Climatic Control of Nitrate Loss from Forested Watersheds in the Northeast United States

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Increased losses of nitrate from watersheds may accelerate the depletion of nutrient cations and affect the acidification and trophic status of surface waters. Patterns of nitrate concentrations and losses were evaluated in four forested watersheds (East Bear Brook Watershed, Lead Mountain, ME; Watershed 6, Hubbard Brook Experimental Forest, White Mountains, NH; Arbutus Watershed, Huntington Forest, Adirondack Mountains, NY; Biscuit Brook, Catskill Mountains, NY) located across the northeastern United States. A synchronous pattern was observed in nitrate concentrations of drainage waters from these four sites from 1983 through 1993. Most notably, high concentrations and high drainage water losses followed an anomalous cold period (mean daily temperature −11.4 to −16 °C in December 1989) for all four sites. After high nitrate losses during the snowmelt of 1990, nitrate concentrations and fluxes decreased at all sites. These results suggest that climatic variation can have a major effect on nitrogen flux and cycling and may influence temporal patterns of nitrate loss in a region.

Introduction

Recent increases in leaching losses of nitrate have been reported for North American and European landscapes (*1*,

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2). Increased inputs of nitrate may contribute to the acidification of surface waters and delay their recovery from the deleterious effects of acidic deposition (*1*, *2*). Increased concentrations of nitrogen may also contribute to eutrophication of aquatic systems, especially coastal waters (*3*). Nitrate leaching may also contribute to the depletion of nutrient cations from forests due to its role as a mobile anion (*4*, *5*). The biogeochemistry of nitrogen has been extensively investigated since nitrogen is an important macronutrient, and its dynamics are closely coupled with many other important elements including carbon and nutrient cations. These biogeochemical evaluations have been facilitated by studies using small watersheds. Numerous studies have demonstrated that small catchments are useful for long-term evaluations of biogeochemical changes as well as the calculation of input and output budgets using mass balance approaches (*6*, *7*). Our major objectives were to examine temporal patterns and some of the factors regulating nitrate loss in four northern hardwood watersheds in the northeast United States (East Bear Brook Watershed, Lead Mountain, ME, BBWM; Watershed 6, Hubbard Brook Experimental Forest, White Mountains, NH, HBEF; Arbutus Watershed, Huntington Forest, Adirondack Mountains, NY, HF; Biscuit Brook, Catskill Mountains, NY, CS).

Site Characteristics

The catchments at all four sites (BBWM, HBEF, HF, and CS) were drained by headwater streams. At the base of the catchment of the Arbutus Watershed (HF), the streams drained into a small, 50-ha lake. Overstory vegetation in these sites was composed mainly of *Acer saccharum* (sugar maple), *Fagus grandifolia* (American beech), *Betula alleghaniensis* (yellow birch), *Picea rubens* (red spruce), *Betula papyrifera* (white birch), and *Abies balsamea (*balsam fir). The soils were either Typic Haplorthods and Fragiothods [BBWM (*8*), HBEF (*9*), and HF (*10*)] or Typic and Lithic Dystrochrepts [CS (*11*)] derived from glacial deposits. The nitrogen biogeochemistry at each of these four watersheds has been extensively characterized, and they represent a range of catchment sizes (10−960 ha), elevations (265−1128 m), and nitrogen deposition regimes (310−570 mol wet only N ha^{-1} yr^{-1}) (Table 1).

Methods

The period of record for analyses varied among the four sites. The HBEF has the most complete information with hydrological data available since 1956 and stream nitrate concentrations from 1964 (*6*). In the current study, data from the HBEF were used from January 1982 through December 1993 while for BBWM, HF, and CS data were available from January 1987, January 1983, and May 1983, respectively. Nitrate concentrations were analyzed by ion chromatography (*12*). Drainage was measured using calibrated weirs and flumes at flow gauging stations at the base of each watershed. Measured flow rates were used for nitrate loss calculations except for HF where hydrological fluxes were modeled (*10*) for the period before October 1991, after which time a weir was installed.

