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Effects of a clearcut on the net rates of nitrification and N mineralization in a northern hardwood forest, Catskill Mountains, New York, USA★

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Abstract. The Catskill Mountains of southeastern New York receive among the highest rates of atmospheric nitrogen (N) deposition in eastern North America, and ecosystems in the region may be sensitive to human disturbances that affect the N cycle. We studied the effects of a clearcut in a northern hardwood forest within a 24-ha Catskill watershed on the net rates of N mineralization and nitrification in soil plots during 6 years (1994–1999) that encompassed 3-year pre- and post-harvesting periods. Despite stream NO_3^- concentrations that increased by more than 1400 μmol l^{-1} within 5 months after the clearcut, and three measures of NO_3^- availability in soil that increased 6- to 8-fold during the 1st year after harvest, the net rates of N mineralization and nitrification as measured by *in situ* incubation in the soil remained unchanged. The net N-mineralization rate in O-horizon soil was 1–2 mg N kg^{-1} day^{-1} and the net nitrification rate was about 1 mg N kg^{-1} day^{-1}, and rates in B-horizon soil were only one-fifth to one-tenth those of the O-horizon. These rates were obtained in single 625 m^2 plots in the clearcut watershed and reference area, and were confirmed by rate measurements at 6 plots in 1999 that showed little difference in N-mineralization and nitrification rates between the treatment and reference areas. Soil temperature increased 1 ± 0.8 °C in a clearcut study plot relative to a reference plot during the post-harvest period, and soil moisture in the clearcut plot was indistinguishable from that in the reference plot. These results are contrary to the initial hypothesis that the clearcut would cause net rates of these N-cycling processes to increase sharply. The *in situ* incubation method used in this study isolated the samples from ambient roots and thereby prevented plant N uptake; therefore, the increases in stream NO_3^- concentrations and export following harvest largely reflect diminished uptake. Changes in temperature and moisture after the clearcut were insufficient to measurably affect the net rates of N mineralization and nitrification in the absence of plant uptake. Soil acidification resulting from the harvest may have acted in part to inhibit the rates of these processes.

Introduction

The nitrogen (N) cycle in forest soil can be viewed as the result of competition among plant roots, heterotrophs, and autotrophs for available ammonium (NH_4^+) and nitrate (NO_3^-) (Riha et al. 1986). The effects of disturbances such as harvesting, soil freezing, and insect infestations can shift the balance

between these groups of organisms, and sharply alter the concentrations of NO_3^- and NH_4^+ in soils (Likens et al. 1969; Groffman et al. 2001; Lovett et al. 2002). Harvesting decreases the uptake of N by plant roots, and thereby allows a temporary excess production of NH_4^+ and NO_3^- by microbes in the soil. After a forest harvest, NO_3^- production by autotrophic nitrifiers is commonly in excess of that taken up by vegetation, resulting in large increases in NO_3^- concentrations in soil water, groundwater, and surface water (Likens et al. 1969; Adamson and Hornung 1990; Dahlgren and Driscoll 1994). Clearcutting in particular, typically results in water chemistry changes that can persist from a few years (Dahlgren and Driscoll 1994) to several decades (Swank 1988).

The removal of trees not only disrupts the N cycle, but is accompanied by several related soil disturbances that can change the rates of N-cycling processes such as compaction and mixing (Ryan et al. 1992), and alteration of the moisture and temperature regime in the vicinity of the removed trees (Stone 1973). An unresolved question regarding the effects of forest harvest is whether the resulting changes in NO_3^- concentrations of surface and subsurface waters are caused mainly by the primary effect of tree removal and consequent decrease of N uptake, or by the secondary effects of soil disturbance and resulting changes in rates of microbial N-cycling processes.

Reported increases in NO_3^- leaching after clearcutting have been attributed to the combined effects of increased N mineralization and nitrification, and decreased N uptake by vegetation (Likens et al. 1969; Vitousek 1981). Increases in N-mineralization and nitrification rates after a clearcut have been attributed to three factors: (1) increased soil temperatures during the growing season as a result of increased direct solar radiation to the forest floor, (2) increased soil moisture resulting from decreased transpiration, and (3) increased availability of labile organic matter in the soil in the form of slash and roots of the cut trees (Stone 1973; Gadgil and Gadgil 1978). Several other factors such as the C:N ratio of soil organic matter and slash, the extent of physical disturbance of soils, the stand age of the forest, and rates of denitrification can affect leaching losses of NO_3^- and NH_4^+ after clearcutting (Vitousek 1981; Lundborg 1997).

Until the late 1970s, most of the evidence that clearcutting increases the rates of microbial N-cycling processes was obtained through indirect methods such as measurements of NO_3^- and NH_4^+ concentrations in soil water and stream water before and after harvest (Vitousek and Melillo 1979). Increased concentrations of NO_3^- and NH_4^+ in drainage waters alone, however, may simply reflect increased availability of NH_4^+ to nitrifiers after the cessation of N uptake by vegetation following clearcutting.

Several studies have used buried-bag and closed-tube incubations to monitor rates of N mineralization and nitrification in soils affected by clearcutting in a wide variety of forest types and geographic locations (Matson and Vitousek 1981; Gordon and Van Cleve 1983; Frazer et al. 1990; Brais et al. 2002), but in none of these studies were rates of microbial N-cycling processes measured in the context of a whole-watershed study in which losses in soil water and stream

water were also measured. In the current study, measurements of these rates were combined with NO_3^- and NH_4^+ concentrations in soil water and stream water, indices of N availability in soil, and soil temperature and moisture data to examine the relative roles of increased microbial N cycling rates and lack of N uptake by vegetation after a clearcut.

The Catskill Mountain region receives atmospheric N deposition at a rate of 10–15 kg ha^{-1} $year^{-1}$, one of the highest rates in the northeastern United States (Ollinger et al. 1993). Concentrations and fluxes of NO_3^- in Catskill stream water vary widely in response to variations in forest history and species composition (Lovett et al. 2000). A trend of increasing NO_3^- concentrations since the 1970s in many Catskill streams has been attributed to the advance of N saturation, whereby atmospheric inputs of N gradually exceed the retention capacity of biota resulting in increased leaching of NO_3^- into drainage waters (Murdoch and Stoddard 1992). Stream NO_3^- concentrations in the Catskills fluctuate annually, seasonally, and episodically in response to factors that affect (1) the rate of net nitrification in soils (Murdoch et al. 1998; Lovett et al. 2000), and (2) the hydrologic transport of nitrified NO_3^- to streams (Burns et al. 1998; Burns and Kendall 2002).

