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**EFFECT OF CLIMATE CHANGE ON C:N POOLS IN A BOREAL
WATERSHED ECOSYSTEM**

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SUMMARY

The following report summarizes research findings, principally for Isle Royale (ISRO), from field and laboratory studies conducted June 1992, through June 1993. The data collected since have not been fully analyzed.

Our study objective for 1993 was to assess if possible changes in the nitrogen cycle, as might occur from global climate scenarios for temperature and moisture, could complement inorganic precipitation nitrogen (N) inputs to the boreal forests of Isle Royale. Total atmospheric N input ($>6 \text{ kg ha}^{-1} \text{ yr}^{-1}$) exceeds the ecological requirements of major forest species. A decade of ecosystem study shows strong N retention (92%). There are significant differences in mineral soil N pools (492, 564, and 1153 kg ha^{-1} for birch, spruce, and alder respectively). Annual soil NO_3^- N concentrations varied with vegetation ($p < 0.05$) being higher beneath alder ($11.6 \text{ mg N kg}^{-1}$) than spruce and birch (1.1 and 0.9 mg N kg^{-1} respectively). Soil NH_4^+ concentrations marginally increased with time ($p = 0.07$), but did not significantly differ among vegetation types (5.4 , 6.8 , and 8.1 mg N kg^{-1} for birch, spruce and alder). Field net N mineralization was inversely related ($p < 0.001$) to soil temperature, but laboratory incubations showed a gain ($p < 0.03$) in mineralization over temperatures from 10° to 20°C . Field net N mineralization varied with incubation period ($p < 0.01$) and species ($p = 0.05$). Annual net mineralization was 35 , 38 , and $84 \text{ kg N ha}^{-1} \text{ y}^{-1}$ for birch, spruce, and alder respectively. There was no apparent relationship between field net mineralization, net nitrification, and initial mineral N concentrations and soil moisture. A comparison of most mineral N sources (vegetation blowdown, atmospheric inputs, herbivory) indicates that a $2 - 5^\circ\text{C}$ increase in summer soil temperature would significantly increase available N more than from these other sources.

INTRODUCTION

Linked forest productivity/soil process models suggest that the boreal ecosystem fringe could be the most sensitive of eastern North American forests to climate change (Pastor and Post, 1988; Solomon, 1988). The rate of climate change in this region may be more significant than its magnitude (Solomon and Bartlein, 1992). Unfortunately, the boreal ecosystem has been little studied outside of Alaska (Botkin and Simpson, 1990; Mooney et al., 1991; Strain and Bazzaz, 1983).

Change in ecosystem C is dependent on nutrient status especially available inorganic N (NO_3^- , NH_4^+). Global climate scenarios for the Upper Great Lakes region fail to take into account present atmospheric contaminant inputs of N ($>6 \text{ kg ha}^{-1} \text{ yr}^{-1}$), a level which exceeds the ecological requirements of all major boreal forest species. Almost half this inorganic N input is high energy NH_4^+ possibly preferred by boreal conifers (Reuss and Johnson, 1986). It has been thought that much of this N would be unavailable to forest species, but $>10 \text{ y}$ of boreal watershed-level study shows strong ($>90\%$) N retention (Stottlemeyer, R., D. Rutkowski, D. Hanson, Jr., C. Friesen, and M. Larson. 1984. Effects of atmospheric acid deposition on watershed/lake ecosystems of Isle Royale and Michigan's Upper Peninsula. GLARSU Tech. Rept. #9, Dept. Biol. Sci., Michigan Technological Univ., Houghton, MI 49931; Stottlemeyer and Hanson, 1989; Stottlemeyer and Toczydlowski, 1991).

The effect of chronic N input to northern forested ecosystems appears nonlinear, and conifers appear more responsive than northern hardwoods (Aber et al., 1993; Gundersen, 1991). Due to its ecotonal nature, the Upper Great Lakes region is characterized by large differences among major forest species in potential N mineralization and nitrification rates (Zak et al., 1986). Species variation in response to climate change in the region appears more important than site variation, and groups of species can be separated based upon growth response to climate over time (Graumlich, 1993). Extreme climate events appear especially important in creating a growth response, and some evidence now exists showing species response to the decline in precipitation and increase in temperature of the past decade (Graumlich, 1993; Jones et al., 1993). The complexity of species interaction with both climate change and increased atmospheric N inputs in an ecotonal region point out the need for additional study of major forest species potential response to both climate change and continued high nitrogen inputs especially in the southern boreal fringe.

The overall objective of this five year study, initiated in 1992, is to relate change in mineral nitrogen availability resulting from modest changes in soil temperature and moisture to mineral N availability from sources such as atmospheric inputs and forest blowdown. The focus of the research results reported here is on N mineralization in boreal forest soils in response to changes in temperature and, to a lesser degree, moisture.

