EFFECTS OF HARVESTING ON SOIL NITROGEN (N) DYNAMICS IN A N-SATURATED HARDWOOD FOREST

Frank S. Gilliam and Mary Beth Adams[1]

Abstract—Recent evidence suggests that soils of some central Appalachian hardwood forests have become nitrogen (N) saturated, a condition that develops when availability of soil N exceeds demand for N by plant roots and soil microbes. Among many environmental concerns associated with N saturation are the following: (1) greatly altered N cycle seen as a de-coupling of N dynamics from the high degree of biotic control that occurs in N-limited forest ecosystems and (2) greatly enhanced nitrification and leaching of NO_3^- along with calcium (Ca^{++}) and magnesium (Mg^{++}) from the soil and into streams, depleting base cation availability in the soil. Both of these have been demonstrated for hardwood forests of the Fernow Experimental Forest (FEF), West Virginia. Because increases in rates of nitrification and loss of soil cations often are associated with forest harvesting, it is important to determine whether the simultaneous effects of N saturation and harvesting may accelerate ecosystem degradation. Accordingly, we established a plot-based study to examine the effects of harvesting with and without addition of N and cations on soil N dynamics at FEF. Our treatments (each with four replicate 0.2-ha plots) were as follows: (1) Control (no treatment), (2) Harvest only (whole-tree harvesting [WTH] of entire plot), (3) Harvest+N (WTH plus 36 kg N/ha/yr), and (4) Harvest+N+cations (WTH plus 36 kg N/ha/yr plus 22.4 and 11.9 kg/ha/yr each of Ca and Mg, respectively). The cation addition treatment was done to simulate a mitigative treatment to replace loss of base cations to leaching. As expected at this N-saturated site, even our control plots exhibited high rates of N mineralization, mostly as net nitrification. However, these high rates were increased significantly by all harvest treatments. The addition of N in combination with harvesting did not increase nitrification significantly. By contrast, the addition of cations in combination with harvesting and N resulted in nitrification rates significantly higher than the other harvest treatments. These results illustrate the increasing complexities and challenges facing management of hardwood forests in the context of pollutant conditions.

INTRODUCTION

Deciduous forests of the eastern United States have exhibited an extremely high degree of resilience to a variety of historical perturbations and stresses. For example, although most of these forests originated after the heavy cutting and fires that occurred during the era of railroad logging (1880-1930), present forests have generally high species richness and productivity (Marquis and Johnson 1989, Gilliam and others 1995). While overall forest productivity remains reasonably high despite a growing demand for wood, the question of sustainable productivity, biodiversity, and health of forest ecosystems of the eastern U.S. is one of increasing concern. Indeed, recent data indicate that several eastern deciduous forest species are experiencing higher-than-normal rates of mortality (Twardus 1995). Despite on-going debate among forest ecologists, foresters, and resource managers, the observed mortality has been attributed to a variety of factors, alone or in combination. Some of these are acidic deposition, nutrient cation depletion, and excess nitrogen deposition, all of which have the potential to decrease survivorship of several forest species by weakening the trees and increasing their vulnerability to other stresses, including temperature and moisture extremes, disease, and insects (Adams and Eagar 1992, Eagar and Adams 1992).

One of the primary hypothesized agents of observed declines is base cation depletion of poorly buffered soils via forest harvesting and atmospheric inputs of nitrogen and sulfur (Eagar and Adams 1992, Gilliam and Richter 1991). Although typical central Appalachian soils are not considered infertile (Auchmoody 1972), recent concerns about sustainability of central Appalachian forests have been linked with soil fertility. Declines in nutrient cation levels in soil, particularly calcium (Ca) and magnesium (Mg), from intensive harvesting of forest products have been documented in some parts of the United States (Federer and others 1989, Mann and others 1988). Because timber harvesting is expected to increase in this region, and because the shift in forest utilization is toward fiber and more intensive harvesting, cation export in forest biomass could amount to a significant loss from some forest sites.

Earlier research on the effects of acidic deposition on forest systems indicated that the productivity of many soils in the humid east could decline significantly within 50-70 years (Binkley and others 1989), the span of a typical timber rotation for many stand types (Marquis and Johnson 1989). The central Appalachian region receives some of the highest inputs of acidic deposition in the United States (Adams and others 1993, Gilliam and Adams, 1996). The Clean Air Act contained provisions primarily targeting sulfur (S) emissions, not N emissions. Indeed, U.S. emissions of sulfur in 1990 were >25 percent less than those in 1970, while emissions of N were 2

[1] Professor, Department of Biological Sciences, Marshall University, Huntington, WV 25755-2510; and Soil Scientist, Timber and Watershed Laboratory, USDA Forest Service, Parsons, WV 26287, respectively.