In this study, our objectives were to measure changes in (1) stream water NO_3^- concentrations, (2) indices of N abundance in soil, and (3) net rates of N mineralization and nitrification in the soil before and after a clearcut in a 24-ha forested watershed in the Catskill Mountains. We answer the question of whether the increase in NO_3^- concentrations can be explained solely by decreased vegetation N uptake after harvesting. The higher rates of atmospheric N deposition and the more advanced N-saturation status of Catskill forested ecosystems than in previous clearcut studies in North America (such as at Hubbard Brook, NH) were expected to result in a greater release of N and greater NO_3^- concentrations in drainage waters than have been reported previously.

Study area

The Catskill Mountains is a forested region in southeastern New York consisting of an uplifted plateau that has been eroded and dissected by streams and overlain by a veneer of till from the most recent glaciation of North America (Rich 1934; Buttner 1977). The study area is in the Neversink River basin (Figure 1), is underlain by sandstone and conglomerate, and is overlain by 1–2 m of till in which Inceptisols have developed. The soil is classified in the Arnot-Oquaga-Lackawana series (Tornes 1979) and is a bouldery silt loam with shallow organic horizons (1.5–8 cm). Vegetation consists of northern hardwood forest dominated by American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), and yellow birch (*Betula alleghaniensis*). The elevation range in the study watersheds is 650–890 m.

The climate of the Catskill Mountains is classified as humid continental, with cold winters and moderately warm summers. The mean annual temperature

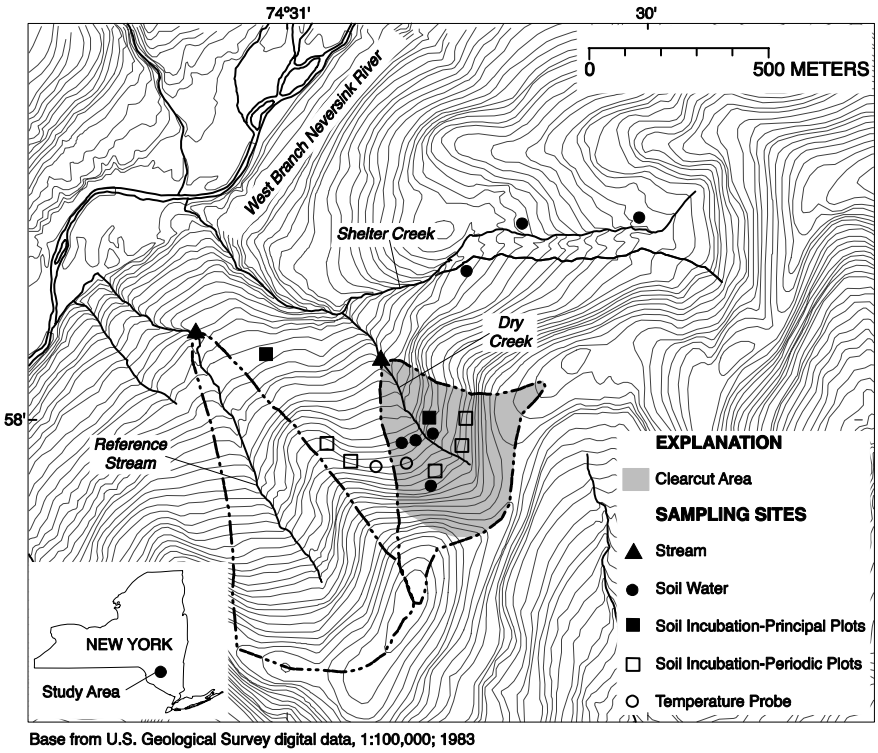

Figure 1. Principal features of study area and locations of sampling sites.

at the Slide Mountain weather station (~5 km east of study site, 808 m elevation) is 4.6 °C (1961–1990 mean, National Oceanic and Atmospheric Administration). Mean annual precipitation is 153 cm, of which 20–25% falls as snow. Precipitation amounts are uniformly distributed throughout the year, but 32% of the 970 mm annual runoff in the Neversink River basin occurs during the snowmelt period of March and April, whereas only 28% occurs in May through September (1951–1994 means, Firda et al. 1995).

Methods

The study used a paired watershed approach in which a 24-ha watershed (Dry Creek) was clearcut in early 1997, and an adjacent 48-ha watershed (reference) was left undisturbed. Most of the soil-based measurements were done on undisturbed forested land that was located closer to the clearcut than the adjacent reference watershed. During the 3-year pre-harvest period (1994–1996) and the 3-year post-harvest period (1997–1999), soil temperature and

Table 1. Biomass, N content, and basal area of trees calculated from plots in the clearcut and reference watersheds before and after the 1997 clearcut (Yorks 2001)

Variable	Clearcut[a]	Reference
Pre-harvest		
Biomass (Mg ha^{-1})	232	295
N content (kg ha^{-1})	703	909
Basal area (m^2 ha^{-1})	27.8	36.4
Post-harvest		
Biomass (Mg ha^{-1})	5.6	294
N content (kg ha^{-1})	17	905
Basal area (m^2 ha^{-1})	0.7	36.3

Values apply to trees with diameter at breast height >5 cm.
[a]Values apply only to harvested part of watershed.

moisture and the net rates of N-mineralization and nitrification were measured in soil plots, and these data were supplemented with measurements of NO_3^- and NH_4^+ concentrations in stream water, soil water, and buried ion-exchange-resin.

Forest harvest

The Dry Creek watershed was clearcut from December 1996 through March 1997, and the slash (branches and tree tops) was left behind. About 80% of this watershed above the principal stream sampling site was clearcut; the uppermost (southwest) corner is owned and protected by New York State and, therefore, could not be harvested.

Biomass, N content, and the basal area of trees were determined in several representative 20×20-m vegetation plots; nine were in the clearcut watershed, and 10 in the reference watershed (Yorks, 2001). These measurements indicate that the reference watershed had 25–30% greater biomass, N content, and basal area than the clearcut watershed prior to the harvest (Table 1). Clearcutting decreased the basal area in the Dry Creek watershed (cut area only) by about 97%.

Field measurements

Stream water and soil water

Stream stage was recorded every 15 min at Dry Creek by a transducer/data logger system in an H-flume; these values were converted to streamflow using a rating curve.

Stream-water samples were collected biweekly at the Dry Creek stream gage and at the reference stream. Samples were collected in 500-ml polyethylene bottles and stored on ice until the samples were brought to the USGS laboratory. Additional samples were collected during high flows at Dry Creek only,

by an automated sampler/pressure transducer system in which sampling was initiated by a rise or fall in stream stage.

