# AN ANALYSIS OF NITROGEN DYNAMICS IN THE LYE BROOK WILDERNESS AREA, VERMONT, USA

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**Abstract.** Nitrogen (N) deposition and its impact on terrestrial and aquatic ecosystems is a concern facing federal land managers at the Lye Brook Wilderness in Vermont and other protected areas throughout the northeastern United States. In this study, we compared N production in soils with N concentrations and outputs in leachates to determine how forest cover types differ in regulating N losses. Also, precipitation inputs and streamwater outputs, were used to calculate a watershed N budget. Most ammonium and nitrate were produced in organic soils with deciduous cover. Softwood stands were more N-limited, with low nitrification rates and minimal N leaching. A comparison of watershed inputs and outputs showed a net gain in total dissolved N ($4.8 \, kg \, ha^{-1} \, yr^{-1}$) due to an accumulation of dissolved inorganic N. The Lye Brook Wilderness ecosystem has N budgets similar to other forested ecosystems in the region, and appears to be assimilating the accumulating N, but seasonal losses of nitrate observed in mineral soils and streamwater may be early warnings of the initial stages of N saturation.

**Keywords:** nitrogen budget, nitrification, nitrogen, nitrogen mineralization, wilderness area

## 1. Introduction

High inputs of nitrogen (N) have raised concerns about N saturation in forests of the northeastern United States. Throughout the region, undisturbed forests are typically N-limited and some forests have a tremendous capacity to retain additional N in biomass and soils (Aber *et al.*, 1995). Other forested ecosystems are more limited in this capacity and may reach a point where N inputs exceed the biological demand for N (Kahl *et al.*, 1993; Norton *et al.*, 1994; Gilliam *et al.*, 1996). Forests that are exposed to elevated N additions may exhibit several characteristic responses, including plant nutrient imbalances (Schulze, 1989; Aber *et al.*, 1995; Cronan and Grigal, 1995), cation depletion (Reuss and Johnson, 1986), and acidification and eutrophication of streamwater due to additions and production of $NO_3$-N (Henriksen *et al.*, 1992; Stoddard, 1994).

Fenn *et al.* (1998) summarized forest management practices aimed at ameliorating the effects of high N deposition. These strategies include removing N in biomass through harvesting or burning, altering stand composition to reduce N-fixing species, and enhancing denitrification through riparian zone management. These options may be effective in forests that are intensely managed, but in some protected areas such activities are not permitted. In this

study we investigate issues surrounding N saturation in the Lye Brook Wilderness (LBW) in southeastern Vermont. The wilderness designation poses a challenge to land managers; it charges them with preserving the wilderness characteristics of the site, such as water quality, vegetation and soils, but eliminates the aforementioned options for removing N from the ecosystem.

The only option available to wilderness area managers that protects forests from increases in N deposition is limiting emissions of N. This is accomplished through a permitting process pursuant to the Clean Air Act Amendments of 1977. This process requires permits for new sources of pollution or modifications of existing sources that may have an impact on wilderness areas such as the LBW. In order to evaluate permit applications, it is necessary to assess of effects of N deposition, and to estimate the sensitivity of ecosystems to deposition changes (Adams *et al.*, 1993). The purpose of this paper is to determine the N status of the LBW by examining N production and retention at the forest stand and watershed scale. This analysis is used to determine whether the ecosystem is accumulating N and to gain insight as to the potential for N saturation. The analysis, which relies on a relatively low level of field data collection, also serves as an example for examining N cycling in other protected areas.