SITE DESCRIPTION

The Wallace Lake watershed (48° 03' N, 88° 38' W) is located in Isle Royale National Park, northwestern Lake Superior. The watershed is underlined by metamorphosed ophitic flood basalts covered by scattered alkaline glacial till originally derived from limestone bedrock immediately south of James Bay. The soils are 3000-5000 y old, Alfic Haplorthods, sandy to coarse loamy, mixed and frigid. They are predominantly of the Michigamme-Arcadian-Rock Outcrop Association (Shetron, S. G., and R. Stottlemeyer. 1991. Isle Royale National Park Soil Survey and map. School of Forestry, Michigan Technological Univ., Houghton, MI 49931, 365 p.). The surface O horizons have the highest percentage organic matter content (Stottlemeyer and Hanson, 1989). In mineral soil horizons, the A and Bh_s under aspen/birch have the highest organic matter content. Calcium is the most important exchangeable cation.

Isle Royale lies within the vegetational transition zone between the boreal forest found on the north shore of Lake Superior and the northern deciduous forest which predominates the lake's south and eastern shores. The 176 ha Wallace Lake watershed is dominated by the boreal forest formation. The overstory is a mixture of white birch (*Betula papyrifera* Marsh.), quaking aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) A. Voss) and balsam fir (*Abies balsamea* (L.) Mill.). Scattered stands of white cedar (*Thuja occidentalis*) also exist within the watershed. There has been no known direct human disturbance of the watershed except for a small portion of the drainage burned in 1936.

These boreal forests contain 10 canopy species with an aboveground biomass of 108 t ha⁻¹ while nearby mature northern hardwoods have about 15 species and a biomass >250 t ha⁻¹ (Rutkowski and Stottlemeyer, 1993). The boreal understory has a larger number of saplings and much greater biomass (2275 kg ha⁻¹) than did northern hardwoods (85 kg ha⁻¹). Its vascular ground cover also contained more biomass (1180 to 34 kg ha⁻¹ for northern hardwoods). The boreal forest floor contained 21% of the aboveground biomass, the largest above-ground N pool (390 kg ha⁻¹ in Oa), and 68% of above ground N.

The 11-yr hydrologic record for the watershed was used to estimate water and ion flux beneath the forest litter layer and soil (Table 1). Spruce canopy retention of precipitation NO₃⁻ is likely due to leaf absorption and uptake by lichens. Overall, NO₃⁻ and K⁺ inputs are retained by the ecosystem even beneath alder. However, NO₃⁻ retention beneath alder and within the entire watershed ecosystem is reduced in spring. The ecosystem is SO₄²⁻ saturated due to the long-term atmospheric inputs and low biological demand (Stottlemeyer and Hanson, 1989).

It is difficult to show differences in N dynamics unless the study plots occur on relatively similar soils and in a similar climate. Variation in the elevation among all study plots was <10 m. All plots were located in the Michigamme-Arcadian-Rock Outcrop Association, a combination of scattered rock outcrops and moderately steep, shallow to moderately deep, well drained loamy soils on moraines. All plots were within 300 m of Wallace Lake, a sheltered interior lake.

METHODS

The emphasis in 1992-93 was on successional species (alder, birch) and immature (50 y) white spruce. Mature spruce stands are very rare apparently due to blowdown (Toczydlowski et al. 1993) assisted by periodic outbreaks of spruce bark beetle (*Dendroctonus rufipennis*).

Within each major vegetation type, three 0.1 ha plots were selected in the watershed. On each plot a partial Li-Cor meteorological station, consisting of instrument shelter, datalogger, five temperature sensors (thermistors at 5 and 10 cm depth beneath the organic layer, forest litter, 10 cm and 1.3 m above the forest floor) was installed the last week in May 1992, and operated until the third week of October. A subset of dataloggers was left in place for over-winter monitoring in all vegetation types. Daily mean, maximum, and minimum air temperature and daily mean soil temperature at both depths were logged throughout the study. Solar radiation (solar pyranometer recording total daily solar radiation in MJ m⁻² d⁻¹), air and soil temperature, and precipitation (NADP event collector, bulk collector, manual and automated Belfort raingages) at an open site was monitored at the primary meteorological station installed in 1982, 200 m from the nearest birch plot.

Within each 0.1 ha plot, three randomly placed 25 m² subplots were established. Each month from May to October, 1992, three sites for incubations, soil sampling, litter fall, and forest floor sampling were randomly selected within the subplots. Due to limited winter access, for over winter sampling three sets of incubating samples were placed in each subplot in late October 1992. Replicate bags were removed in mid January, mid February, and late April. The monthly schedule was resumed in late April. Nitrogen mineralization and nitrification rates in each vegetation type were estimated using the buried polyethylene bag technique (Eno, 1960). After pulling back the surface organic layer, the upper 10 cm of soil was collected with a 5 cm diameter soil corer. Three paired cores were taken in each subplot. One sample, representing a nonincubated sample, was placed in a Whirl Pac, brought to the field laboratory, and stored at 2°C. The other was placed in a 0.025-mm thick polyethylene bag and returned to the same hole for incubation. The original surface organic matter was then replaced. After about 30 d, the incubated sample was collected, returned to the field laboratory, and stored at 2°C.