Soil water samples were collected monthly during summer (June–Sept.) and winter (Dec.–Feb.) and biweekly during fall (Oct.–Nov.) and spring (March–May) from seven zero-tension lysimeters installed just below the forest floor (5–10 cm depth), and seven installed in the B horizon (about 25-cm depth). Three of these lysimeter sites were in an adjacent watershed in which about 10% of the biomass was removed in a thinning harvest in 1995–1996, but a 1000 m^2 area surrounding each of these lysimeter sites was not harvested, and sites were assumed to represent undisturbed conditions. The other four lysimeter sites were located in the clearcut area (Figure 1).

N-Mineralization and nitrification rates

N-mineralization and nitrification rates were measured at two paired plots (hereafter referred to as the N cycling study plots), one in the clearcut part of the Dry Creek watershed, and one in an uncut area located between the Dry Creek and reference watersheds (Figure 1). The representativeness of the principal study plots was later assessed through measurements in six plots – four in the clearcut area and two in the reference area during August 1999, and three in the clearcut area and three in the reference area during October 1999. Two of these six plots were the same as the N cycling study plots sampled routinely throughout the study.

Each plot was about 25 × 25 m, and was located in mixed deciduous forest dominated by American beech (*Fagus grandifolia*) and sugar maple (*Acer saccharum*). New plots were established each year within the same general area to avoid soil disturbance from the previous year. Eight replicate measurements were made at each plot during each sampling period. Samples were collected every 4 weeks from April through November except during 1999, when they were collected every other 4-week period from April through November.

Net nitrification and N-mineralization rates were measured in 1994 and 1995 by an *in situ* buried bag incubation procedure described by Eno (1960). For each soil sample, a 15-cm square of the combined O_e and $O_a$horizons was removed and placed in a plastic bag, then reburied in the forest floor for a 28-day incubation. Similarly, a 2 cm-diameter core of B-horizon soil 5 cm long (from a depth of 12–17 cm) was incubated. Samples were collected at the beginning of the incubation to establish initial concentrations of NO_3^- and NH_4^+ in the O and B horizons. These measurements provided the KCl-extractable NO_3^- and NH_4^+ concentrations discussed in this paper.

Soil samples were incubated during 1996–1999 by a closed-tube incubation method in which a 5 cm ID PVC pipe was driven into the ground to isolate a core of soil (Raison et al. 1987). The pipe was driven to a depth of 20 cm, and then capped to prevent infiltration. This method is believed to be superior to the buried-bag technique because the core remains intact, resulting in less disturbance of the soil. A side-by-side comparison of the two techniques, performed on 32 forest floor and mineral soil samples from two plots, indicated

that the net nitrification rates obtained by the buried-bag method were slightly higher, but not significantly different than those obtained with the pipe method ($p = 0.068$, two-tailed t-test).

Soil temperature

Soil temperatures in the O and B horizon were measured hourly from March 1997 through September 1999 by a thermistor probe and data-logger system at a site in the clearcut watershed and at a site under deciduous canopy in the adjacent reference area. Soil temperature in the O and B horizon also were measured with a thermistor probe immediately adjacent to every other soil sample collected at the start of each incubation.

Ion-exchange resin bags

During 1997–1999, N cycling measurements were supplemented with measurements of N availability as indicated by buried resin bags. Eight replicate ion-exchange resin bags made from nylon stockings were buried 3–4 times $year^{-1}$ at the base of the forest floor (about 5 cm depth) in each of the routine measurement plots for a period of 8 weeks that spanned two of the routine soil-incubation periods (method slightly modified from Binkley and Matson 1983; Giblin et al. 1994). These resin bags consisted of mixed cation–anion-exchange resins (OH^-/H^+ type) to which NO_3^- and NH_4^+ adsorbs. This method differs from the pipe-incubation method in that the resin bags are open to infiltrating water and, thus, provide an index of inorganic-N availability in excess of biological uptake.

Laboratory measurements

Stream and soil water samples for NO_3^- analysis were passed through 0.4 μm membrane filters at the laboratory in Troy, NY and stored at 4 °C until analysis. An aliquot of each stream-water and soil-water sample was poured off for NH_4^+ analysis at the laboratory and stored frozen. Nitrate concentrations were analyzed by ion chromatography, and NH_4^+ concentrations were analyzed by the phenolate method in an automated flow-injection spectrophotometric system (Lawrence et al. 1995). Data-quality objectives for precision and accuracy of these analyses were 10% (coefficient of variation), and these objectives were generally met more than 95% of the time (Lincoln et al. 1996).

Soil samples were weighed and extracted upon returning to the laboratory – usually within 3 h of collection. About 10 g of field moist B-horizon soil or 15 g of O-horizon soil were added to 50 ml of 1 M KCl and agitated for 20 min on a rotary-arm shaker. After shaking, samples settled overnight and were passed through GF/F glass fiber filters the next morning. Filtered extracts were stored frozen until analysis. The extracts were analyzed for NH_4^+ by the same method that was used for the stream- and soil-water samples. Nitrate

concentrations were determined by a cadmium column/sulfanilamide method in an automated flow injection spectrophotometric system (Lawrence et al. 1995).

The ion-exchange resin was air dried upon arrival from the field, then oven dried at 105 °C for 24 h prior to extraction with 1 M KCl. The KCl extracts were then stored frozen until analysis by the same methods as the soil extracts.

The percent moisture in each soil sample was measured gravimetrically by first weighing the sample at field (moist) condition, then reweighing after 24 hr of drying in an oven (65° C for O-horizon soil, 105° C for B-horizon soil).

Stream and soil NO_3^- export

Stream NO_3^- export, and the total amount of NO_3^- theoretically generated by net nitrification at the rates measured in the soil, were estimated for the one-year period with highest stream NO_3^- concentrations (August 1997 – July 1998) through Eqs. (1) and (2):

$$\text{Stream } NO_3^- \text{ export} = \text{mean daily } NO_3^- \text{conc.} \times \text{mean daily discharge} \quad (1)$$

$$\text{Nitrified } NO_3^- = \text{median nitrification rate} \times \text{soil thickness} \times \text{soil bulk density} \quad (2)$$

No flow-concentration relation was detected for NO_3^- using either a log-discharge relation or a hyperbolic regression model (Johnson et al. 1969) during the year following the clearcut because NO_3^- concentrations varied widely with time after the cut. Daily NO_3^- concentrations were instead estimated using linear interpolation for days between sample collection; this approach likely provided a reasonable load estimate because of the high frequency of sample collection at the site (110 fixed interval and storm samples were collected during the period).