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percent higher in 1990 compared to 1970 (World Resources Institute 1994). In short, pollutant emissions of oxides of N are not expected to decline greatly in the near future. Thus, considering the likelihood of several eastern deciduous forests becoming N saturated in the future and the increased demand on these forests for the production of wood products, information on interactions between N saturation and forest harvesting will be of great importance for forest ecologists, forest and resource managers, and policy makers. Research suggests strongly that some sites have reached or are nearing N saturation (Stoddard 1994, Gilliam and others 1996, Fenn and others 1998, Aber and others 1998). Furthermore, studies of stream chemistry at other eastern forest sites have shown that elevated N additions resulted in elevated losses of N (as NO_3) and base cations, especially calcium (Ca) and magnesium (Mg), suggesting a direct connection between N saturation (N additions) and the leaching of nutrient cations (Kahl and others 1993, Rustad and others 1993, Norton and others 1994).

The effects of forest harvesting on ecosystem nutrient cycling have been studied for many forest types and harvesting practices. Indeed, much has been learned to indicate that response of the biota (recovering vegetation) is largely responsible for regulating nutrient change as the forest recovers from the disturbance of the harvest regime (Binkley 1986, Tritton and others 1987, Martin 1995, Gilliam and Adams 1995, Johnson 1995). It also has been learned, however, that there is great inter-site variability in these responses, precluding broad generalizations across forest ecosystems. Despite their great ecological and economic importance, forests of the central Appalachian region have not been studied extensively with respect to nutrient responses to forest harvesting.

We know of no studies that have examined N saturation in the context of commercial forest harvesting. Accordingly, the purpose of this study was to examine the effects of harvesting on N mineralization and nitrification in a N-saturated forest. Harvesting was carried out alone and in combination with additional treatments to simulate different pollutant and mitigation scenarios. In addition, because mineralization and nitrification rates are often found to be directly related to soil temperature, the effect of harvesting on the temperature of surface soils was examined in a sub-set of sample plots. Finally, we will review current knowledge on N dynamics at the Fernow Experimental Forest as an example of a central Appalachian forest under conditions of N saturation.

METHODS

Study Site

This study was done on the Fernow Experimental Forest (FEF), Tucker County, West Virginia, a 1900-ha area of montane hardwood forests within the unglaciated Allegheny Plateau (39°03'N, 79°49'W). Prior to treatments, stands of all sample plots were typical of mature forests of the region (Gilliam and others 1995), dominated by sugar maple (*Acer saccharum* Marsh.) and northern red oak (*Quercus rubra* L.), with occasional large stems of black cherry (*Prunus serotina* Ehrh.) and yellow poplar (*Liriodendron tulipifera* L.). Soils of the study site within FEF have been described in great detail by Lusk (1998). In general, they are acidic (pH 4.1-4.7), shallow (30-40 cm to C horizon), and loamy in texture (Lusk 1998), similar to characteristics of soils of other watersheds of FEF (Gilliam and others 1994).

Field Design and Sampling

A single 4-ha mixed hardwood forest site was located on uniform soil at FEF. Slopes were gentle with a southeast aspect. Sixteen 0.2-ha plots, separated by 15 m buffer areas, were located and treatment assignments made prior to harvest. Twelve of the 16 plots were designated as harvest plots; four plots remained unharvested as controls. The treatments (each with four replicate plots) were as follows: (1) Control (C, no treatment), (2) Harvest only (H, whole-tree harvesting of entire plot), (3) Harvest+N (HN, harvesting as in 2 plus 36 kg N/ha/yr), and (4) Harvest+N+cations (HNC, as in 3 plus 22.4 and 11.9 kg/ha/yr each of Ca and Mg, respectively). The base cation treatment was carried out by adding dolomitic limestone by hand; rates were chosen to be twice the annual loss in stream flow from the reference watershed (WS4) at FEF (Adams and others 1997). All sampling and analyses were carried out during a one-year pre-treatment period and, for this paper, a one-year post-treatment period.

Available (extractable) N pools and rates of N mineralization and nitrification were measured with in situ incubations (buried bag technique of Eno 1960), based on the method described by Gilliam and others (1996). Following removal of forest floor material at a single sample point within each subplot, mineral soil was sampled by hand trowel to a 5-cm depth. Each sample was divided into two sub-samples and placed in polyethylene bags, one bag buried in the mineral soil at 5 cm for ~28 d and the other brought back to the lab. To minimize disturbance to the soil, samples were not sieved, but pebbles, rocks, and larger roots were excluded from sub-samples. All bags were refrigerated immediately in the field (using icepacks within backpacks) and then stored at 4 C prior to extraction. Sampling was carried out from approximately the middle of May to the middle of September for each of the 2 years.