Following collection, all soil samples were refrigerated for no more than 3 to 4 d. This allowed time for completion of sample collection. Percent moisture was determined by oven drying (105°C for 24 to 30 h) a subsample. The ratio of air-dried moisture to oven-dried moisture was determined gravimetrically. A larger subsample was then separated in a 2-mm sieve. The >2-mm fraction was weighed, and discarded. The <2-mm material was then weighed and divided into two samples. One provided the subsample extracted for NO₃⁻ and NH₄⁺ using 2M KCL. The other was frozen for total N determination.

In mid July 1992, three replicated samples from each subplot were collected for laboratory incubations at 10, 15 and 20 °C (27 samples at each temperature). The incubations were conducted from July 17, to Sept. 3, in Percival growth chambers operating at 75% relative humidity with 16 h of light daily, located at Michigan Technological Univ. Mid July samples were picked because the influence of N release due to snowmelt was gone, optimal field soil moisture conditions existed, and the samples would be representative of soil conditions at the midpoint of the growing season before leaf abscission (late August). We did not determine possible response to moisture change or gross mineralization rates.

Laboratory Analyses of Soil Samples

Nitrate (cadmium reduction) and ammonium (indophenol) were determined on 5 g soil subsamples extracted with 50 ml of 2M KCl by Lachat autoanalyzer. The net mineralization rate for each incubation period was estimated from the difference between initial and final NO₃⁻ and NH₄⁺ content, and net apparent nitrification was estimated by the difference between initial and final NO₃⁻ content. Total N was determined using Kjeldahl digestions.

Stream and Precipitation Samples

The Wallace Lake watershed hydrology and chemical input/output has been monitored since 1982. The watershed is gauged with a Parshall flume. Stage height is determined with a Stevens pressure transducer connected to a LiCor Model 1000 datalogger. A fully instrumented meteorological station is present where both the quality (NADP station and bulk collector) and quantity of precipitation are measured. Snowpack quality and quantity is determined several times during winter.

Details of the procedures used in precipitation, snowpack, and streamwater sampling and laboratory analyses are presented elsewhere (Stottlemeyer and Hanson, 1989; Stottlemeyer and Rutkowski, 1990; Stottlemeyer and Toczydlowski, 1991). The NADP collector at Wallace Lake can not be operated year round. Adjacent the NADP station are bulk collectors sampled throughout the year since 1982. For the last eight years we have operated a bulk collector immediately adjacent our other NADP station at Michigan Technological Univ. (station MI99, Chassell), in operation throughout the year also since 1982. Samples from both stations are analyzed in our laboratory. Comparison of precipitation concentration between the two university stations shows no significant difference for NH₄⁺, H⁺, or K⁺. For NO₃⁻, the bulk collector has shown a consistent 16% positive bias in concentration. Our estimates of ion concentration and loading for the bulk collector at Wallace Lake assume a similar bias

RESULTS AND DISCUSSION

Ecosystem Input and Retention of Nitrogen

During the last 10 y, annual precipitation amount and ion input have declined at Wallace Lake, but the trend was not significant (Table 1). However, annual precipitation amount has significantly declined since the mid 1980's. Since 1982, there were significant declines in the concentration of NO_3^- ($p < 0.05$, $n = 10$, $R^2 = 0.41$) and H^+ ($p < 0.05$, $n = 10$, $R^2 = 0.56$). Estimates of nitrogen species loading at Wallace Lake are consistent with the findings of the NADP (1991). Total annual N inputs, including aerosol deposition, to the Wallace Lake watershed average 6 Kg ha^{-1} (Stottlemeyer, 1992). About 20% of this is inorganic NO_3^- , 45% as NH_4^+ , and the remainder from "dry deposition" as calculated from data at the NPS ambient air quality station on Mt. Ojibway. Wet precipitation N inputs now commonly exceed sulfur on an equivalent basis. In the early 1980's, sulfur exceeded N.

Annual inputs would, at first glance, appear small relative to annual internal cycling. However, it must be recognized that this is a sustained input. In this region, up to 40% of this input may be released in snowmelt (Stottlemeyer and Rutkowski, 1990). At Wallace Lake, the mean late winter (mid-March) snow water equivalent (SWE) averages 12.8 (6.0) cm. Its average pH is 4.72 (s.d. = 0.1), and H^+ , NO_3^- , NH_4^+ and SO_4^{2-} loads are 24.3, 29 and 16.4 Eq ha^{-1} respectively. For NO_3^- , the peak snowpack load is about 20% of annual inputs, and for NH_4^+ 15%. Also, it is not uncommon to have significant late spring inputs from rainfall. Together, these inputs result in a high seasonal availability of inorganic nitrogen. Late spring is also the time of maximum ecosystem incorporation of N which means improved opportunities for atmospheric N inputs to be directly incorporated by vascular plants. With a diversity of plant ability to take advantage of seasonal N inputs, the result could be changes in biodiversity both above and below ground.