## 2. Methods

### 2.1. SITE DESCRIPTION

The 6,280-ha LBW is located within the boundary of the Green Mountain National Forest in southwestern Vermont. Combined wet and dry deposition of N is approximately 9 to 11 kg ha$^{-1}$ yr$^{-1}$ (Ollinger *et al.*, 1995), annual precipitation in the region averages 1150 mm, and the mean annual temperature is 7 °C. A 130-ha watershed (43°07'N, 73°02'W), draining a perennial, first-order stream, was chosen to investigate N cycling within the wilderness. The watershed ranges in elevation from 725 to 850 m and has an average of slope of 7%. Underlying bedrock is of the Mount Holly Complex and Mendon Formation composed primarily of quartzite, schist, amphibolite and gneiss. Soils consist of Typic Humaquepts, Epiaquads, and Haplorthods that have formed in compact, loamy, glacial till. Most of the watershed was logged between 1915 and 1920, resulting in an even-aged forest with a species composition of 51% hardwood, 29% softwood and 20% mixed hardwood and softwood. Conifer species consist almost entirely of red spruce (*Picea rubens*) and balsam fir (*Abies balsamea*) and deciduous species include sugar maple (*Acer saccharum*), red maple (*Acer rubrum*), paper birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*), and American beech (*Fagus grandifolia*).

## 2.2. ECOSYSTEM PRODUCTION OF N

Net mineralization and nitrification rates were measured by in situ incubation in buried bags from June 1994 through October 1995. Details from the method are given in Eno (1960) and Federer (1983). Buried bags were located at three soil pits at each of 3 sites consisting of softwood, mixed hardwood and softwood, and hardwood cover types. The sites were located 100 to 250 m apart and were approximately 1.2 km southeast of the watershed boundary in stands that were representative of the watershed. Soil bags were incubated at 28-day intervals from about May through November, and were left in the ground from about December through April to measure rates of N mineralization and nitrification during winter.

N mineralization and nitrification rates were converted from units of mass ($\mu$gN g soil$^{-1}$) to an areal basis (kg N ha$^{-1}$) using bulk density, horizon thickness, and percent rock fraction. Soil bulk density was estimated from the organic matter fraction based on the inverse relationship found in forest soils of New England (Federer *et al.*, 1993). Because the percent rock fraction was not measured, ranges for N mineralization and nitrification were calculated based on rock fractions of 0 to 30%. N mineralization and nitrification rates were weighted for the entire watershed by multiplying the rate at each site times the percent hardwood (51%), softwood (29%) and mixed (20%) cover types for the watershed.

## 2.3. WATER SAMPLES

Streamwater sampling was conducted bi-weekly from May 26, 1994 to August 30, 1995 and every three weeks from May 15 to October 18, 1996. In November 1994, three tension lysimeters were installed at each of the three sites where N mineralization and nitrification rates were measured. Soil water samples were collected bi-weekly from June 6 to October 4, 1995 and every three weeks from May 15 to October 18, 1996. Measurements of ammonium ($NH_4$-N) and nitrate ($NO_3$-N) in soil water and streamwater were made using continuous flow colorimetry. Total dissolved nitrogen (TDN) was measured using an Antek N detector and dissolved organic nitrogen (DON) was calculated by subtracting dissolved inorganic nitrogen (DIN: $NH_4$-N + $NO_3$-N) from TDN (Merriam *et al.*, 1996).

To calculate stream and soil water fluxes, estimates of hydrologic fluxes were made using the Brook90 model (Federer, 1998). Brook90 simulates water movement through multiple soil layers, making it possible to approximate the flux of soil water from different horizons, in addition to streamwater. Brook90 was run on a daily timestep using daily precipitation and minimum and maximum temperatures collected at the closest National Weather Service station in Dorset, Vermont, approximately 10 km from the sampling area at an elevation of 284 m.

Solute fluxes were calculated by multiplying the stream or soil water concentration (mg L$^{-1}$) for each sampling date by the daily water flux (L ha$^{-1}$ day$^{-1}$) surrounding each chemical sample. Lysimeter samples were not collected during the winter months; therefore soil water flux for this period was based on concentrations from the last sample collected in the fall to the first sample collected in the spring. Relatively few lysimeter samples were collected from the Oa horizon of the hardwood stand because the organic soil at this site was nearly always too dry to extract a sample. Therefore, the watershed flux calculation for the Oa horizon only includes data from the mixed and softwood sites.

Inputs of NH$_4$-N and NO$_3$-N were calculated using chemical data collected at the Bennington, Vermont NADP/NTN station located approximately 50 km south of the site. Since NADP/NTN data do include organic N measurements, concentrations of DON in precipitation were obtained from the Hubbard Brook Experimental Forest in New Hampshire.