Soil temperature was measured with HoboTemp (Onset Corporation) thermister temperature probes. Temperature was monitored continuously from 1 May to 30 November by placing probes at a 10-cm depth in four locations in each of two control and two harvest plots.

Laboratory and Data Analyses

Sub-samples of soil from paired sample bags were extracted for determination of net N mineralization and nitrification. Moist soils were extracted with 1N KCl at an extract:soil ratio of 10:1 (v:w). Extracts were analyzed colorimetrically for NH_4 and NO_3 with a Bran+Luebbe TrAAcs 2000 automatic analysis system. Net N mineralization was calculated as post-incubation (NH_4 and NO_3) minus pre-incubation (NH_4 and NO_3); net nitrification was calculated as post-incubation NO_3 minus pre-incubation NO_3.

To determine the relative amount of N mineralized that was eventually nitrified, N mineralization rates were compared to net nitrification rates using Pearson product-moment correlation and linear regression. Monthly rates of N mineralization and nitrification were averaged across all sample times in each year for each plot, four plots per treatment (i.e., N=4 for all means). Pre-treatment means were compared among treatments using ANOVA, whereas pre- versus post-treatment means were compared using t-tests for each treatment separately (Zar 1994).

RESULTS

Response of Soil Temperature to Harvesting

Seasonal patterns of soil temperature were similar among all four plots in which temperature was measured during the pre-treatment (pre-harvest) period (data not shown). Harvesting greatly increased maximum daily temperature of surface soil, especially from early June to mid October (fig. 1). Seasonal patterns of maximum soil temperature were highly similar between the two plots within each treatment type (harvest or control).

Response of Soil N to Harvesting and Additional Treatments

There was a highly significant correlation ($P<0.01$) between N mineralization and nitrification during the pre-treatment period ($r = 0.93$) (fig. 2). This was also highly significant for the post-treatment period ($r = 0.95$) (fig. 3).

Analysis of variance revealed no significant differences ($P<0.05$) among treatments during the pre-treatment period for net N mineralization (fig. 4). T-tests showed no differences in net N mineralization in pre- versus post-treatment periods for control (C) plots. However, net N mineralization was significantly higher ($P<0.05$) in post-treatment than pre-treatment plots for all harvest treatments, particularly for the HNC treatment.

The pattern for net nitrification was similar to that for mineralization. There were no significant differences ($P<0.05$) among treatments during the pre-treatment period, but there were significant differences between pre- and post-treatment means for most of the harvest treatments (fig. 5). Post-treatment nitrification rates were slightly (by about 25 percent), but significantly ($P<0.10$) higher in C plots. Net nitrification increased 2- to 2.5-fold from pre- to post-treatment periods on all harvest plots. This was significant ($P<0.10$) for all harvest treatments, except HN plots (fig. 5).

DISCUSSION

Although not always measured, soil temperature is assumed to increase following whole-tree harvesting. Because activity of nitrifiers is usually highly temperature-dependent,