Median net nitrification rates were derived from the median values measured during the post-harvest period (1997–1999) of 0.78 mg N kg^{-1} day^{-1} in the O-horizon and 0.15 mg N kg^{-1} day^{-1} in the B-horizon. The O-horizon was assumed to be 5 cm thick and the B-horizon 25 cm thick based on observations during soil sampling (an A-horizon is rarely present in these soils). Nitrification was assumed to be the sum of NO_3^- derived by the rates in the O and B horizons. No nitrification was assumed to occur below the B horizon. Bulk density values were from a previous study in the Dry Creek watershed and were 0.18 Mg m^{-3} in the O-horizon and 0.91 Mg m^{-3} in the B horizon (Ashby et al. 1998). The B horizon was assumed to be one-third rock based on observations during soil sampling. The calculated rates were assumed to apply for 270 days during the year (rates were not measured in winter and were assumed to be negligible).

Data analysis

Despite the use of replicate measurements within each plot, neither the plots nor the clearcut watershed were replicated; inference is therefore limited to the population sampled (Hurlbert 1984). The risk of unreplicated treatments is that plot or watershed differences will be falsely attributed to the effects of the treatment. We attempted to overcome this limitation by: (1) collecting 3 years of pre-treatment data to examine background differences between reference and harvested plots, watersheds, and lysimeters, (2) measuring N-mineralization and nitrification rates during 1999 at multiple plots on two occasions, (3) using a multi-evidence approach to draw conclusions wherever possible, and (4) comparing the results with those from harvesting studies in similar forest settings such as the Hubbard Brook Experimental Forest in New Hampshire. The net rates of N-mineralization and nitrification in the clearcut and reference plots were not normally distributed, and were therefore compared using the Mann–Whitney rank sum test for nonnormal populations. The rates of these processes for data collected at multiple plots on the same date were compared through application of the Kruskal–Wallis test (Conover 1980). A p value of 0.05 was used as a measure of significance for all statistical tests.

Results

This section presents (1) stream NO_3^- and NH_4^+ concentrations and NO_3^- export, (2) NO_3^- and NH_4^+ concentrations in soil water, soil extracts, and ion-exchange-resin bags, (3) N-mineralization and nitrification rates, and (4) soil temperatures and soil-moisture content in the clearcut and reference watersheds (or reference areas) during the pre- (1994–1996) and post-harvesting (1997–1999) periods.

Stream NO_3^- and NH_4^+ concentrations and NO_3^- export

Three months after the clearcut, NO_3^- concentrations in Dry Creek increased from about 20 μmol l^{-1} to >100 μmol l^{-1}, an unprecedented value at this site, and continued to increase sharply through August 1997; concentrations reached a peak of about 1400 μmol l^{-1} during a storm (Figure 2). The NO_3^- concentrations in Dry Creek remained elevated above those in the reference stream through the rest of the study (through 1999), and both streams continued to show seasonal variation similar to the pre-harvest period. The NO_3^- concentrations in Dry Creek did not decrease to <200 μmol l^{-1} until late spring of 1998, more than one year after harvest, and had decreased to about 90 μmol l^{-1} by December 1999, 33 months after harvest – still greater than any NO_3^- concentrations measured in the reference stream.

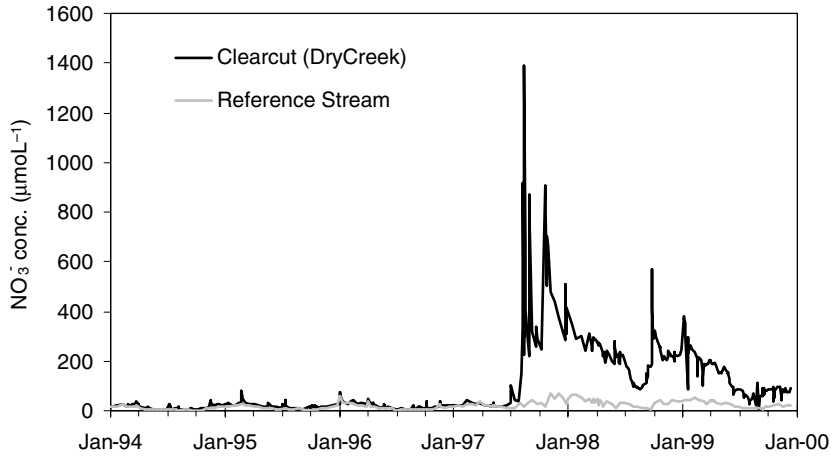

Figure 2. Nitrate concentrations in Dry Creek and the reference stream, 1994–1999. The vertical line represents the date when the clearcut was completed.

Ammonium concentrations in Catskill streams typically range from only 1 to 2 μmol l^{-1}, values that are below the laboratory reporting limit of 2 μmol l^{-1} (Lincoln et al. 1996); therefore, NH_4^+ concentrations are not routinely measured in surface water samples. Limited measurements of NH_4^+ concentrations during this study, however, indicate that elevated values of 5–10 μmol l^{-1} were common in Dry Creek samples collected during 1997–1998 after the clearcut, whereas reference-stream samples were near or below the reporting limit (data not shown).

Stream export of NO_3^- at Dry Creek was 34.2 kg N ha^{-1} during the August 1997 through July 1998 year of highest NO_3^- concentrations, whereas the potential export of NO_3^- as estimated from the rate of net nitrification was 81 kg N ha^{-1}. This contrasts with stream export that ranged from 1.4 to 2.4 kg ha^{-1} $year^{-1}$ in Dry Creek during the 1994–1996 water years that preceded the harvest. Similar values in the range of 1–3 kg ha^{-1} $year^{-1}$ have been published for nearby undisturbed forested watersheds in the Neversink River basin (Lawrence et al. 2000; Lovett et al. 2000).

Measures of N availability in soil

Three measures were used to evaluate N availability and mobility in the soil after harvesting, including NO_3^- and NH_4^+ concentrations in: (1) soil-water from lysimeters, (2) KCl extractions of soil collected at the beginning of each incubation, and (3) ion-exchange-resin bags. All three measures showed a similar pattern of a 6- to 10-fold increase in NO_3^- concentrations in the clearcut.