In canopy throughfall, the annual concentration of NO_3^- is reduced about 40% beneath both hardwoods and conifers relative to precipitation (Table 2; Stottlemeyer and Hanson, 1989). NH_4^+ concentration is little changed beneath hardwoods, but increases beneath conifers. Annual NO_3^- flux in throughfall beneath both spruce and hardwood canopies, however, is reduced about 60% relative to precipitation inputs. Annual inorganic N flux in surface mineral soils nearly ceases by the Bsl or Bhs horizons. Ecosystem retention of NO_3^- is $>90\%$ and NH_4^+ $>95\%$ (Table 1). In excess of two thirds of the inorganic N lost annually occurs just prior to and during snowmelt.

Soil Moisture and Temperature

Among sample plots, there were significant differences ($p < 0.005$, Table 3) in soil moisture by season. Alder moisture levels were higher ($p = 0.001$) than beneath spruce and birch. The higher surface soil moisture content observed from mid-May through June reflected snowmelt inputs which occur up through early May (Stottlemeyer and Toczydlowski, 1991), increased seasonal rain input, and reduced evapotranspiration due to the absence of leaves which just begin to appear in the understory by mid May. Beneath alder, soils were saturated to within 5 cm of the surface at this time. Moisture levels increased again in fall reflecting reduced evapotranspiration. The most uniform moisture content was among spruce plots while birch was the most variable. Birch is characterized by high variation in spatial distribution of understory biomass (Rutkowski and Stottlemeyer, 1993), and its canopy is quite patchy. While the plots monitored are apparently in reasonable health, overall this species is in decline within the park (T. Sharik, R. Stottlemeyer, School of Forestry, Michigan Technological Univ., Houghton, MI 49931, pers. observation) and likely the region (Jones et al., 1993).

Mean air and inorganic soil (@5 cm depth) temperatures for most of the sampling period (Fig. 1) showed no significant differences among vegetation types. Significant differences did exist at 10 cm above the forest floor, in forest litter layers, and at deeper soil horizons (@10 cm). The maximum air temperature beneath birch (20.3°C), spruce (19.1°C), and alder (19.2°C) occurred August 23. Peak soil temperatures (birch = 14.0°C , spruce = 13.5°C , alder = 13.4°C) occurred July 25, August 24, and August 24 respectively. Early in the study soil temperatures in spruce were lower than those beneath birch or alder (Fig. 1, Table 4), and considerably lower in spring of 1993. Overall, mean air temperature was highest beneath birch especially near the beginning and end of the growing season. This resulted in the highest mean temperatures just above and especially within the forest litter layers. Beneath birch the temperature of the forest floor was always higher than that just above or at 1 m above the forest floor. Beneath alder this condition was observed only late in the season when the leaves were beginning to thin.

Variance in soil mineral N concentration among vegetation types and incubation periods was significantly greater than within these respective groupings (Bartlett's test for homogeneity of variance). Therefore, comparisons of means were made using parametric tests. Initial soil NO_3^- N concentrations did not vary significantly with time (Fig. 2), but did with vegetation ($p < 0.05$) being significantly higher beneath alder ($11.6 \text{ mg N kg}^{-1}$). Average soil NO_3^- N concentrations beneath spruce and birch were 1.1 and 0.9 mg N kg^{-1} respectively. Soil NH_4^+ concentrations decreased with time ($p = 0.07$), but did not differ among vegetation types. Average soil NH_4^+ N concentrations were 5.4 , 6.8 , and 8.1 mg N kg^{-1} for birch, spruce and alder respectively. Except for alder, these mineral N values are about half those for hardwood forests and plantations in the southern Great Lakes region (Gower and Son, 1992; Nadelhoffer et al., 1983). Relative to nitrogen pools, mineral N in forest soils was highest early in the season. Spruce had the highest value in June-July (3.7%) while alder was lowest (0.9%). Likely these trends are, in part, due to the mineral N contributions from a melting snowpack, reduced winter uptake, and late thawing of soils beneath spruce. Initial mineral soil N concentrations increased with soil temperature ($p = 0.10$).

Net N mineralization rates varied considerably among and within species over the year (Fig. 2). Overall, there was a significant decline in net monthly mineralization during the study ($p < 0.05$). This was even more pronounced during the growing season ($p < 0.01$). This was due primarily to declines in alder ($p < 0.01$) and birch ($p < 0.02$). Blocking field net mineralization by incubation period showed a significant difference in net mineralization by period ($p < 0.01$, $r^2 = 0.35$) and species ($p = 0.05$). Annual net mineralization was 35 , 38 , and 84 kg N ha^{-1} for birch, spruce, and alder respectively. The differences were significant among species ($p < 0.001$). These *in situ* values are high relative to plantation studies in the lower Great Lakes region (Gower and Son, 1992), and somewhat exceed annual results from other sites on Isle Royale (Pastor et al., 1993).

During the growing season (May - Sept.) net mineralization was inversely related to soil temperature at the 5 cm ($p < 0.10$) and 10 cm depths ($p < 0.01$). By species, this relationship was most pronounced in spruce ($p < 0.06$, $r^2 = 0.33$) and alder ($p < 0.10$, $r^2 = 0.26$). This likely resulted from higher soil microbial uptake (immobilization) relative to nitrification increases with warmer soil temperatures (Binkley et al. 1994, in press). Increased vascular plant uptake during the growing season is also a factor, but the buried bag incubation method would not detect much of that within a given incubation period.