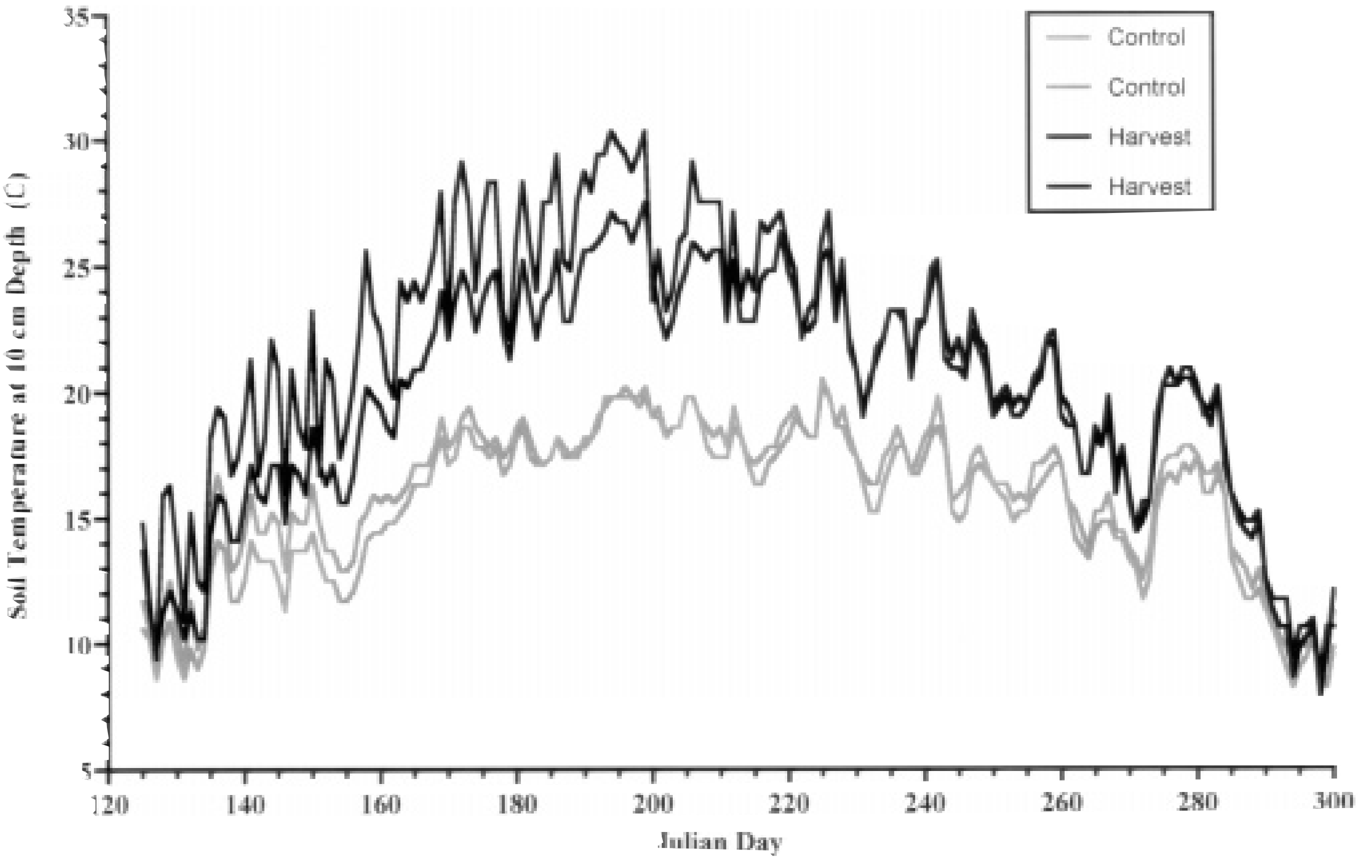

Figure 1—Soil temperature in two control and two harvest plots at Fernow Experimental Forest, WV. Data are daily maximum temperatures monitored continuously at a 10-cm depth.