Soil water

Mean annual NO_3^- concentrations in O-horizon soil water at Dry Creek increased from 50 to 60 μmol l^{-1} before the clearcut, to about 360 μmol l^{-1} during the first year after the clearcut (1997), then decreased steadily to about 170 μmol l^{-1} by 1999, whereas concentrations in reference O-horizon soil water remained at 20–25 μmol l^{-1} throughout the study (Figure 3a). Mean annual NO_3^- concentrations in B-horizon soil water in the Dry Creek watershed increased from 20 to 30 μmol l^{-1} before the clearcut to 370 μmol l^{-1} during 1997, then increased further to 430 μmol l^{-1} in 1998, before decreasing to about 170 μmol l^{-1} in 1999, whereas those in the reference area remained at about 10 μmol l^{-1} throughout the study (Figure 3a). The variation in soil water NO_3^- concentrations in the O and B horizons in the Dry Creek watershed increased substantially after harvesting.

Changes in NH_4^+ concentrations in soil water after the clearcut were less than the changes in NO_3^- concentrations. Mean annual NH_4^+ concentrations in O-horizon soil water in the Dry Creek watershed during 1994–1996 ranged from 10 to 20 μmol l^{-1}, increased to about 35 μmol l^{-1} after the clearcut in 1997, then decreased to about 20 μmol l^{-1} in 1998, and to <10 μmol l^{-1} in 1999 (Figure 3b). Mean annual NH_4^+ concentrations in O-horizon soil water from the reference area remained at 5–10 μmol l^{-1} throughout 1994–1999. Mean annual NH_4^+ concentrations in B-horizon soil water were <5 μmol l^{-1} in both the reference area and the Dry Creek watershed before the clearcut, and did not measurably change at Dry Creek after the clearcut Figure 3b).

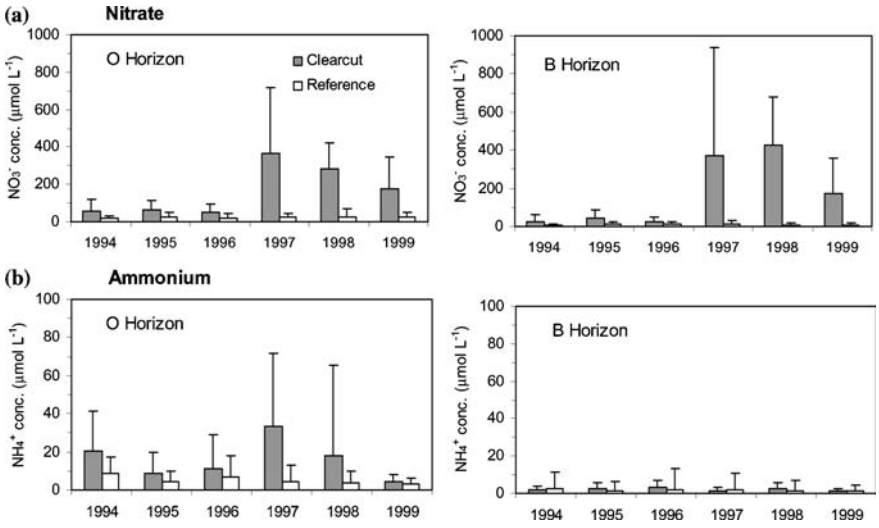

Figure 3. Mean annual NO_3^- and NH_4^+ concentrations in soil water in the clearcut (Dry Creek) watershed ($n = 4$) and in undisturbed soil (reference, $n = 3$), 1994–1999. (a) Nitrate in O-horizon and B-horizon soil; (b) ammonium in O-horizon and B-horizon soil. Error bars are the standard deviation of the mean.

Soil extracts

Mean KCl-extractable NO_3^- concentrations showed a response pattern similar to that of soil water. O-horizon values at the Dry Creek study plot increased 6- to 8-fold in response to the clearcut, and reached a peak value of about 40 mg NO_3–N kg^{-1} in 1998, the second full year after the clearcut (Figure 4a). Unlike soil water NO_3^- concentrations, however, KCl-extractable NO_3^- returned to background values of <5 mg NO_3–N kg^{-1} by 1999. Mean concentrations in B-horizon soil followed a pattern of change similar to that of the O-horizon soil in response to the clearcut, except the values were about an order of magnitude lower (Figure 4a).

Mean KCl-extractable NH_4^+ was 60 mg NH_4–N kg^{-1} during 1997 in O-horizon soil from the Dry Creek N cycling plot, about 3-fold higher than the pre-harvest values during 1994–1996 (Figure 4b). This value then decreased to about 40 mg NH_4–N kg^{-1} in 1998, and to < 5 mg NH_4–N kg^{-1} by 1999. The mean annual concentration in Dry Creek soil samples was similar to that of the reference plot during 1998, but was less than the reference during 1999.

Mean KCl-extractable NH_4^+ in B-horizon soil in the Dry Creek N cycling plot was 6 mg NH_4–N kg^{-1} in 1997, 2- to 3-fold higher than the pre-harvest values in 1994–1996 (Figure 4b). This value then decreased to about 4 mg NH_4–N kg^{-1} in 1998, and to < 1 mg NH_4–N kg^{-1} by 1999. Mean KCl-extractable NH_4^+ in the reference plot ranged from 2 to 3 mg NH_4–N kg^{-1}

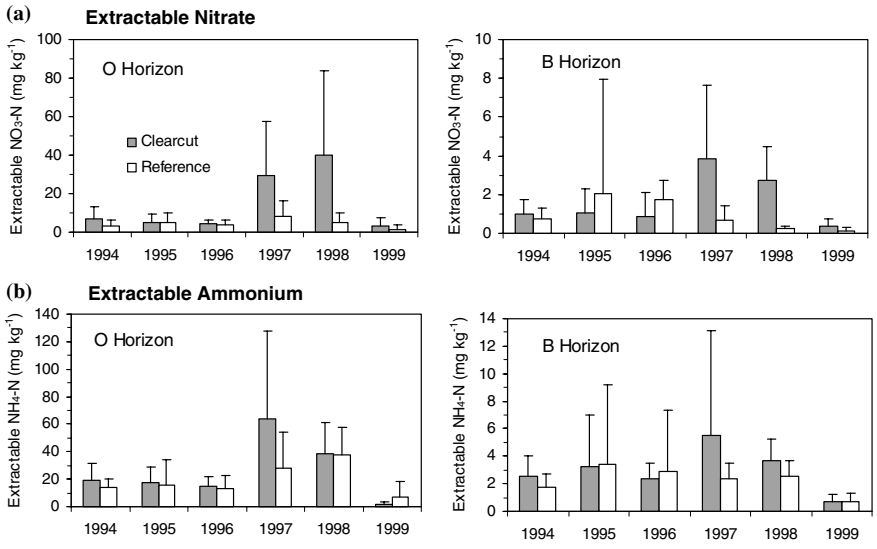

Figure 4. Mean nonwinter KCl-extractable NO_3^- and NH_4^+ concentrations in soil from the principal study plots in the clearcut watershed and in the reference area, 1994–1999. (a) Extractable nitrate in O-horizon and B-horizon soil; (b) extractable ammonium in O-horizon and B-horizon soil. Error bars are the standard deviation of the mean by horizon and constituent.