Results and Discussion

Nitrate Concentration Patterns. Nitrate concentrations showed the typical seasonal pattern of many watersheds

Study Sites in the Northeastern United States

watershed	abbrev	location	size (ha)	elevation (m)	wet-only nitrogen deposition		ref
					amount (mol of N ha^{-1} yr^{-1})	period (yr)	
East Bear Brook Watershed, ME	BBWM	44°51′ N 68°6′ W	10	265−475	310	1987−1992	8
Watershed 6, Hubbard Brook Experimental Forest, NH	HBEF	43°56′ N 71°45′ W	13.1	490−775	525	1992−1993	6
Arbutus Watershed, Huntington Forest, NY	HF	43°59′ N 74°14′ W	309	513−701	358	1992−1993	10
Biscuit Brook, NY	CS	41°59′ N 74°25′ W	960	628−1128	570	1985−1986	11

in the region with highest values during the spring snowmelt period and lowest concentrations during summer base flow coinciding with uptake of nitrogen by the soil microbiota and the vegetation (6, 13). According to Stoddard's (1) classification of watershed nitrogen saturation, BBWM would be at stage 0 (measurable nitrate only during snowmelt), HBEF and HF would be at stage 1 (large peaks of nitrate in spring and base flow concentrations near 0), and CS would be at stage 2 (high nitrate concentrations at base flow), suggesting less retention of nitrogen by the watershed ecosystem during the growing season at this latter site (14).

From 1983 through 1990, a significant ($p \leq 0.05$) increase ($0.5-2.0 \mu$equiv L^{-1} yr^{-1}) in nitrate concentration was found for 9 of 16 lake outlets in the Adirondack Mountains, including Arbutus Lake at the base of HF (1.2 μequiv L^{-1} yr^{-1}) (15) using a seasonal Kendall−Tau times series analysis (16). Also during this period, 5 of 8 streams in the Catskill Mountains showed significant ($p \leq 0.05$) increases in nitrate (1.3−3.0 μequiv L^{-1} yr^{-1}), including Biscuit Brook [CS] (2.0 μequiv L^{-1} yr^{-1}) (17) whereas for Watershed 6 at HBEF the increase was smaller (0.29 μequiv L^{-1} yr^{-1}) and not significant ($p = 0.17$). For Adirondack watersheds including HF (18) as well as CS and HBEF, the highest concentrations of nitrate were found in 1990 followed by declining concentrations through 1994. These declines resulted in no significant trends by Kendall−Tau time series analyses (16) in surface water nitrate for the entire period from 1982 to 1994 for these watersheds. Remarkably, these four watersheds (BBWM, HBEF, HF, and CS), located over a wide geographical area and with different values of atmospheric deposition of nitrogen, showed a striking synchrony in the temporal pattern of nitrate concentrations and losses (Figures 1 and 2).

Nitrogen Mass Balances. Most of the nitrate in these watersheds was lost during the dormant season (October 1−May 30) (98, 98, 95, and 87% for BBWM, HBEF, HF, and CS, respectively) (Figure 2). Despite large losses, these watersheds were net sinks for atmospheric deposition of nitrogen. At HF, 74 (wet only) to 85% (total deposition) of the nitrogen from the atmosphere (NH$_4^+$ + NO$_3^-$) has been either retained or lost through denitrification (10); similarly nitrogen retention at BBWM, HBEF, and CS has been reported at 75% (8), 81% (6), and 63% (11), respectively, for wet-only inputs.

Annual Differences in Nitrate. For HBEF, HF, and CS, both concentrations (Figure 1) and fluxes (Figure 2) of nitrate peaked during the 1989−1990 dormant period with subsequent declines through 1993. At Hubbard Brook Experimental Forest, this same temporal pattern in nitrate
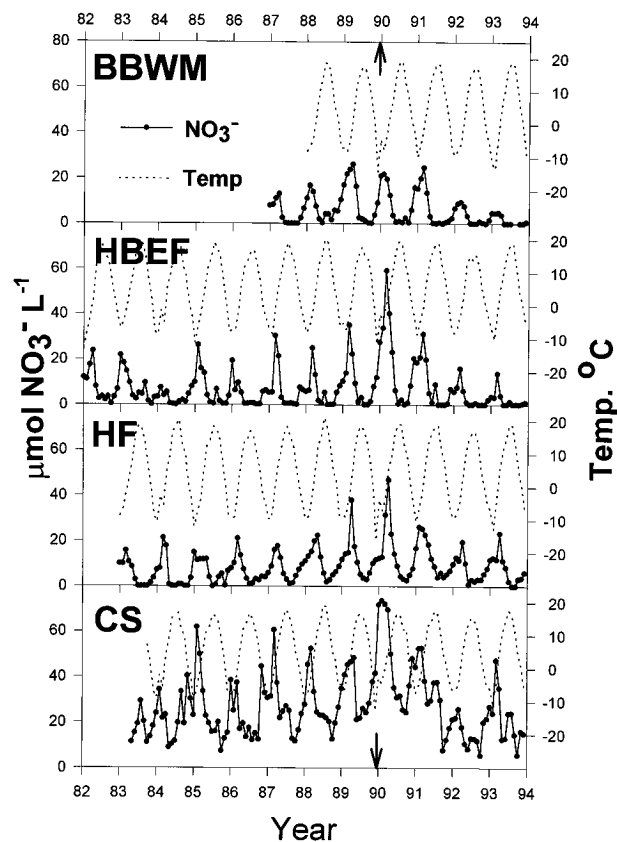