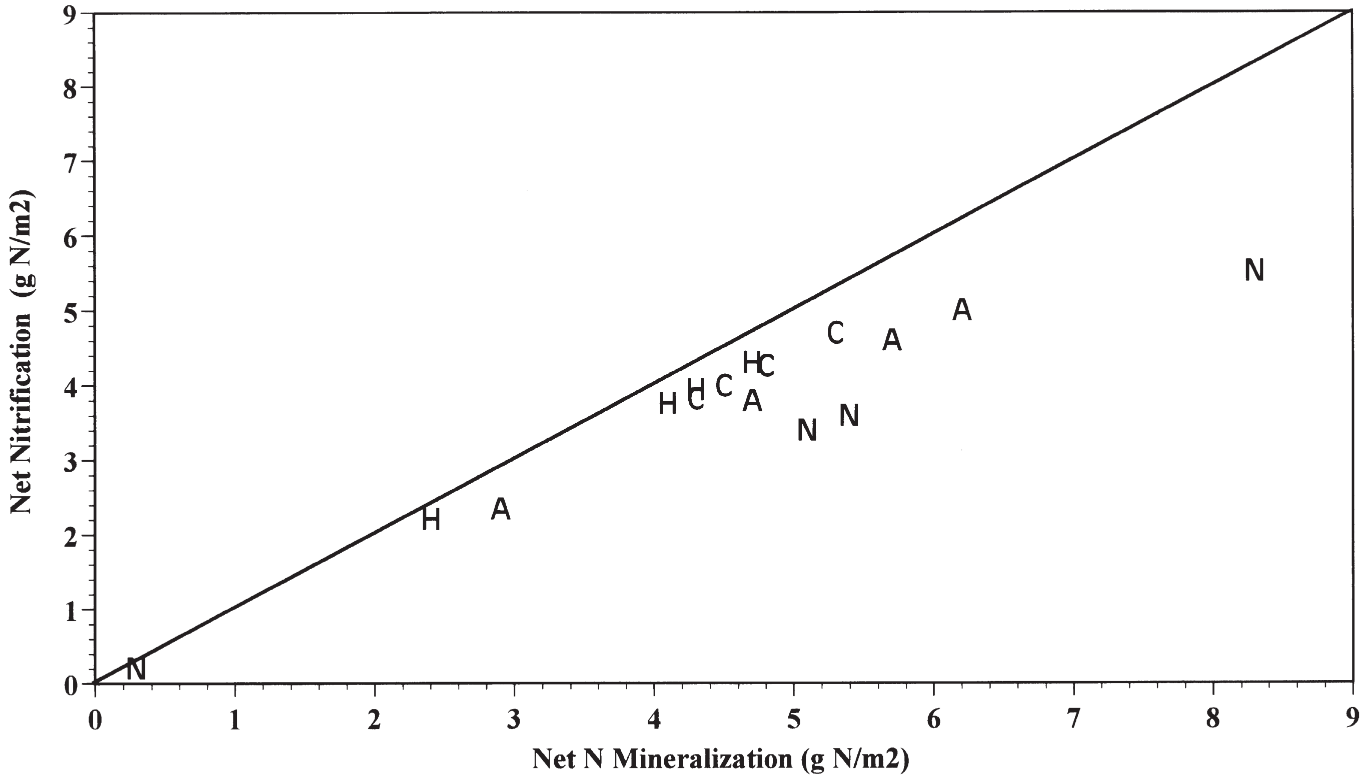

Figure 2—Nitrification versus N mineralization for individual plots during the pre-treatment period. Data are mean values for each of four plots for four treatments as follows: C = control; H = harvest; N = harvest + N; A = harvest + N + cations (i.e., A = all). Correlation was significant at P<0.01, r = 0.93. Line given is a 1:1 line representing a condition wherein N mineralization is 100 percent nitrification.

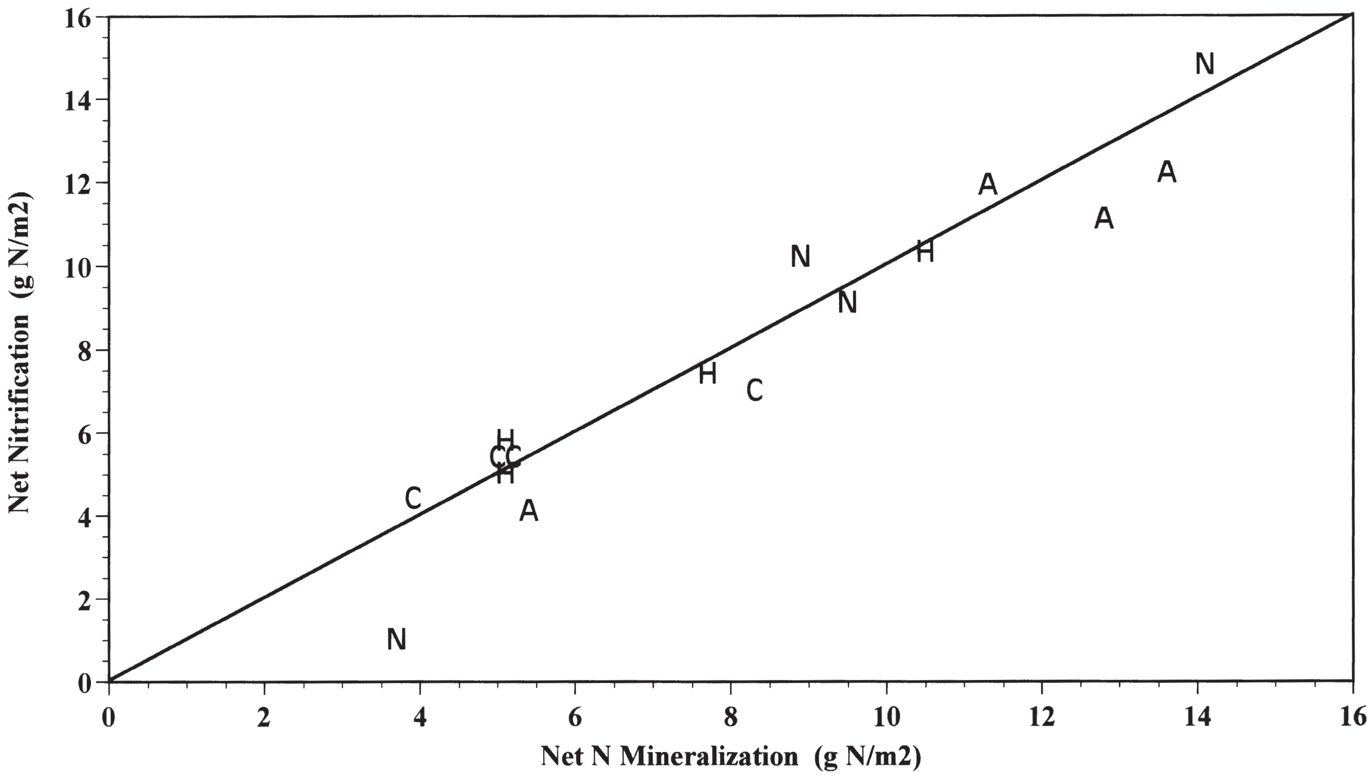

Figure 3—Nitrification versus N mineralization for individual plots during the post-treatment period. Data are mean values for each of four plots for four treatments; see fig. 2 for meaning of symbols. Correlation was significant at P<0.01, r = 0.95. Line given is a 1:1 line representing a condition wherein N mineralization is 100 percent nitrification.