Table 2. Mean concentrations of NO_3–N and NH_4–N in ion-exchange resin bags at the principal study plots in the clearcut watershed and a reference area during 1997–1999

	NO_3–N		NH_4–N	
Year	Clearcut	Reference	Clearcut	Reference
1997	3.0 (5.1)	0.09 (0.07)	0.25 (0.24)	0.12 (0.11)
1998	2.8 (4.8)	0.05 (0.04)	0.05 (0.04)	0.09 (0.08)
1999	0.06 (0.10)	0.11 (0.16)	0.05 (0.05)	0.17 (0.17)

Concentrations are in mg N g^{-1} resin and are based on four 8-week sample periods each year (April–November) and 8 replicate measurements at each plot. Concentrations in parentheses are the standard deviation of the mean.

during 1994–1998, then decreased to < 1 mg NH_4–N kg^{-1} by 1999, similar to that of the Dry Creek plot.

Resin bags

The buried ion-exchange resin bags at the Dry Creek plot had a mean value of 3.0 mg NO_3–N g^{-1} the first year after harvest (1997) and were 2.8 mg NO_3–N g^{-1} in 1998, more than an order of magnitude greater than in the reference plot (Table 2). The mean value then decreased precipitiously in 1999 to 0.06 mg NO_3–N g^{-1} at the Dry Creek plot, but remained about the same during 1997–1998 (0.11 mg NO_3–N g^{-1}) at the reference plot. Ammonium values on ion-exchange resin showed a smaller response to clearcutting than those of NO_3^-. Mean values in the Dry Creek plot during 1997, the first post-harvest year were 0.25 mg NH_4–N g^{-1}, about twice the mean value in the reference plot, but then decreased to 0.05 mg NH_4–N g^{-1} in 1998 where they remained through 1999. The values at the reference plot remained fairly constant throughout 1997–1999.

N-Mineralization and nitrification rates

Mean N-mineralization rates in O-horizon soil at the Dry Creek plot ranged from 1 to 2 mg N kg^{-1} day^{-1} during 1994–1999, without an obvious response to the clearcut (Figure 5a). These rates were similar at the reference plot except during 1997–1998, when they were somewhat higher (> 2 mg N kg^{-1} day^{-1}). Mean nitrification rates in O-horizon soil also showed no noticeable response to the clearcut in the Dry Creek plot; most values were about 1 mg N kg^{-1} day^{-1}, except for a mean value during 1994 of about 2 mg N kg^{-1} day^{-1} (Figure 5b).

Mean N-mineralization rates in B-horizon soil were nearly an order of magnitude lower than in O-horizon soil and ranged from 0.2 to 0.4 mg N kg^{-1} day^{-1} at both sites throughout 1994–1999 (Figure 5a). Again, the rates showed no obvious response to the clearcut at the Dry Creek plot. Mean nitrification rates, like N-mineralization rates, were more than an order of magnitude lower

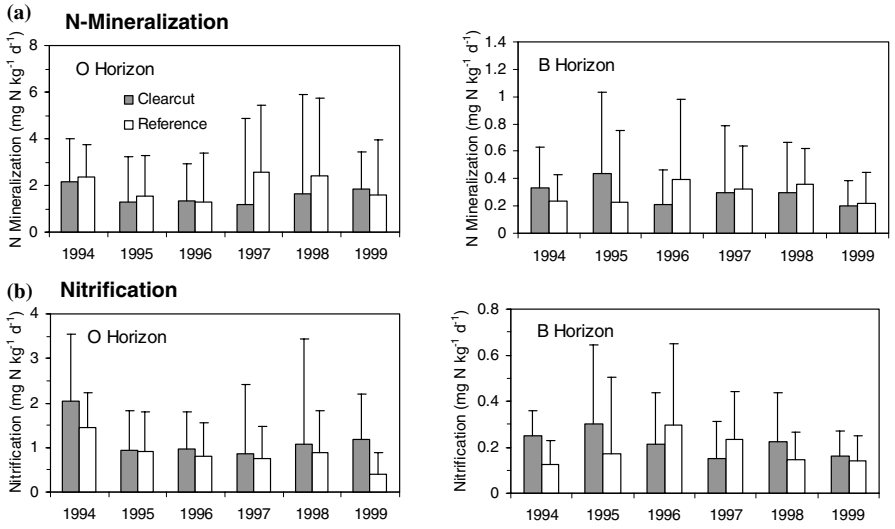

Figure 5. Mean nonwinter rates of soil N-cycling processes in soil from the principal study plots in the clearcut watershed and in the reference area, 1994–1999. (a) N mineralization in O-horizon and B-horizon soil; (b) nitrification in O-horizon and B-horizon soil. The error bars are the standard deviation of the mean.

in the B-horizon than in the O-horizon and showed no noticeable response to the clearcut (Figure 5b). Mean rates at both sites ranged from about 0.1–0.3 mg N kg^{-1} day^{-1}, and the rate in the reference plot was higher than that in the Dry Creek plot during 1997, the first year after the clearcut.

The results of Mann–Whitney rank sum tests largely confirmed the qualitative observations described above (Table 3). The N-mineralization and nitrification rates generally showed no significant differences between the clearcut and reference plots, with two exceptions: (1) N-mineralization rates in the O-horizon during the post-harvest period were greater in the reference plot than in the clearcut plot, and (2) nitrification rates in the B-horizon during the pre-harvest period were greater in the clearcut plot than in the reference plot (Table 3). The Mann–Whitney results indicate that the median net nitrification rate in O-horizon soil in the clearcut plot would have had to exceed that of the reference plot by 0.39 mg N kg^{-1} day^{-1} to be considered significantly greater during the post-harvest period (1997–1999), and the net nitrification rate in B horizon soil would have had to exceed that of the reference plot by 0.03 mg N kg^{-1} day^{-1} to be considered significantly greater. Instead, these median rates in the clearcut plot were only 0.13 mg N kg^{-1} day^{-1} greater than the reference plot in O-horizon soil after harvesting and 0.02 mg N kg^{-1} day^{-1} greater than the reference plot in B horizon soil (Table 3).