## 3. Results

### 3.1. N MINERALIZATION AND NITRIFICATION

Most N mineralization and nitrification occurred in the Oa or organic soil horizons at all sites and very low rates were measured in B or mineral soil horizons (Figure 1). Average annual N mineralization in the Oa horizon was highest at the hardwood site (1.64 $\mu$N g soil$^{-1}$ day$^{-1}$), followed by the mixed site (1.43 $\mu$N g soil$^{-1}$ day$^{-1}$) and the softwood site (0.09 $\mu$gN g soil$^{-1}$ day$^{-1}$). Nitrification in the Oa horizon followed a similar pattern with highest average annual rates occurring at the hardwood site (1.17 $\mu$gN g soil$^{-1}$ day$^{-1}$), lower rates occurring at the mixed site (0.64 $\mu$gN g soil$^{-1}$ day$^{-1}$), and rates close to zero at the softwood site (<0.01 $\mu$gN g soil$^{-1}$ day$^{-1}$).

Seasonal patterns for N mineralization and nitrification were observed at all sites in organic soils (Figure 1). At the hardwood and mixed sites, rates were higher from about March through October and were lower during the rest of the year. The softwood site had higher N mineralization in the Oa horizon during June and July and had rates that were less than zero during August through October, indicating that immobilization occurred during this time. Nitrification rates in the Oa horizon of the softwood site were low throughout the year and did not exhibit strong seasonal effects.

### 3.2. SOIL WATER AND STREAMWATER CHEMISTRY

Mean annual chemistry of soil water in the Oa and B horizon at the softwood, mixed, and hardwood sites is presented in Table I. Soil water concentrations of NH$_4$-N were similar at all sites, but were 0.53 to 0.62 mg L$^{-1}$ higher in Oa

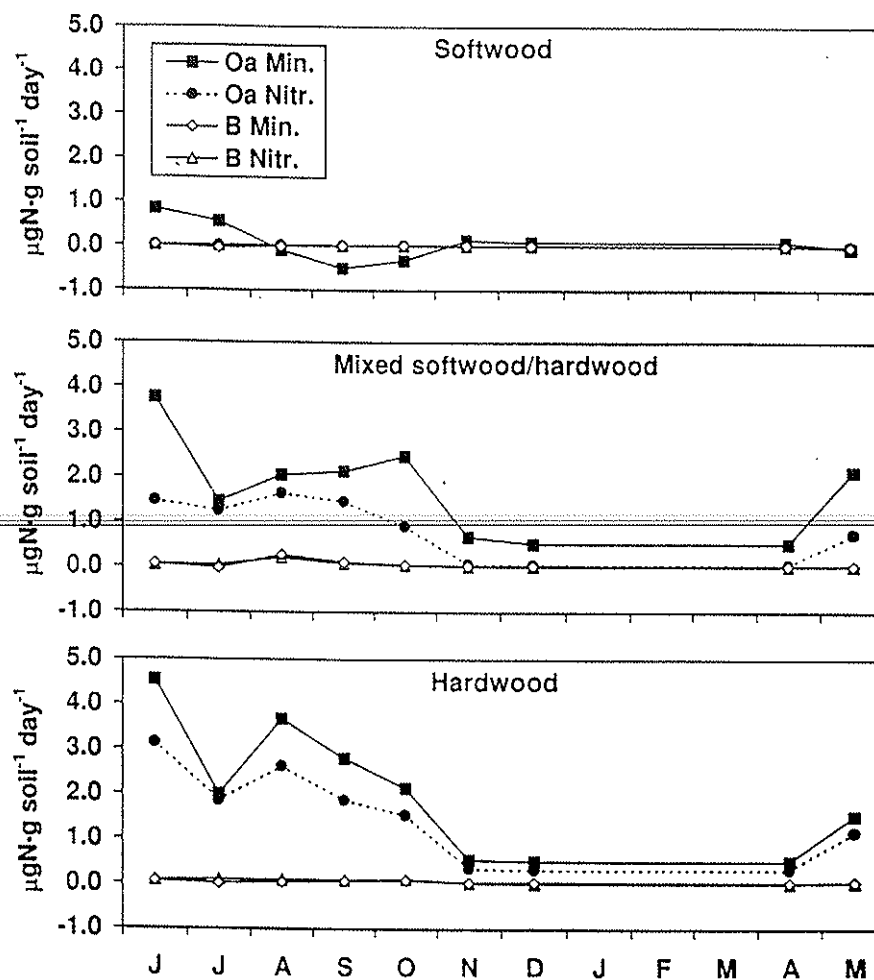*Figure 1.* Mean mineralization and nitrification rates. Sampling period is June, 1994 through May, 1995.