Field studies showed no significant relationship between net mineralization, net nitrification, initial mineral N concentrations and soil moisture. There was a positive ($p < 0.01$) relationship between initial NO_3^- concentrations and soil moisture, and an inverse relationship ($p < 0.001$) between initial soil NH_4^+ concentrations and soil moisture. These opposing trends with increased moisture likely help account for the lack of relationship between net mineralization and soil moisture. There was no significant interaction between soil temperature, soil moisture and net mineralization, net nitrification, or initial NO_3^- concentrations.

Controlled laboratory incubations at three temperatures (10 , 15 and 20°C) gave somewhat different results. For all species combined there was a significant ($p < 0.03$) gain in mineralization rates over a temperature range of 10° to 20°C . Primarily, this was the result of gains in nitrification ($p < 0.001$). But on a species basis, only alder showed a significant response to temperature ($p < 0.05$).

Using the laboratory relationship between gain in net N mineralization with temperature and global change scenarios, some of which suggest a change of about $2\text{--}5^\circ \text{C}$ at these latitudes, a gain in surface soil temperatures of this order could result in an increase of about $5 \text{ kg ha}^{-1} \text{ mo}^{-1}$ available nitrogen, an order of magnitude greater than average monthly atmospheric N inputs. Based upon soil temperature data collected to date (Fig. 1), on average surface mineral soil temperatures are $10\text{--}15^\circ \text{C}$ for about four months a year which could increase available mineral N $> 20 \text{ kg ha}^{-1} \text{ y}^{-1}$ or almost 3% of soil N reservoirs. The fate of this increased mineral N is not known, but based upon the field net mineralization rates during summer most would likely remain in soil reservoirs temporarily absorbed by soil microbes. There is some evidence that soil microbial immobilization rates respond more to temperature changes in this range than do mineralization rates (Binkley et al. 1994, in press).

All methods used to assess N mineralization are but indices (Binkley and Hart, 1989). Laboratory conditions represent the ideal where moisture and temperature levels can be kept constant likely resulting in mineralization values greater than actually occur in the field. Also, vascular plant uptake, very significant during much of the growing season, is mostly removed as is any leaching to lower mineral soil horizons. Conversely, net mineralization change over one incubation period does not show the change in gross mineralization rates which over time could affect net mineralization rates as gains in soil microbial biomass come into equilibrium.

The longer-term effects of moose herbivory on plant community composition and soil conditions has been the subject of much study on Isle Royale (Brandner et al., 1990; Pastor et al., 1993; Risenhoover and Maass, 1987; Snyder and Janke, 1976). The potential gain in summer N mineralization in response to modest gains in soil temperature meets or exceeds change in annual mineralization rates as a result of the long-term effects of moose herbivory (Pastor et al., 1993). The latter study was conducted on three exclosures, established in 1947, with controls. These plots had biomass levels about 50% greater than observed in the Wallace Lake watershed and throughout much of the boreal forest of the northern third of Isle Royale (McInnes et al., 1992; Rutkowski and Stottlemeyer, 1993; Toczydlowski et al., 1993). They are located in low elevation sites and appear more productive than much of the northern third of the park. The one cluster of exclosure and control sites in the region of Wallace Lake had biomass levels closest to those of the Wallace Lake watershed and showed no significant differences in N mineralization rates due to herbivory.

These annual estimates of nitrification and net mineralization permit us to compare the potential importance of shifts in climate on the nitrogen cycle to mineralization of nitrogen from other processes. For southern boreal forests on Isle Royale, annual net mineralization rates are about 4 - 10 times annual precipitation inputs (Pastor et al., 1993; Stottlemeyer, 1992; Stottlemeyer and Toczydlowski, 1991). Due to the apparent long-term effect of sustained herbivory on vegetation, litter, and soil quality, the effects of moose on more productive sites appear to have decreased soil N mineralization rates about $20 \text{ kg ha}^{-1} \text{ y}^{-1}$, but on less productive sites, as at Wallace Lake, only about $1 - 1.5 \text{ kg ha}^{-1} \text{ y}^{-1}$ (Pastor et al., 1993). Direct annual N removal by moose herbivory appears much smaller than precipitation. On average, moose remove from $0.1 - 25 \text{ kg ha}^{-1} \text{ y}^{-1}$ of biomass with an average N content of $<1\%$ (McInnes et al., 1992; Risenhoover and Maass, 1987). Tree blowdown, which was intensively studied on transects with a combined area $> 6 \text{ ha}$ during 1989 - 1991, contributed $6 - 9 \text{ kg N ha}^{-1} \text{ y}^{-1}$ in this section of the park (Toczydlowski et al., 1993). Annual litterfall, measured at replicated plots under major species since 1984, contains about 50 Kg N ha^{-1} (Rutkowski and Stottlemeyer, 1993). In mature forested ecosystems, such as in the Wallace Lake vicinity, annual litterfall and throughfall provide some reasonable index of annual uptake. Potential mineralization due to insects has not been quantified, but likely is significant in view of the current level of spruce dieback due to the bark beetle.