FIGURE 1. Monthly nitrate concentrations at the base of watershed and temperatures (average of daily maxima and minima temperatures) taken from meteorological stations close to four sites in the northeast United States (East Bear Brook Watershed, Lead Mountain, Maine, BBWM; Watershed 6, Hubbard Brook Experimental Forest, White Mountains, NH, HBEF; Arbutus Watershed, Huntington Forest, Adirondack Mountains, NY, HF; Biscuit Brook, Catskill Mountains, NY, CS). The arrows show the month (December 1989) of extremely cold temperatures that preceded the large increase in NO$_3^-$ in surface waters during the snowmelt of 1990.

concentration was also found for three other watersheds (W2, W4, and W5) that had different land use histories (19). A decline in nitrate concentration and flux was not evident until the 1991−1992 dormant period at BBWM. For HBEF, information on soil water chemistry using zero tension lysimeters (20) is available for making temporal comparisons over this study period. At HBEF, the same temporal pattern of nitrate concentrations that occurred in the stream also occurred in soil solutions collected beneath deciduous stands at 730 m elevation near Watershed 6 (Figure 3). Nitrate concentrations generally decreased with soil depth (O$_a$ horizon < B$_h$ horizon < B$_{s2}$ horizon), but the 1990
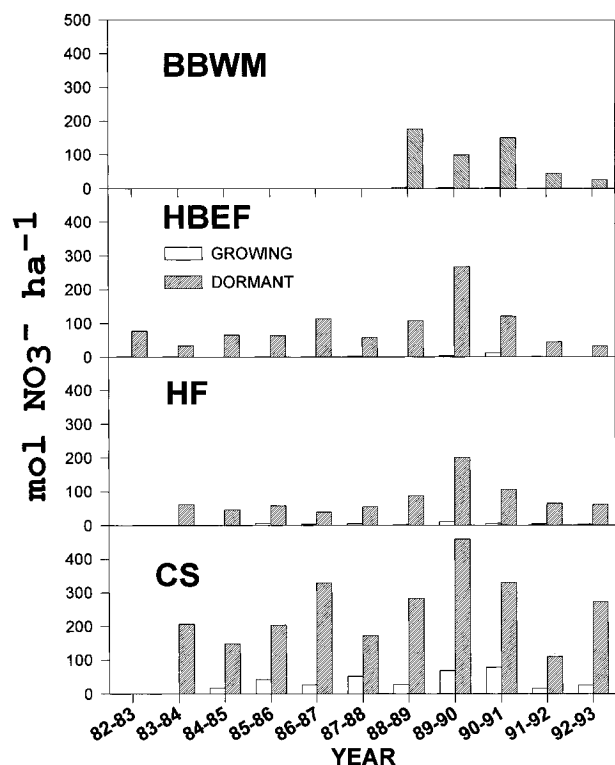
FIGURE 2. Nitrate flux for growing (June 1–September 30) and dormant (October 1–May 30) seasons. The dormant period includes months from two calendar years (October–December and January–May, respectively). For abbreviations, see legend for Figure 1.
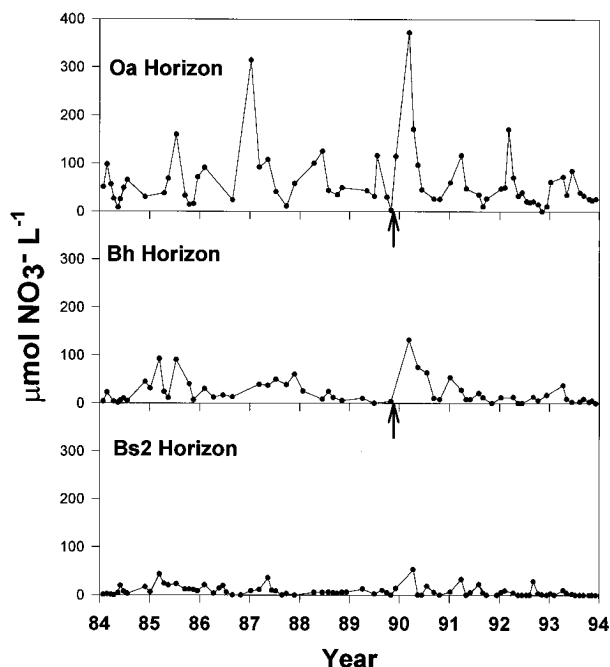