than in B horizons. Concentrations of $NO_3$-N in organic horizons were lowest at the softwood site (0.03 mg $L^{-1}$), intermediate at the hardwood (0.16 mg $L^{-1}$) site, and highest at the mixed site (0.27 mg $L^{-1}$). This same pattern for $NO_3$-N occurred in mineral soils, but concentrations were 0.13 to 0.51 mg $L^{-1}$ higher in the B than in the Oa horizons. Concentrations of DON in the Oa horizon were also highest at the mixed site (1.06 mg $L^{-1}$) with lower concentrations occurring at the softwood (0.59 mg $L^{-1}$) and hardwood site (0.25 mg $L^{-1}$). The DON value at the hardwood site is based on one sample.

Seasonal trends were evident for some of the measured solutes in soil water and streams (Figure 2). In soil solution from the Oa, $NH_4$-N, $NO_3$-N and DON were highest during the summer usually peaking in August. In

Table I. Average annual soil water concentrations (mg $L^{-1}$) of $NH_4$-N, $NO_3$-N and DON for softwood, mixed softwood and hardwood, and hardwood sites.

| | Oa Horizon | | | B Horizon | | |
|---|---|---|---|---|---|---|
| | $NH_4$-N | $NO_3$-N | DON | $NH_4$-N | $NO_3$-N | DON |
| Softwood | | | | | | |
| Mean | 0.67 | 0.03 | 0.59 | 0.05 | 0.16 | 0.25 |
| Std. Dev. | 0.22 | 0.04 | 0.28 | 0.03 | 0.06 | 0.05 |
| N | 26 | 26 | 13 | 41 | 41 | 19 |
| Mixed | | | | | | |
| Mean | 0.60 | 0.27 | 1.06 | 0.06 | 0.78 | 0.48 |
| Std. Dev. | 0.24 | 0.41 | 0.13 | 0.03 | 0.46 | 0.18 |
| N | 23 | 23 | 13 | 41 | 41 | 19 |
| Hardwood | | | | | | |
| Mean | 0.58 | 0.16 | 0.25 | 0.05 | 0.32 | 0.34 |
| Std. Dev. | 0.28 | 0.25 | — | 0.03 | 0.29 | 0.07 |
| N | 5 | 4 | 1 | 38 | 38 | 20 |

the B horizon, $NO_3$-N was lower from June through September while other measured solutes remained relatively constant throughout the year (Figure 2). In streamwater, the only form of N exhibiting a seasonal pattern was $NO_3$-N, which had low concentrations during the growing season, followed by an increase in winter, reaching the highest level in March (Figure 2).

