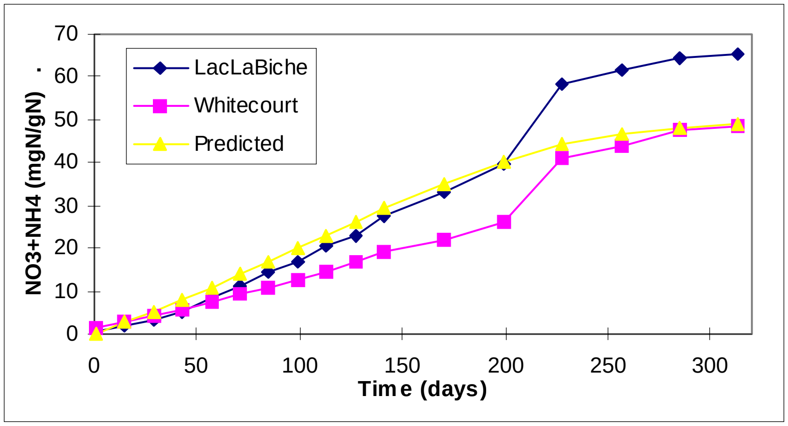

**Figure 4: Predicted and actual cumulative specific net $NH_4^+$+$NO_3^-$ -N mineralization during 313 days from samples of Ae horizons incubated at 22°C.**

Therefore, the amount of N mineralized (mg N $cm^{-2}$) can be estimated for different sites using the following assumptions: k can be used to describe soils from both organic and Ae horizons; $N_o$ and h are horizon specific; the total N (g N $kg^{-1}$ soil) and ρb (g $cm^{-3}$) of a soil is known [Eq 6]:

$$Mineralized\ N\left(\frac{mg\ N}{cm^2}\right)=\frac{g\ soil\ N}{kg\ soil}*\rho b\left(\frac{g\ soil}{cm^3}\right)*\left(\frac{kg\ soil}{10^3\ g\ soil}\right)*depth(cm)*predicted\ N\left(\frac{mg\ N}{g\ soil\ N}\right) \quad [6]$$

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For example, if a site with the following properties was harvested (compares to the organic horizon from the upper site at Whitecourt), the amount of N mineralized from the organic horizon could be predicted:

Total N = 24.1 g N $kg^{-1}$ ρb = 0.11 g $cm^{-3}$

Organic horizon depth = 10.5 cm Predicted $N_o$ = 30.93 mg N $g^{-1}$ soil N

$$Mineralized\ N = \frac{24.1\,g\ soil}{kg} * \frac{0.11\,g}{cm^3} * \frac{kg\ soil}{10^3\ g\ soil} * 10.5\,cm * \frac{42.85\,mg\ N}{g\ soil\ N}$$

$$Mineralized\ N = \frac{0.86\,mg\ N}{cm^2}$$

$$Mineralized\ N = \frac{86\,kg\ N}{ha}$$

**Table 1: Estimated N mineralization potential of organic and Ae horizons from Whitecourt**

| Variable | Units | Upper | Middle | Lower |
|---|---|---|---|---|
| Organic Horizon | | | | |
| Depth | cm | 10.5 | 8.1 | 8.7 |
| Bulk Density | g $cm^{-3}$ | 0.11 | 0.13 | 0.18 |
| Total N | g $kg^{-1}$ | 24.1 | 23.1 | 15.7 |
| $N_o$ | mg N (g soil N)$^{-1}$ | 30.93 | 30.93 | 30.93 |
| $N_o$ | kg N $ha^{-1}$ | 86 | 75 | 76 |
| Ae Horizon | | | | |
| Depth | cm | 6 | 5 | 5 |
| Bulk Density | g $cm^{-3}$ | 0.96 | 1.1 | 1.03 |
| Total N | g $kg^{-1}$ | 2.8 | 1.7 | 1.8 |
| $N_o$ | mg N (g soil N)$^{-1}$ | 42.85 | 42.85 | 42.85 |
| $N_o$ | kg N $ha^{-1}$ | 69 | 40 | 40 |
| Total | kg N $ha^{-1}$ | 155 | 115 | 116 |

Therefore, quantification of the amount of mineral N released from different horizons can be compared (Table 1). In addition, generation of mineral N from different sites can be compared (Table 2). From both sites, the mineralization potential from the organic horizon was higher than the Ae horizon. Further analysis of these assumptions is needed; they were used here to illustrate how N mineralization on an aerial basis may be predicted.

**Table 2: Estimated N mineralization potential of organic and Ae horizons from Lac La Biche**

| Variable | Units | Upper | Middle | Lower |
|---|---|---|---|---|
| Organic Horizon | | | | |
| Depth | cm | 7 | 8 | 9 |
| Bulk Density | g $cm^{-3}$ | 0.18 | 0.13 | 0.17 |
| Total N | g $kg^{-1}$ | 9 | 10 | 11 |
| $N_o$ | mg N (g soil $N)^{-1}$ | 30.93 | 30.93 | 30.93 |
| $N_o$ | kg N $ha^{-1}$ | 35 | 32 | 52 |
| Ae Horizon | | | | |
| Depth | cm | 4 | 3 | 2 |
| Bulk Density | g $cm^{-3}$ | 1.42 | 1.27 | 1.54 |
| Total N | g $kg^{-1}$ | 0.7 | 0.6 | 1.1 |
| $N_o$ | mg N (g soil $N)^{-1}$ | 42.85 | 42.85 | 42.85 |
| $N_o$ | kg N $ha^{-1}$ | 17 | 9 | 14 |
| Total | kg N $ha^{-1}$ | 52 | 41 | 66 |

## CONCLUSIONS

Laboratory incubations in this research provided an understanding of N mineralization from samples of organic and Ae horizons without the presence of vegetation. In the absence of vegetation, this research indicated that samples of Ae horizons mineralized proportionally more N than samples of organic horizons. This suggested the specific net mineralization of N is horizon-specific not site-specific.