In conclusion, regions dominated by northern forests contain $>20\%$ of the globe's stored carbon. Any factor affecting the potential mineralization rates of this reservoir could have major ramifications on global carbon cycles. Change in ecosystem C is quite sensitive to available inorganic nitrogen. Boreal forests have a large proportion of their N reservoir in shallow mineral soils. This study suggests that very modest changes in soil temperature during the summer months could significantly increase the level of ecosystem mineral N. Temperature change appears potentially the most important factor which could increase available N in the future. A comparison of net mineralization rates in the field to laboratory results suggests that, at least initially, most of this increase in available N would be taken up by soil microbes and secondly vascular plants. The early effects of an increased temperature on these ecosystems would appear to be on the biomass and diversity of soil microbes, shrubs, and any tree species which can take advantage of the increase in mineral N. Trends over the last decade in watershed ecosystem input/output ratios and surface water chemistry, ionic flux in soil solution, and far less precise indicators as a comparison of mineral N concentration in lake or stream water relative to that in precipitation, do not indicate these ecosystems are approaching N saturation at present.

1994 PLANNED RESEARCH

First, the 1993 results clearly show the need to complete the ^{15}N tracer study to quantify gross N mineralization for the four vegetation types over a range of perhaps three temperatures. This will be done in the laboratory using the basic approach developed by Nadelhoffer and refined by others.

Second, it does appear that the influence of herbivory on N mineralization at Isle Royale is significant for the more productive sites, but not much of the boreal sites. This justifies some replication of our past research on Passage Island where there is excellent examples of boreal forest by no herbivory by moose. This is something we proposed about ten years ago, but funding and context were not available. This will be a relatively minor effort, and will likely confirm what we are finding at Wallace Lake. Herbivory is not that major a factor in N mineralization in boreal forests which has also been the finding for interior Alaskan sites as the Bonanza Creek Experimental Forest.

Third, more model applications and especially field studies indicate that changes in CO₂ will have very minor effects on ecosystem carbon pools relative to the changes in the carbon pool which will result from increasing the availability of mineral N. As proposed in the original six year research plan, we need now to spend most of the effort on linking ecosystem response to increased mineral N to change in the carbon pool. This will be our primary emphasis this summer to the extend budget limitations permit. This will entail more sampling of the carbon pool size, soil gas emissions following small plot (1 m²) and/or laboratory fertilization, and likely on those plots we have increased the temperature. Any interaction studies (soil w/ and w/o carbon pool variation, temperature, nutrients, perhaps moisture) will first be conducted in the laboratory before possibly replicating in the field. Most field interaction studies would not be conducted until next field season.

1993 PRESENTATION OF RESULTS

These references include presentation of data directly obtained from the 1993 research, and closely related studies.

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LIST OF FIGURES

Fig. 1. Mean daily temperature ($^{\circ}\text{C}$) of air, litter, and mineral soil at 5 cm depth beneath birch, spruce, alder, May 1992 - June 1993.

Fig. 2. Mean monthly initial soil (top 10 cm) NO_3^- and NH_4^+ concentration, net nitrification, and net mineralization beneath birch, spruce, and alder, Isle Royale, Michigan. Each bar represents the mean of nine samples.