### 3.3. NITROGEN BUDGETS

Annual N input in precipitation (7.3 kg $ha^{-1}$ $yr^{-1}$) was dominated by DIN, ~ *dissolved inorganic N* with $NO_3$-N (4.3 kg $ha^{-1}$ $yr^{-1}$) and $NH_4$-N (2.1 kg $ha^{-1}$ $yr^{-1}$) accounting for 88% of total inputs (Table II). In soils, production of $NH_4$-N by N mineralization was greatest in the Oa horizon (1.9-2.7 kg $ha^{-1}$ $yr^{-1}$). More $NO_3$-N was also produced in organic soils (1.2 to 1.6 kg $ha^{-1}$ $yr^{-1}$). Soil leachates draining the Oa horizon were dominated by $NH_4$-N (2.8 kg $ha^{-1}$ $yr^{-1}$) with lesser amounts of $NO_3$-N (0.7 kg $ha^{-1}$ $yr^{-1}$), but flux from the B horizon was dominated by $NO_3$-N (2.8 kg $ha^{-1}$ $yr^{-1}$) with lesser amounts of $NH_4$-N (0.4 kg $ha^{-1}$ $yr^{-1}$). Streamwater outputs of DIN were dominated by $NO_3$-N (0.6 kg $ha^{-1}$ $yr^{-1}$) and $NH_4$-N outputs were low (0.1 kg $ha^{-1}$ $yr^{-1}$). The greatest DON flux occurred from the Oa horizon (5.9 kg $ha^{-1}$ $yr^{-1}$) and decreased with depth, resulting in a lower streamwater flux (1.7 kg $ha^{-1}$ $yr^{-1}$). TDN values showed that for the period of the study, the watershed is accumulating N at a rate of 4.8 kg $ha^{-1}$ $yr^{-1}$, due exclusively to a net gain in DIN.
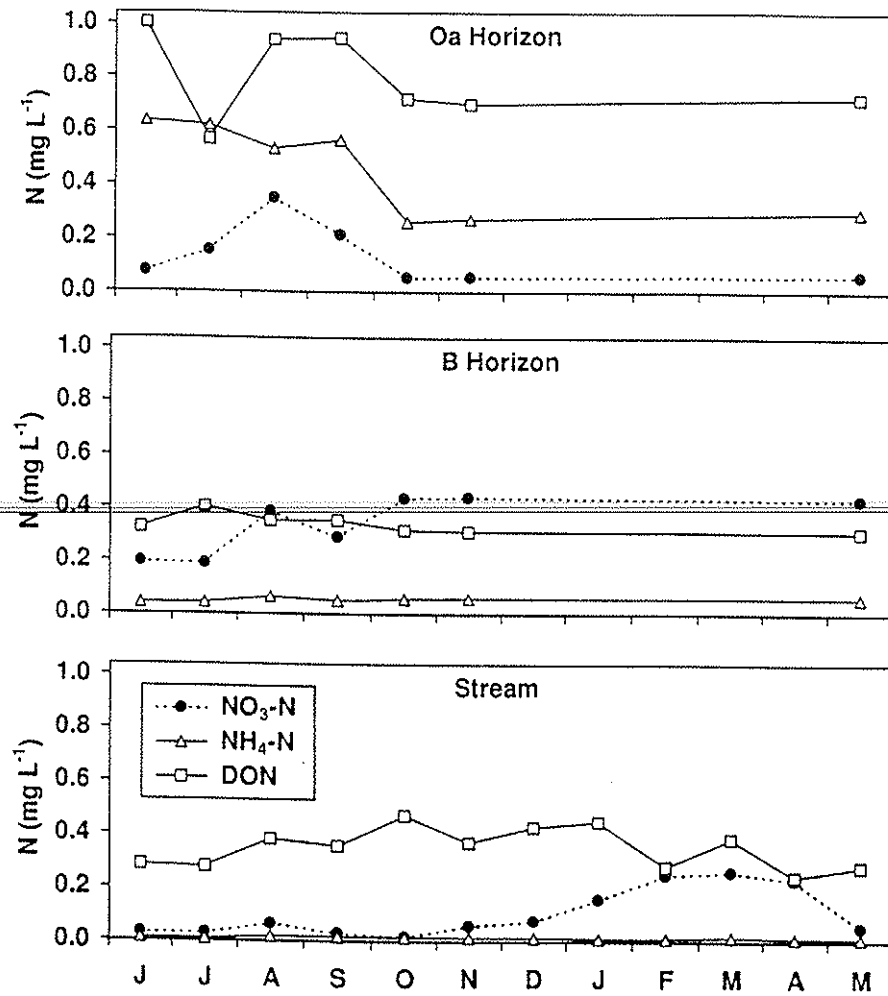
*Figure 2.* Mean monthly concentrations of NO₃-N, NH₄-N, and DON (mg L⁻¹) in soil water of the Oa and B horizons. and streamwater.