The data collected from multiple plots during July and October 1999 show that the principal plots used in the study were generally representative of the soil in the clearcut and reference areas. Five of eight comparisons made among

Table 3. Median net rates of N mineralization and nitrification at the principal study plots in the clearcut watershed and a reference area during the pre-harvest (1994–1996) and post-harvest (1997–1999) periods

	Pre-Harvest (1994–1996)				Post-Harvest (1997–1999)			
	O-horizon		B- horizon		O-horizon		B-horizon	
Measurement	Clr	Ref	Clr	Ref	Clr	Ref	Clr	Ref
N-mineralization	0.90	1.21	0.23	0.17	1.19	2.22*	0.21	0.26
Nitrification	0.75	0.67	0.19*	0.11	0.78	0.65	0.15	0.13

Asterisk denotes highest value of measurements that differ significantly among the clearcut and reference plots according to the Mann–Whitney rank sum test.

the groups showed no significant difference among the six plots. All four instances in which the mean rank of values was significantly greater than the overall mean rank were for plots in the reference area, and in six of seven instances in which the mean rank of values was significantly less than the overall mean rank, these plots were in the clearcut watershed. In only one case was the mean rank of one of the single study plots either significantly greater or less than the mean rank of all plots.

Soil temperature and moisture

The data from continuously recording temperature probes and from temperature measurements associated with the incubations indicate that the soil was generally warmer after the clearcut than before (Figure 6a, b). O-horizon soil at the Dry Creek site was generally 0.3–1.3 °C warmer on average than the reference site during the post-harvest years, except during 1999, when the continuously recording probes indicated that the Dry Creek site was about 1.5 °C cooler on average than the reference site (Figure 6a). The B horizon showed an even greater temperature difference – both sets of measurements during 1997–1999 indicated that Dry Creek B-horizon soil was on average 0.6–1.8 °C warmer than at comparable locations in the reference area. The temporal variation at these sites results from seasonal changes in soil temperatures, however, a clear pattern emerged of consistently warmer temperatures at the Dry Creek site than the reference site throughout the summer, and little difference between the sites during winter.

Comparison of temperature data from the soil incubations with those from the continuously recording probes entails two considerations: (1) these two sets of measurements were not made in the same locations and (2) the incubations represent point measurements made every 4 weeks, whereas the probes provided a continuous record. Despite these differences, the two sets of measurements show a relatively consistent pattern in which soil in the

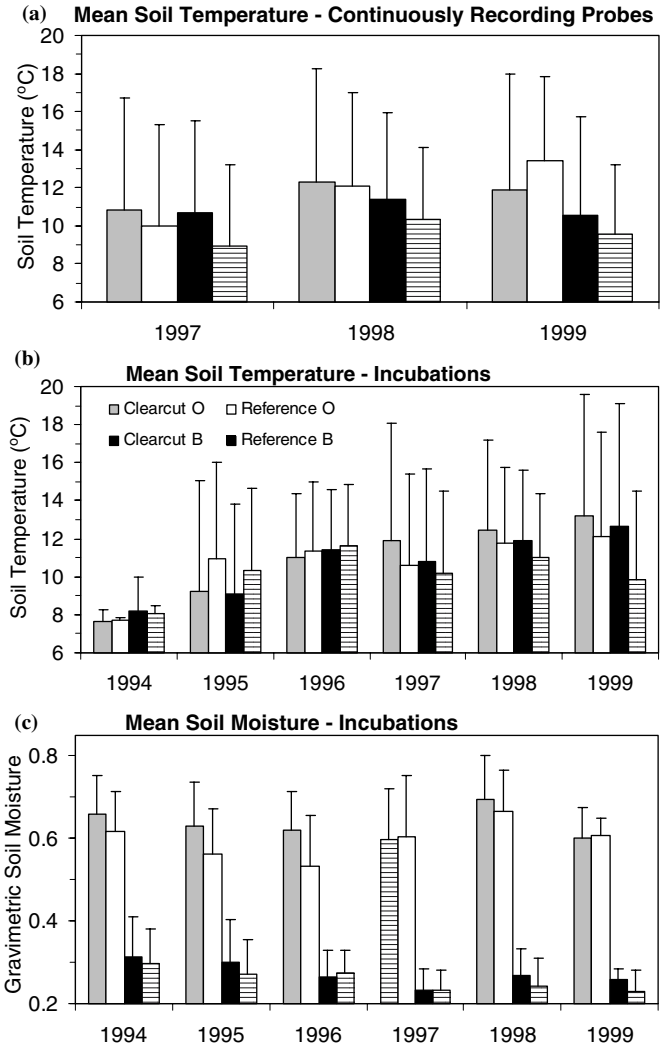

Figure 6. Mean nonwinter measurements of soil temperature and soil moisture in the clearcut watershed and in the reference area. (a) Soil temperature in shallow and deep soil as measured by thermistor probes, 1997–1999; (b) soil temperature from measurements at the beginning and end of each soil incubation in the principal study plots, 1994–1999; (c) gravimetric soil moisture from measurements made at the beginning and end of each soil incubation in the principal study plots, 1994–1999.

clearcut watershed was 1 $\pm$0.8 °C warmer than in the reference area during the first 3 years after harvest (with one exception during 1999 noted above).

Gravimetric soil-moisture data collected at the start and end of each incubation do not show the expected increase in soil moisture at the Dry

Creek plot after the clearcut (Figure 6c). Mean soil moisture values at the Dry Creek plot during the first post-harvest year (1997) were virtually indistinguishable from those in the reference plot. Mean soil moisture in the Dry Creek plot during 1998 was somewhat greater than in the reference plot, but a similar difference was measured in 1994 and 1995, before the clearcut. Mean soil moisture in the B-horizon was greater at the Dry Creek plot during 1999 than at the reference plot, but the O-horizon values were indistinguishable.