The major implications is that much of the variability among sites may be taken into account by readily accessible site data such as horizon thickness, density and N concentration. The decomposition rate data, being more universal may then be obtained from fewer samples and used widely with site data. This yields rate specific N mineralization rates expressed as kg $ha^{-1}$. Consequently the cost of estimating N mineralization over large areas can be reduced mainly to the cost of obtaining sites characteristics that determine total N present in organic and mineral horizons.

After disturbances such as cutting, soil pH generally increases and a new microbial community appears which oxidizes $NH_4^+$ to $NO_3^-$. As well, many site preparation operations are aimed at removing organic layers from sites and exposing the mineral soil because it is considered to be a reliable seed bed. On one hand, proportionally more N will be mineralization in the Ae horizon providing N to seedlings. However, boreal forests are characterized by low temperatures and short growing seasons. For these sites, there were 138 days above 2°C, therefore vegetation establishment may be limited within the first growing season, allowing N mineralization to proceed without adequate vegetation present. In addition, there was evidence that nitrification rates would increase after 50 to 100 days. We hypothesized that this was because establishment of nitrifier communities took 50 to 100 days. If forest management practices do not include or permit the establishment of quick growing vegetation nitrate may leach into streams, rivers, lakes or aquifers. On the other hand, forest managers may also want to consider the implications of establishing quick growing vegetation because the N cycle may be short-circuited, preventing new seedlings from obtaining adequate amounts of N. Nonetheless, high concentrations of $NO_3^-$ in surface water is toxic to animals i.e. transformation of blood hemoglobin to methaemoglobin, or formation of carcinogenic nitrosamines (Tamm et al. 1974), and may foster eutrophication of lakes and streams if complementary nutrients such as P are available.

Kronzucker et al. (1997) demonstrated that white spruce seedlings preferentially absorbed 20 times more $NH_4^+$ than $NO_3^-$. If white spruce seedlings were planted the following season after cutting, the production of $NO_3^-$ would be at its highest therefore decreasing chance for survival and forest regeneration.

Generally there was no difference in total specific net N mineralized from samples of organic horizons incubated at 12°C or higher. However, there were differences in maximum specific rate of net N mineralization and time to reach the maximum rate for organic horizons incubated at different temperatures. This suggests that maximum N mineralization rates are altered by temperature, however the cumulative amount of N that can be mineralized was not. One hypothesis was that the microbial communities established in samples of organic horizons are more adapted to an environment with a temperature of 12°C. Malhi et al. (1990) indicated that there was a climatic control over temperature activity relations of denitrification in soils and the optimum temperature for denitrification in Alberta soils was lower than in soils from warmer regions.

On the other hand, there was no difference in mean specific net N mineralization as temperature increased (except the 6°C treatment) for samples of Ae horizons. We expected the higher mean specific net rate obtained from samples of Ae horizons incubated at 0°C was due to freeze thaw cycles. It may be possible to obtain the same N mineralization patterns as samples of organic horizons if soil was incubated where freeze thaw cycles did not occur (i.e. incubation at 1 °C). The mean specific net N mineralization from samples of Ae horizons incubated at 0 and 6°C may then be significantly less than the samples incubated between 12 and 32°C which were not significantly different. There is evidence that soil temperature increases following disturbances (Meng et al. 1995; Tamm et al. 1974). The microbial community adaptation to lower soil temperatures may be beneficial if with an increase in temperature, an increase in N mineralization does not always occur. Of course the microbial community may adapt to these changes as well, however there is limited knowledge to know how long this would take. Further study of microbial community adaptation in forest soils to changes in temperature and moisture are needed.

Another component of this project was the calibration of ion exchange membranes (IEM), exchange resin bags (ERB) with 0.01 $CaCl_2$ extraction. Both the IEM and ERB provided in situ measurements of N mineralization rates. Use of IEM in the field was easy and efficient. Extraction and analysis were also less cumbersome than using ERB. However confusion still exists about the use of IEM because it is not clear what dimension of measurement is taken with the IEM. This confusion applies to the ERB, but because IEM are relatively new products, questions regarding their use have been raised.

The volume of soil sampled using the IEM is a question that many researchers have asked. Does the IEM sample N from the soil it comes into contact with? Results suggest ped size fractions greater than 2 mm may decrease the amount of N predicted by the IEM. Does this imply that IEM sample from an area? Is a diffusion gradient created by the IEM and N ions from the surrounding soil move toward the IEM, therefore sampling a volume of soil? Do IEM out compete microorganisms for N and retain N ions on the surface of the membrane? The results of this research provided one way to calibrate the IEM to a standard laboratory method and the calculated effective volumes were consistent throughout the experiments completed in Chapter 5. However further analysis and replication of these experiments using IEM should be completed.

If these experiments were to be repeated, it is recommended that both horizons would consist of 17 to 19 replications. The number of replicates required was determined by [Eq. 7] (McNabb et al. 1986):

$$n = \left[ \frac{t * s}{E} \right]^2 \qquad [7]$$

where n is the number of replicates; t is the student's t-value, approximately 2.1 at p = 0.10; s is the mean standard deviation for all treatments per experiment; E is the allowable error from the mean.

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