## 4. Discussion

The LBW presents an interesting dilemma to land managers because of mandates to protect the area against anthropogenic N deposition. In forests that are intensely managed, practices such as harvesting and burning, result in continued removal of N from the ecosystem. These activities also create biomass sinks for N because aggrading forests require more N for growth (Vitousek and Reiners, 1975). The elimination of forest harvesting results in mature forests with higher N capitals, that may be more vulnerable to N saturation.

Table II. Average annual N budgets (kg ha$^{-1}$ yr$^{-1}$). Net values equal input in preciptation (Ppt) minus output in soil water from the Oa and B horizons, and streamwater. DIN budgets for HB. CP and SR are from Hornbeck *et al.* (1997) and budgets for BNA are from Martin (1979).

| | LBW | | | | | HB | CP | SR | BNA |
|---|---|---|---|---|---|---|---|---|---|
| | NH$_4$-N | NO$_3$-N | DON | TDN | DIN | DIN | DIN | DIN | DIN |
| Input | | | | | | | | | |
|   Ppt | 2.1 | 4.3 | 0.9 | 7.3 | 6.4 | 7.6 | 6.9 | 6.4 | 8.8 |
| N min./Nitr. | | | | | | | | | |
|   Oa | 1.9-2.7 | 1.2-1.6 | — | — | 3.1-4.3 | — | — | — | — |
|   B | 0.3-0.5 | 0.4-0.6 | — | — | 0.7-1.1 | — | — | — | — |
| Output | | | | | | | | | |
|   Oa | 2.8 | 0.7 | 5.9 | 9.4 | 3.5 | — | — | — | — |
|   B | 0.4 | 2.8 | 2.3 | 5.5 | 3.2 | — | — | — | — |
| Stream | 0.1 | 0.6 | 1.7 | 2.4 | 0.7 | 0.6 | 0.2 | 1.4 | 7.0 |
| Net (input minus output) | | | | | | | | | |
|   Oa | -0.7 | 3.6 | -5.0 | -2.1 | 2.9 | — | — | — | — |
|   B | 1.1 | 1.5 | -1.4 | 1.8 | 3.2 | — | — | — | — |
| Stream | 1.9 | 3.7 | -0.8 | 4.8 | 5.6 | 7.0 | 6.7 | 5.0 | 1.8 |

Thus it is important to understand the processes and recognize changes that may signal N saturation.

Elevated NO$_3$-N leaching is considered an indicator of excess N in forested ecosystems. The amount of NO$_3$-N in soil leachates and streamwater is dependent on N mineralization and nitrification rates (Aber *et al.*, 1989; Stoddard, 1994). These processes vary with forest cover type, so an understanding of differences among stands is important in assessing the N-status of sites. Our study is consistent with other studies that have compared N mineralization and nitrification rates at sites with different cover types (Nadelhoffer *et al.* 1985; Hill and Shackleton, 1989). Like these studies, we found low N mineralization and almost no nitrification in conifer stands, and higher rates in deciduous stands. These differences are attributed to differences in soil moisture, temperature, pH, as well as biotic controls related to competition between plants and microbes (Robertson, 1982; Hill and Shackleton, 1989; Aber *et al.*, 1993).

These differences in N mineralization and nitrification among stands can be compared to N concentrations in soil water to clarify relationships between production and losses of N in soil leachates. In the softwood stand, low rates of nitrification resulted in lower NO$_3$-N concentrations in leachates, indicating an N-limitation (Figure 1, Table I). The highest NO$_3$-N concentrations

in soil water at the mixed site were unexpected because nitrification rates were lower compared to the hardwood site. This suggests that factors in addition to nitrification, may be important in regulating $NO_3$-N concentrations in soil water, such as greater uptake of N by deciduous species (Nadelhoffer et al., 1995). Concentrations of $NH_4$-N in soil water were nearly equal at all sites and it appears that although N mineralization rates are lower in the softwood stand, less $NH_4$-N is being nitrified, resulting in similar $NH_4$-N concentrations among sites.