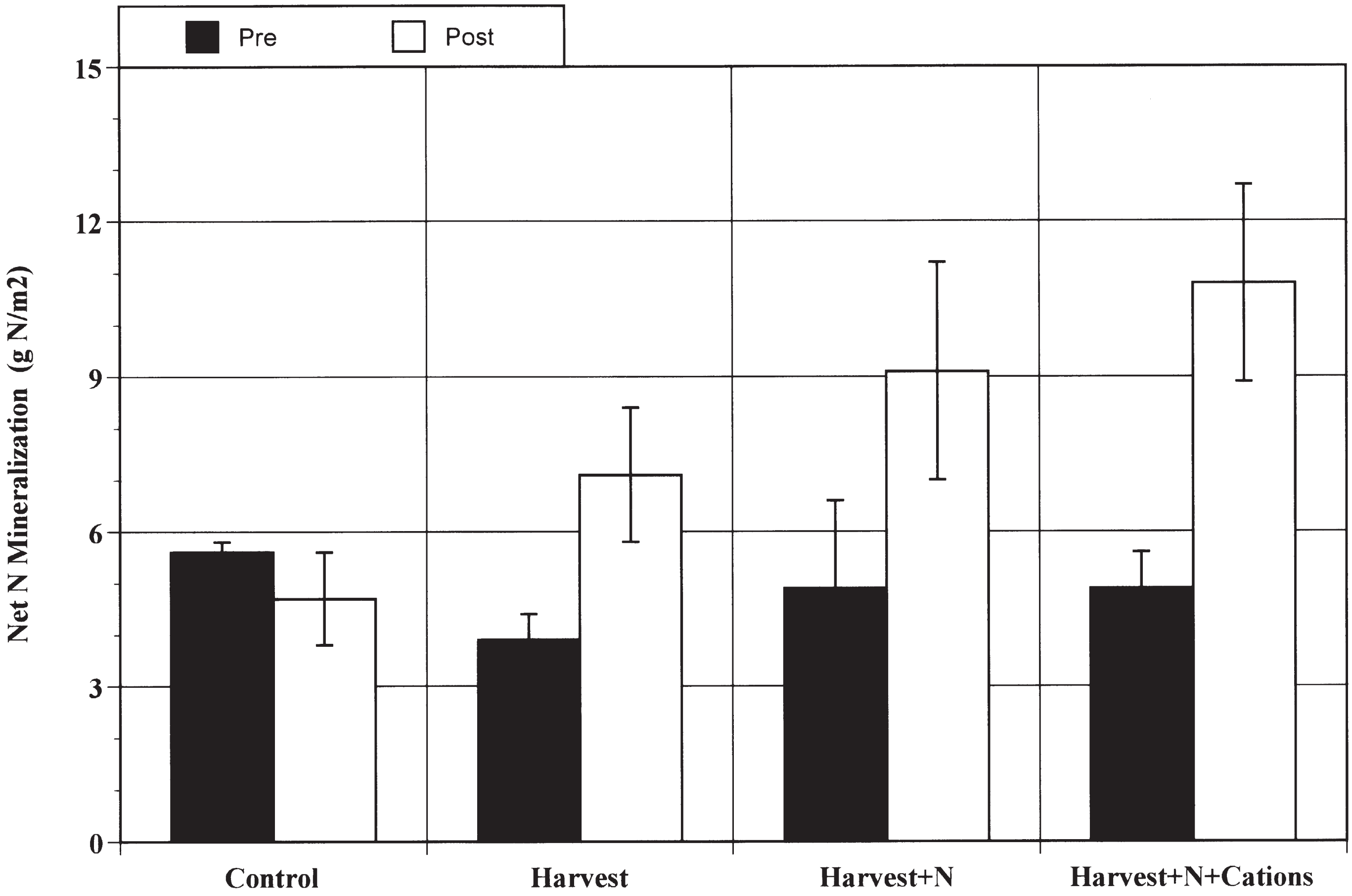

Figure 4—Net N mineralization for pre- and post-treatment periods for control and harvest treatment plots at Fernow Experimental Forest, WV. Data are means plus and minus one standard error of the mean. Analysis of variance revealed no significant differences among pre-treatment means. Pre- versus post-treatment differences were significant ($P<0.05$) for all harvest plots, but not for control plots.