FIGURE 3. Nitrate concentration in soil solution collected by zero-tension lysimeters in a northern hardwood forest site (elevation 730 m) adjacent to Watershed 6 at the Hubbard Brook Experimental Forest, NH. The arrows show the month (December 1989) of extremely cold temperatures that preceded the large increase in NO_3^- in surface waters during the snowmelt of 1990.

snowmelt period had the highest NO_3^- concentrations in all three horizons, respectively. Lower (600 m) and higher (750 m) elevational zones at HBEF generally had lower soil nitrate concentrations and did not exhibit this marked temporal pattern. High concentrations of nitrate were also

found in soil solutions at CS during the 1989−1990 dormant period.

Effect of Soil Freezing on Nitrate. The high concentrations and losses of nitrate at HBEF, CS, and HF followed an extremely cold period in December 1989 (Figure 1). For the study period, this was the coldest month at all the sites (average daily temperature: −14.3, −11.4, −16.0, and −12.7 °C for BBWM, HBEF, HF, and CS, respectively), except for HBEF where January 1982 was colder (−12.8 °C). For HF, which has the longest meteorological record of all four sites (1941−1993), this was the coldest month ever recorded coinciding with the lowest precipitation (26.9 mm water versus an average of 88.1) of any December since 1941. In December 1989, snowpack depth at HF ranged from 10 to 31 cm, with lowest depths early in the month (days 1−14) when mean daily temperatures ranged from −11.4 to −18.6 °C. At HBEF during this period, when mean daily temperatures ranged from −7 to −19 °C, freezing of the forest floor occurred beneath a 13-cm (43 mm of water) snow pack (station 2, December 4, 1989) (21). Although the actual extent and depth of soil frost were not known for these catchments, it is expected that freezing would have been greatest in exposed areas at high elevations. Thus, in December 1989 apparently much of the northeastern United States was subject to extremely cold temperatures with little snow cover for insulation and freezing of soils likely occurred.

Freezing and thawing cycles can have marked effects on biotic activity and nutrient release in wetland (22) and upland soils (23), both of which are found in these watersheds. High concentrations of nitrate in stream waters at HBEF were also found after the winters of 1969−1970 and 1973−1974, during which widespread freezing of soils was reported (6). Currently no models (24, 25) used to predict nitrogen dynamics and nitrate losses from forests ecosystems account for processes such as freezing and thawing during the dormant season. Soil freezing followed by thawing releases nitrogen and carbon previously immobilized by soil microorganisms and can contribute substantially to soil nitrate (26−28). Experimental removal of snow resulted in deep soil freezing with subsequent high nitrate losses in a stand of *A. saccharum* in Quebec, Canada (29).

Controls on Nitrate Loss. From January to March in 1990 at BBWM, HBEF, CS, and HF there were rain and thawing events that would have added additional inputs of nitrogen and increased leaching losses. For HF and CS, atmospheric inputs of inorganic N were also elevated during the 1990 winter period (30). However, mass balance studies (31) and stable isotope analyses (32) both suggest that the snowpack is not the major source of nitrate to surface waters during snowmelt. The anomalous cold period in December 1989, followed by the loss of nitrate during the remainder of the dormant period, may have hastened the release of labile nitrogen and contributed to the decreases in nitrate losses in subsequent years (1991−1993) at these sites.

These findings emphasize the need to consider climatic variation when evaluating the response of forested ecosystems to elevated atmospheric deposition of nitrogen, including assessments of conditions leading to "nitrogen saturation". Soil freezing may markedly affect the loss of nitrate, especially when followed by hydrological conditions that facilitate the transfer of solutes to surface waters. Such processes need to be incorporated into simulation models of nitrogen biogeochemistry. Climatic events must be

considered when evaluating long-term temporal changes in nitrate loss such as those predicted due to nitrogen saturation. Moreover, if these climatic parameters exhibit greater variability as predicted by scenarios of global change (*33*), then more attention will be needed to evaluate the role of this variation in affecting the biogeochemical cycles of nitrogen and other nutrients. Such variation also suggests the need for the continued long-term evaluation of intensively studied watersheds including comparisons among watersheds within a region.

Acknowledgments

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