Control of Nitrogen Loss from Forested Watersheds by Soil Carbon:Nitrogen Ratio and Tree Species Composition

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[1] E 12545, A; [2]D 40546, A

Abstract

Leaching losses of nitrate from forests can have potentially serious consequences for soils and receiving waters. In this study, based on extensive sampling of forested watersheds in the Catskill454.8(and)Mc2ll4Dy1pr.51.1(of)-51.1(orshs)-51.1orshs rshsrshsrshsrs relationships among stream chemistry, the properties of the forest floor, and the tree species composition of watersheds. We report the first evidence from North America that nitrate export from forested watersheds is strongly influenced by the carbon:nitrogen (C:N) ratio of the watershed soils. We also show that variation in soil C:N ratio is associci-

regulates litter decomposition and the accumulation of carbon (C) and N in soil organic matter. Previous studies in European forests have shown that soil C:N ratio is inversely related to forest NO_3^- leaching, after taking into account differing atmospheric deposition regimes (Gunderson and others 1998; Dise and others 1998; Emmett and others 1998); however, these studies were done primarily in coniferous forests, some of which receive very high rates of atmospheric N deposition (up to 80 kg N $ha^{-1}y^{-1}$). In contrast, most of the mid-Atlantic and northeastern United States is dominated by deciduous forests that receive low or moderate levels of N deposition (less than 15 kg N $ha^{-1}y^{-1}$).

In the Catskill Mountains of southeastern New York State, our survey of 39 streams draining small, forested watersheds showed a 17-fold range of NO_3^- concentration (Lovett and others 2000). All of these watersheds are vegetated almost entirely by unmanaged forest, so the variation in NO_3^- concentration was not a result of differences in current land use. Dissolved organic N concentrations were much less variable and ammonium concentrations were very low, so NO_3^- explained more than 96% of the variation in total dissolved N concentration among streams. Because water discharge per unit of watershed area is relatively constant within this area, variation in mean N concentration in stream water is a good index of variation in N export among watersheds (Lovett and others 2000). Our estimates of N input and export from these watersheds indicate that N retention (deposition minus export) ranges from about 49% to 90% of the atmospheric N deposition (Lovett and others 2000). Previous work indicated that variation in stream water N concentration among watersheds in this area was probably not due to variation in atmospheric deposition, topography, in-stream N retention, or groundwater input to streams (Lovett and others 2000; West and others 2001). In this study, we examine the relationship between stream water concentration in Catskill streams and characteristics of watershed soils and forests.

Site and Methods

A.

Our research took place in the Catskill Mountains, an area of about 5000 km^2 with several ranges of mountains (peak elevations, 1100–1274 m) separated by deeply incised valleys and underlain by shales and sandstones of Devonian age (Stoddard and Murdoch 1991). The climate is moist and cool, with a mean annual temperature of 4.3°C and mean annual precipitation of 153 cm at a station located at 808 m elevation near Slide Mountain in the central Catskills (Lovett and others 2000). Soils in the Catskills are predominantly acidic inceptisols, generally shallow, stony, and well-drained (Stoddard and Murdoch 1991; Lovett and others 2000). Atmospheric N deposition (wet + dry) is about 11 kg N $ha^{-1}y^{-1}$ (Lovett and Rueth 1999). Forests are predominantly of the northern hardwood association dominated by sugar maple (*Acer acchar m* Marsh), American beech (*Fag grandifolia* Ehrh.)

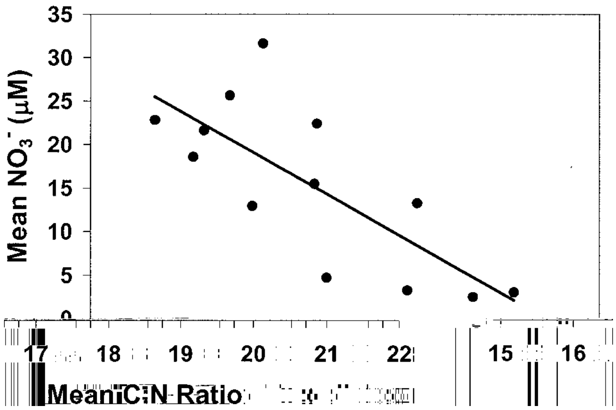
ified random design such that stands were distributed among watersheds in proportion to the watershed area and within watersheds in proportion to the area in elevational zones. Trees greater than 10 cm dbh were measured in each plot, and a sample of organic horizon (Oe + Oa layers) soil was taken. Basal area (at breast height) was calculated by species assuming a circular bole cross section. The vegetation data from the five plots in a stand were averaged, and the five soil samples were composited before analysis of C and N concentration (on a Carlo-Erba NA 1500 element analyzer, Carlo Erba Strumetazione, Milan, Italy). This yielded a data set of 145 stands with mean vegetation and soil C:N data.