however, it was important in this study to quantify harvest-mediated changes in soil temperature. Our data confirm that post-harvest increases in soil temperature can be prolonged and substantial (fig. 1). These increases likely arose from changes in the relationship between soil heat flux (S) and net radiation (Rn)(Rosenberg and others 1983). Idso and others (1975) showed that S (increases of which lead to increases in soil temperature) is highly positively correlated to Rn under a variety of soil conditions. The removal of the tree canopy during harvesting decreases interception of solar radiation and increases Rn, which increases S and results in the increased soil temperatures seen in fig. 1. These patterns have important implications for N dynamics and their responses to harvesting.

Not only was net nitrification highly correlated to net N mineralization, nitrification was also an extremely high proportion of N mineralization in both the pre- and post-treatment periods, regardless of treatment (figs. 2 and 3). Linear regressions of each of the sample periods closely approximated the theoretical 1:1 line that indicates a condition wherein nitrification is 100 percent of mineralization. These high rates of nitrification (relative to mineralization) are indicative of N saturation (Aber 1992), supporting findings and conclusions of Gilliam and others (1996) for three watersheds of FEF. This was especially the case during the post-treatment period for the harvest plots, suggesting that harvesting may enhance the relative predominance of nitrification in the N dynamics of N-saturated soils.

Patterns of soil temperature (fig. 1) combined with the relationships shown in figs. 2 and 3 are helpful in interpreting pre- versus post-treatment comparisons for N mineralization and nitrification rates (figs. 4 and 5). Koopmans and others (1995) have shown that increases in temperature greatly enhance N mineralization in N-saturated soils in Europe. Thus, the substantial increases in soil temperature caused by harvesting in our study, especially from early June to around mid September, caused significant increases in N mineralization in the soil. Furthermore, virtually all this enhancement was related to increases in nitrification, i.e., temperature-mediated increases in the activity of nitrifying bacteria.

Data from our study show also that there may be further increases in N mineralization/nitrification ratios under simulated conditions of additional N inputs and additions of