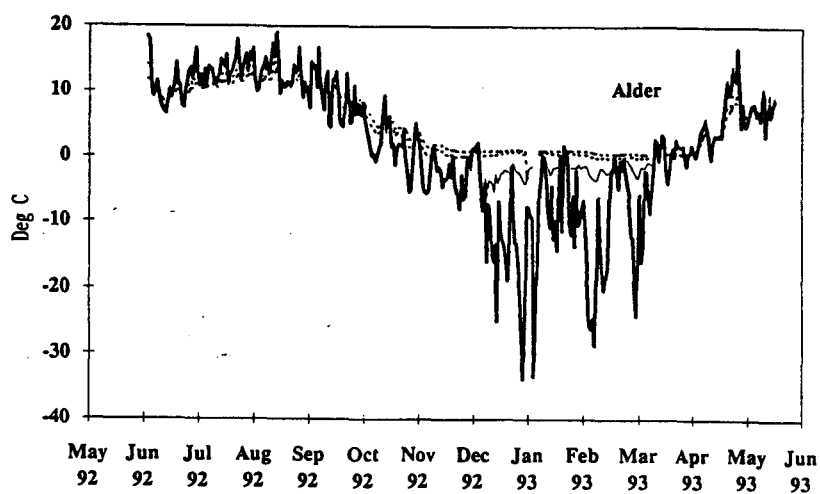
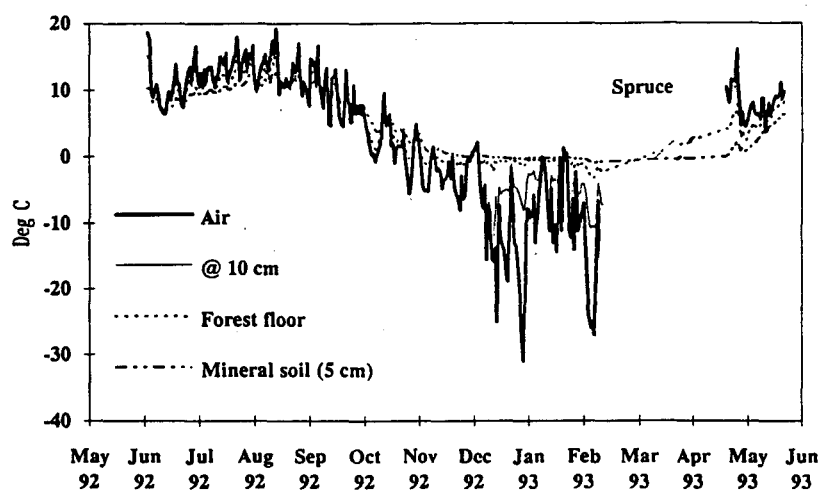
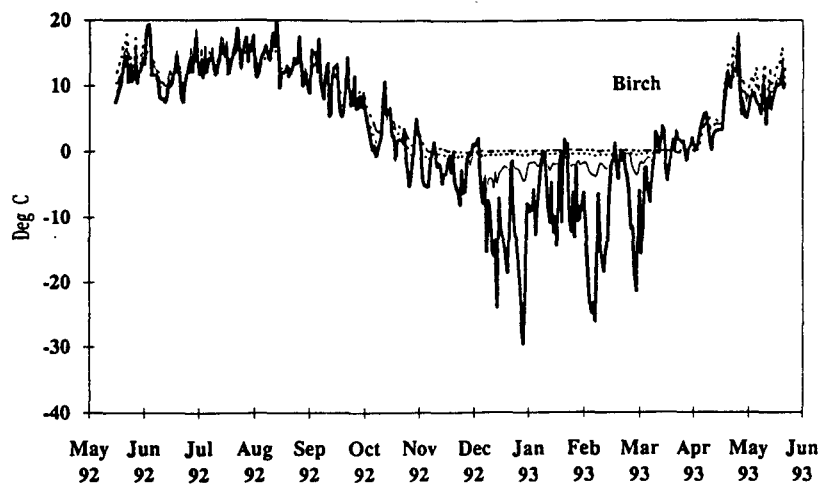


Fig 1.

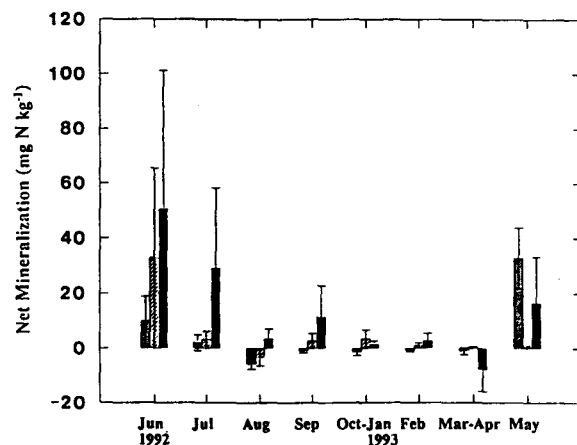
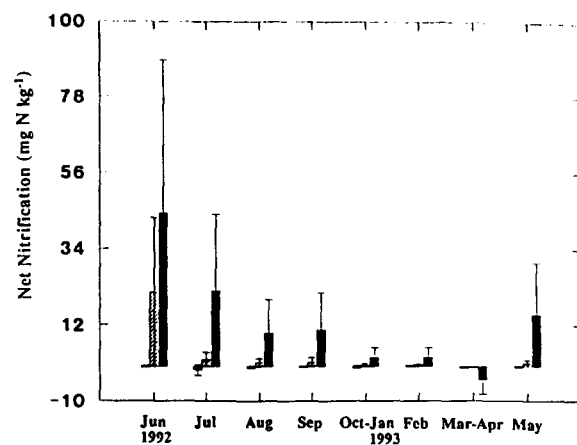
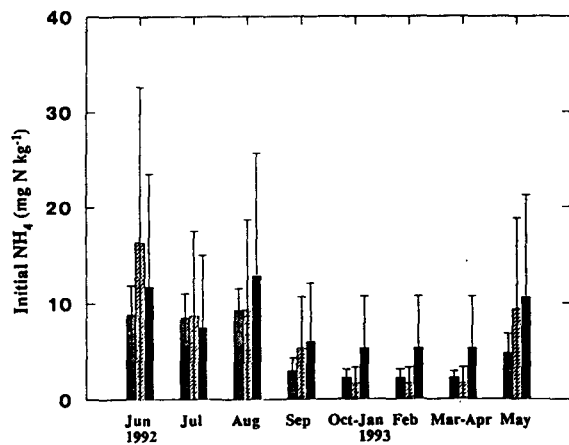
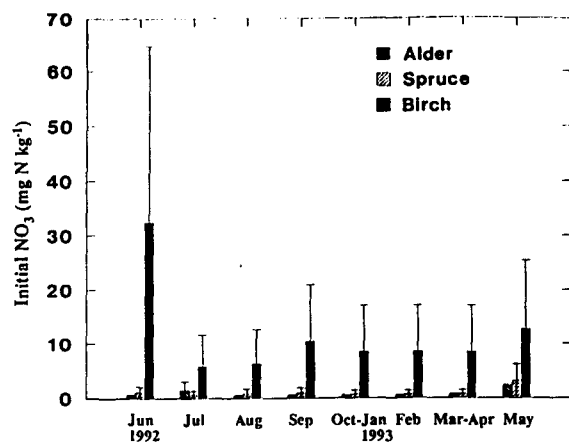


Fig. 2.