Forest history information for each stand was obtained using a Geographic Information System by plotting the location of each stand (measured with a global positioning system (GPS) unit in the field) on a digital version of the Catskill forest history map published by Kudish (2000). The forest history classifications used by Kudish are based on extensive field observations and searches of local land-use records. The forest history categories present in the watersheds that we studied were as follows: old growth (forest that has not been harvested or burned), second growth (forest that shows evidence of harvest), burned (forest with a confirmed record of forest fire), and pasture (forest that was formerly pastureland).

Statistical analysis was done with the SAS statistical package (SAS Institute, Cary, NC, USA) using the procedures REG (for regression analysis), ANOVA (for analysis of variance) and GLM (for general linear model analysis). In the stepwise regression, variables were entered and removed at $P = 0.15$, and statistical significance was assessed at $P < 0.05$.

Results and Discussion

Using stepwise regression, we found that the C:N ratio in organic horizon soils was the only significant predictor of mean annual stream NO_3^- concentration among a suite of independent variables, including the basal area of all major tree species and topographic variables such as minimum and maximum elevation, slope, area, and stream length. Soil C:N explained 57% of the variance in mean annual stream NO_3^-, and the two variables were inversely related (Figure 1). Soil C:N was also the best single-variable predictor of NO_3^- concentration in both the summer (June–September) and winter (December–March) periods (r^2 values of 0.60 and 0.46, respectively). This result implies that organic soil



1. Mean stream NO_3^- concentration versus mean C:N ratio in organic horizon of watershed soils. The points represent the 13 watersheds. The line is the best fit regression line ($y = -4.741x + 100.81$, $r^2 = 0.57$, $P = 0.0027$)

C:N controls NO_3^- export and retention in these watersheds, or that some other factor controls both soil C:N and NO_3^- export. The former explanation is likely because a high soil C:N ratio produces a strong demand for N by heterotrophic soil microbes, leaving less N available for nitrification and subsequent NO_3^- leaching (VanMiegroet and others 1992; Riha and others 1986). Strong negative associations between soil C:N and nitrification rate have been observed in both hardwood and coniferous forests in the northeastern United States (McNulty and others 1991; Lovett and Rueth 1999; Goodale and Aber 2001; Ollinger and others 2002).

This is the first evidence, to our knowledge, of the relationship between stream NO_3^- loss and soil C:N ratio in the forested watersheds of North America. This finding leads us to ask what controls soil C:N in the forested watersheds we studied. In our 13-watershed data set, the variable most strongly associated with mean soil C:N was mean basal area of sugar maple (inverse relationship, $r^2 = 0.57$, $P = 0.003$). However, a much more powerful analysis can be done on our stand-level data set ($n = 145$), which includes vegetation, soil C:N, elevation, and forest history information for each stand we sampled. In this data set, the variables that explained the most variance in soil C:N (using stepwise linear regression) were the basal areas of sugar maple and red oak (Figure 2); variables of secondary importance were the basal areas of red maple (*Acer r br m*) and white ash (*Fra in americana*). These four vegetation variables were the only significant variables in the stepwise regression analysis; together they explained 40% of the variation in soil C:N ($P < 0.0001$). The partial r^2 for each variable was: sugar maple, 0.22; red oak, 0.12; red maple, 0.03; and white ash, 0.02. All variables were significant at $P < 0.05$. Sugar maple and white ash basal areas were inversely related to C:N, whereas red

In some areas, watershed NO_3^- export has been related to geological sources of N from weathering of N-bearing sedimentary rocks (Holloway and others 1998). This additional source of N would presumably also influence the soil C:N ratio (Dahlgren 1994). However, the central Catskills area that was the site of this study has relatively homogeneous bedrock mineralogy (Stoddard and Murdoch 1991), although the N concentration of the rocks has not been reported. Moreover, in our stand-level data set, the range of stand C:N ratios within most watersheds was greater than the range of mean values among watersheds, suggesting variation on a scale smaller than would be expected from differences in bedrock geology but appropriate for the scale of tree species heterogeneity.

It has been argued that in-stream retention or processing of N is a major factor influencing stream NO_3^- concentrations in a variety of ecosystems in North America (Peterson and others 2001). However, the Catskill headwater streams that we studied are steep, rocky, and frequently shaded by overhanging trees, conditions that tend to reduce in-stream N retention. There is a strong 1:1

dation (DEB 9981503), and the A. W. Mellon Foundation. We thank the many able research assistants at the Institute of Ecosystem Studies and the University of Kentucky for their help in the field and the laboratory, especially Jacob Griffin, Charles Schirmer, Rebecca Brown, and Jessica Hancock. We are grateful to Peter Groffman and Ross Fitzhugh for reviews of a draft of the manuscript. This is a publication of the Kentucky Agricultural Experiment Station (No. 002-09-111) and a contribution to the program of the Institute of Ecosystem Studies.

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