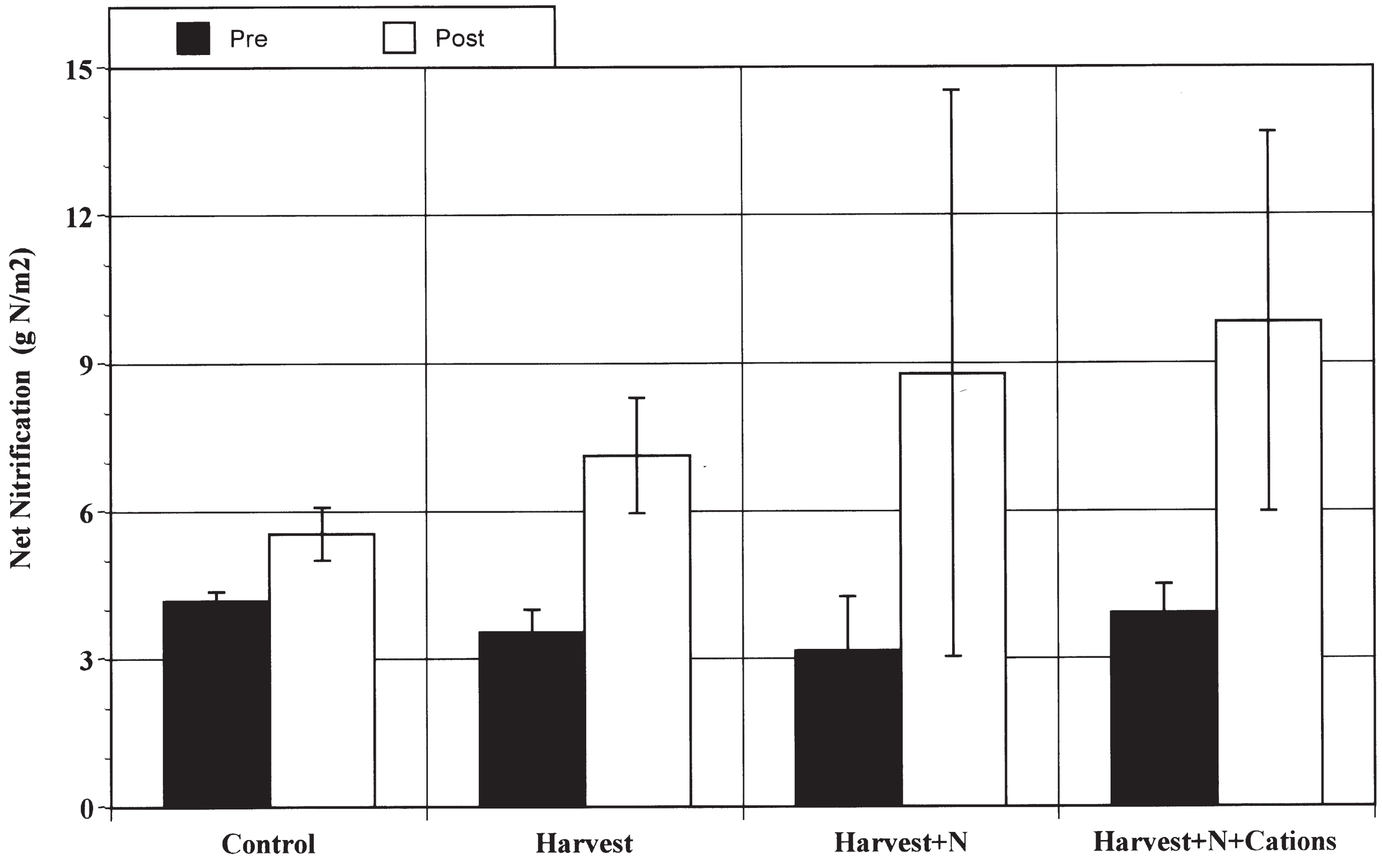

Figure 5—Net nitrification for pre- and post-treatment periods for control and harvest treatment plots at Fernow Experimental Forest, WV. Data are means plus and minus one standard error of the mean. Analysis of variance revealed no significant differences among pre-treatment means. Pre- versus post-treatment differences were significant for control plots at $P<0.10$ and for harvest and harvest+N+cations at $P<0.05$; difference for harvest+N plots was not statistically significant.

base cation designed to mitigate cation loss. Although differences were not significant among harvest treatments, there was a pattern of increases in N mineralization and nitrification related to N additions, and even greater increases with additions of base cations. This latter pattern suggests that mineralization and nitrification might be more pH limited than previously thought (Gilliam and others 1994, 1996). Future work at our site will test this hypothesis. Certainly, it suggests that managing central hardwood forests in a sustainable manner in the context of N saturation represents a complex challenge.

Implications for N Saturation in Central Hardwood Forests

Existing data from FEF strongly suggest a threat of base cation depletion and its relationship to N saturation in central Appalachian forests (Adams and others 1997, Gilliam and others 1996). Indeed, much evidence exists to suggest that soils at FEF already have become N saturated. For example, Gilliam and others (1996) found equally high rates of N mineralization based on one year's data from one N-treated (at rates identical to those in this study) and two untreated watersheds. Furthermore, nearly 100 percent of N mineralized was nitrified. On-going data from this study suggest a pattern of increasing rates through time for all three watersheds, regardless of treatment. Furthermore, available pools of N (extractable NH_4 and NO_3) were significantly higher on the treatment watersheds, suggesting that further additions of N to the treatment watershed are no longer resulting in increased uptake by plants or immobilization by microbes (Vitousek and Matson 1985).

Stoddard (1994) concluded that Watershed 4 (WS4—mature, second-growth forest) at FEF was one of the better examples of watersheds in the eastern United States which are at the later stages of N saturation. It is notable that WS4 supports a mature, mixed-age, second-growth hardwood stand and serves as the long-term control watershed at FEF, receiving no experimental treatments and, thus, it may be considered typical of many second-growth forests of the region (Gilliam and others 1996.

Using long-term (1971-1987) stream chemistry data from WS4 at FEF Edwards and Helvey (1991) found patterns of significant increases in specific conductivity with time. Using correlation analysis they concluded that most of this increase was related to increases in stream NO_3. Based on data from WS4 for an even longer time period (1969-1991), Peterjohn and others (1996) concluded that the patterns found by Edwards and Helvey (1991) were part of a larger scenario indicating N saturation for FEF.

The relative sensitivity of forest soils to accelerated cation leaching, pH depression, aluminum mobilization, and mineral weathering is largely unknown (Cronan and others 1990). Forest soils of the central Appalachians range from very resistant to very sensitive to such changes. Based on criteria established by Turner and others (1986), sensitive soils are those with combinations of low cation exchange capacity (CEC), intermediate base saturation, low pH, low levels of bases released via weathering, low sulfate adsorption capacities, and shallow soils. Given that a large percentage of soils in the Appalachian region falls within these criteria, data from this study strongly suggest that expected increases in timber harvesting, continued high levels of N deposition in the region, base cation depletion, and complications from N saturation all represent major threats to sustainability of central Appalachian forest ecosystems.

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