Table 1. Annual NO_3^- and NH_4^+ input¹ and output for 1983-1992, Wallace Lake watershed, Michigan.

Year	Input Output (cm)	NO_3^- (kg ha ⁻¹)	NH_4^+ (kg ha ⁻¹)
83	59	9.5 0.7	2.2 0.1
84	74	11.5 1.1	2.5 0.1
85	62	6.9 0.8	1.8 0.1
86	43	6.1 0.9	1.4 0.1
87	70	10.4 0.9	1.6 0.1
88	45	5.9 0.6	1.0 <0.1
89	64	9.1 1.2	2.0 0.1
90	52	7.1 0.9	2.1 0.1
91	90	11.7 0.9	2.8 0.1
92	63	9.7 1.0	1.9 <0.1

1. Input from NADP station MI99, Chassell, MI, and Wallace Lake bulk collector. Input and output in kg ha⁻¹.

Table 2. Estimated annual flux (km ha^{-1}) for selected ions in precipitation, forest canopy and mineral soil, Wallace Lake watershed, Isle Royale National Park, MI. Modified from Stottlemeyer and Hanson, 1989.

Stratum ¹	Water	H ⁺	SO ₄ ²⁻ Spruce	NO ₃ ⁻	NH ₄ ⁺
ppt	75	0.15	0.18	0.12	0.15
TF	66	0.01	0.18	0.03	0.12
B	45	0.006	0.25	0.04	0.12
E	45	0.003	0.36	0.01	0.01
Aspen-birch					
TF	61	0.04	0.18	0.05	0.18
B	45	<0.01	0.19	0.02	0.02
E	45	<0.01	0.20	<0.01	<0.01
Alder					
TF	63	0.01	0.12	0.48	0.18
B	45	0.003	0.16	0.76	0.03
E	45	0.003	0.12	0.25	0.01

¹ ppt = precipitation, TF = canopy throughfall, B and E = soil horizons.

Table 3. Mean soil moisture during nitrogen incubations beneath forest stands 1992-1993.

Period	Species	0-10 cm depth ¹
June '92	Birch	41
	Spruce	30
	Alder	55
July '92	Birch	36
	Spruce	31
	Alder	52
Aug. '92	Birch	25
	Spruce	27
	Alder	38
Sept. '92	Birch	27
	Spruce	25
	Alder	45
Oct. '92-Jan. '93	Birch	41
	Spruce	36
	Alder	49
Oct. '92-Feb. '93	Birch	34
	Spruce	28
	Alder	50
Oct. '92-Apr. '93	Birch	21
	Spruce	28
	Alder	45
May '93	Birch	35
	Spruce	33
	Alder	50

1. Moisture is % by weight determined gravimetrically.

Table 4. Mean mineral soil temperature for nitrogen incubations beneath forest stands 1992-1993.

Period	Species	0-10 cm depth (° C)
June '92	Birch	11.0
	Spruce	8.1
	Alder	9.4
July '92	Birch	12.7
	Spruce	10.6
	Alder	11.1
Aug. '92	Birch	12.3
	Spruce	11.2
	Alder	11.6
Sept. '92	Birch	10.2
	Spruce	8.6
	Alder	9.5
Oct. '92-Jan. '93	Birch	1.4
	Spruce	2.5
	Alder	2.6
Oct. '92-Feb. '93	Birch	0.3
	Spruce	-0.4
	Alder	1.3
Oct. '92-Apr. '93	Birch	0.6
	Spruce	-0.8
	Alder	1.1
May '93	Birch	9.2
	Spruce	2.8
	Alder	6.9

Table 5. Mineral soil characteristics by plot and vegetation type¹ beneath birch, spruce, and alder plots. Soils were composites of the top 10 cm, and analyses are for sample which passed through 2 mm sieve. Standard deviation in parentheses.

Plot	Stand	Nitrogen (%)	Nitrogen (kg ha ⁻¹)
1	birch	.19(.07)	504
2	birch	.21(.09)	627
3	birch	.25(.07)	457
4	spruce	.22(.10)	749
5	spruce	.17(.06)	571
6	spruce	.13(.06)	399
7	alder	.45(.28)	1127
8	alder	.83(.40)	1133
9	alder	.44(.11)	1015
Vegetation Type			
Birch		.22(.07)	492(257)
Spruce		.17(.07)	564(283)
Alder		.54(.33)	1153(498)

¹ For each vegetation type, n = 36.

1994 BUDGET

The 1994 budget breakdown will be very similar to that submitted with the original six year proposal. Due to rapid increases in labor costs, the original budget for two technicians now only covers one especially with the elevated fringe benefit costs (38% of wages).