The lysimeter data presented in this study show that leaching losses at the softwood site were low and that at current deposition levels, conifer stands retain more N than mixed and hardwood stands. However, this may not mean that softwood stands will be able to retain more N if deposition increases. Hardwood species are a better sink for N than softwood species because hardwoods assimilate more N in foliage and bolewood (Nadelhoffer et al., 1995). If softwood sites have lower rates of N assimilation, they may be more sensitive to increases in N deposition.

Concentrations of $NO_3$-N in streamwater, which serves as an indicator of how well N is assimilated by forests, averaged 0.1 mg $L^{-1}$ for the study period. A summary by Hornbeck et al. (1997) of $NO_3$-N concentrations in streams of 159 forested watershed in central New England showed a range of 0 to 0.8 mg $L^{-1}$. Forty-eight percent of the 159 watersheds had higher streamwater $NO_3$-N concentrations than the LBW suggesting that forest on LBW are not losing excessive amounts of inorganic N.

Annual N budgets show that the watershed investigated in this study is accumulating TDN at a rate of approximately 4.8 kg $ha^{-1}$ $yr^{-1}$, due primarily to net gains of $NO_3$-N, and $NH_4$-N (Table II). There was a slight net loss in DON (-0.8 kg $ha^{-1}$ $yr^{-1}$), however this did not offset the gain in DIN. Approximately 60% of the $NH_4$-N produced in the Oa horizon was nitrified. The low flux of $NO_3$-N from organic soil horizons suggests that much of this $NO_3$-N was taken up by vegetation. Low $NO_3$-N concentrations in soil water and streams during growing season months also support the idea of uptake by vegetation.

Table II compares DIN budgets at LBW to those published for the Bowl Natural Area (BNA) in New Hampshire (Martin, 1979) and the Hubbard Brook Experimental Forest (HB) and Cone Pond Watershed (CP) in New Hampshire and the Sleeper's River Watershed in Vermont (SR) (Hornbeck et al., 1997). N retention ranged from low at BW (1.8 kg $ha^{-1}$ $yr^{-1}$) to high at HB (7.0 kg $ha^{-1}$ $yr^{-1}$). The low retention at BNA has been suggested to be the result of inefficient N cycling by the old-growth forest that inhabits the watershed (Vitousek and Reiners, 1975). The net gain in DIN at LBW (5.6 kg $ha^{-1}$ $yr^{-1}$) was intermediate in comparison to HB, CP, and SR, suggesting that forests at LBW are cycling N in a manner similar to other second-growth forests in the region.

In mineral soils at the LBW, nitrification rates were low, but the flux of $NO_3$-N from mineral horizons was high (2.8 kg ha$^{-1}$ yr$^{-1}$) compared to organic soils (0.7 kg ha$^{-1}$ yr$^{-1}$)(Table II). Seasonal patterns of $NO_3$-N in the B horizon show that concentrations of $NO_3$-N remained low throughout the summer, and that concentrations were higher during the winter (Figure 2). A similar pattern was evident for streamwater, but $NO_3$-N outputs in streams were low compared to mineral soil outputs. The high $NO_3$-N values in mineral soil and low values in streamwater suggest that $NO_3$-N is either accumulating in mineral soil, being lost through denitrification or uptake in the riparian zone, or is being utilized within the stream. Whatever the mechanism, annual $NO_3$-N losses in streamwater were low compared to inputs of N, indicating that the watershed is a sink for N at current deposition levels.

## 5.  Conclusions

Our study involved a relatively low level of ecosystem measurements, but was able to show that the LBW is accumulating N, and that the ecosystem has not yet exceeded its capacity to assimilate N. $NO_3$-N in streamwater is low, although seasonal increases, and the possible accumulation of $NO_3$-N in mineral soil, may be warning signals of the initial stages of N saturation. Without the benefit of long-term data, it is difficult to determine if additional N inputs will cause an increase in $NO_3$-N leaching. Prior to making this determination, it is essential to establish more detailed baseline levels for N concentrations and budgets and other biogeochemical parameters such as pH and base cations that may be affected by increases in N deposition. Monitoring N retention at the watershed level is an important first step in determining the N status of sites and providing land managers with data to determine if restrictions on N emissions are warranted.

## Acknowledgements

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