Discussion

Stream NO_3^- concentrations and soil N availability

Stream NO_3^- concentrations in Dry Creek increased more than 100-fold relative to the reference stream and to pre-harvest values within 4 months after completion of the clearcut harvest. The enhanced export of NO_3^- from Dry Creek during the first year after completion of the clearcut was estimated to be about 32 kg N ha^{-1} . These increases in NO_3^- concentration and export are generally consistent with observations after a clearcut and whole-tree harvest at the Hubbard Brook Experimental Forest (Likens et al. 1969; Likens and Bormann 1974; Dahlgren and Driscoll, 1994) and with observations at a wide variety of forests throughout North America and Europe in which several different harvesting methods were used (Fredriksen 1971; Krause 1982; Adamson and Hornung 1990; Reynolds et al. 1995; Reuss et al. 1997; Hermann et al. 2001). The NO_3^- concentrations and export rates observed in Dry Creek after the clearcut are among the highest of any values previously reported in the literature (Vitousek and Melillo 1979; Hermann et al. 2001). The high loss of NO_3^- occurred despite the removal of only about 80% of the standing biomass in the watershed (20% of the watershed was not harvested), and despite the residual slash left behind. Previous research has noted that residual slash generally has a high C:N ratio, which favors temporary immobilization of N in decomposers (Vitousek and Melillo 1979).

Many Catskill watersheds, especially those in the Neversink River basin, are believed to be at an advanced stage of N saturation because the streams have relatively high NO_3^- concentrations during base flow throughout the year and even higher NO_3^- concentrations during rain and snowmelt events (Murdoch and Stoddard 1992). The Dry Creek watershed would be classified as stage 1–2 according to the N saturation model (Aber et al. 1989; Stoddard 1994) prior to the clearcut, when NO_3^- concentrations were about 25 μmol l^{-1} at base flow during the dormant season and increased to as high as 80 μmol l^{-1} during a rain-on-snow event in 1996. These high NO_3^- concentrations likely result from the relatively high atmospheric loads of N of 10–15 kg ha^{-1} $year^{-1}$ in the Catskills, which exceed those at Hubbard Brook and most of North America,

and the resulting high values of N stored in the forest floor, coupled with a low C:N ratio (Lawrence et al. 2000; Aber et al. 2003). The Dry Creek ecosystem was apparently poised to release large amounts of NO_3^- in the event of a disturbance; this indicates the presence of abundant nitrifiers in the soil before the clearcut, and no processes to prevent or delay NO_3^- production thereafter (Vitousek et al. 1979).

Three measures of inorganic N availability and mobility in the soil after the clearcut showed large increases, consistent with the stream response. Nitrate concentrations in the O-horizon were 6–10 times greater in soil water, soil, and ion exchange resin in the Dry Creek watershed than in the reference plot and reference lysimeters. The NO_3^- concentrations in the resin bags then declined to background levels during 1999, but those in soil water remained about 2- to 3-times greater than the background level. The response of soil water in the B horizon at Dry Creek was similar to that in the O-horizon, except that soil-water NO_3^- concentrations were higher in 1998 than in 1997, probably from nitrification of NH_4^+ that was transported from the O-horizon and adsorbed in the mineral soil.

In general, NH_4^+ was less abundant in the soil than NO_3^-, and was greater in the O-horizon than in the B horizon. Probably, less NH_4^+ than NO_3^- accumulated because nitrification in these soils is rapid – the net nitrification rate averaged 70% of the net N-mineralization rate in O-horizon soil from the Dry Creek plot during 1997–1998. The greater response of NH_4^+ in the O-horizon than in the B-horizon also reflects the limited mobility of NH_4^+ in the soil. For example, the resin indicated a slight increase in NH_4^+ transport below the forest floor after the clearcut, but NH_4^+ concentrations in B-horizon soil water never exceeded the background level, suggesting that NH_4^+ was readily adsorbed and nitrified, and not generally transported through the soil.

N-Mineralization and nitrification rates

Despite the sharp increase of NO_3^- concentrations in soil water, stream water, and resin bags in the Dry Creek watershed after the clearcut, the N-mineralization and nitrification rates showed no measurable increase in either soil horizon. Relative to atmospheric deposition of 10–15 kg N ha^{-1} $year^{-1}$, the maximum annual rate of NO_3^- export (34.2 kg N ha^{-1}) after harvest greatly exceeded the rate of atmospheric deposition, and therefore, most of the exported NO_3^- must have originated from nitrification. So, why didn't the measured rates of N-mineralization and nitrification increase?

First, the *in situ* technique used in this study measures the rate of N-mineralization and nitrification in the absence of plant uptake. The methods used sever the connection of the soil to the root network. The NO_3^- and NH_4^+

produced during the 4-week incubation periods would have been mostly or completely taken up by vegetation in the absence of the buried pipe or bag. Therefore, the results obtained with this method indicate only whether the rates in the absence of plant uptake changed as a result of the changes in soil temperature, soil moisture, soil structure, and other changes that may have resulted from the disturbance.

Despite this caveat, several studies in a variety of forest types have found that the net rate of N mineralization or (and) nitrification, as measured by a similar *in situ* incubation method, increased after clearcut harvests (Matson and Vitousek 1981; Gordon and Van Cleve 1983; Vitousek and Matson 1985; Frazer et al. 1990; Pierce et al. 1993). Most of these sites, however, had lower pre-harvest rates of N-mineralization and (or) nitrification than these Catskill soils. This suggests that the *in situ* incubation technique may be a more sensitive indicator of increased N mobility after harvest at sites with low rates of atmospheric N deposition, and therefore, low N status.

Studies at the site that is most comparable to the Catskills – the Hubbard Brook Experimental Forest, did not measure *in situ* net rates of nitrification and N-mineralization similar to the current study. These studies at Hubbard Brook did find that (1) the number of autotrophic nitrifiers increased in response to a clearcut (Smith et al. 1968), (2) clearcutting caused a shift from autotrophic nitrification to heterotrophic nitrification (Duggin et al. 1991), and (3) that root dynamics after harvesting are complex and include N loss from decaying roots (Fahey et al. 1988), rapid regrowth of fine roots (Fahey and Hughes, 1994), and immobilization of N in decaying coarse woody roots (Fahey and Arthur, 1994). None of the previous studies at Hubbard Brook, however, clearly demonstrated that the rates of N-mineralization and nitrification increased to a greater extent than the decrease in plant uptake of N.

Several researchers have suggested that the loss of NO_3^- increases after clearcutting because of (1) increased rates of nitrification that result from reduced plant uptake of N, and (2) stimulation of rates N mineralization and nitrification by increased soil temperature and soil moisture (Stone 1973; Bormann et al. 1974; Matson and Vitousek 1981; Huttl and Schaaf 1995; Pardo et al. 1995). Our results indicate that increased NO_3^- and NH_4^+ transport through the soil and loss via surface water was entirely caused by little plant uptake of N during the first 3 years after the clearcut. These data show no evidence of higher soil moisture in the clearcut study plot, and only about a 1–2 °C warming of the soil during the first 3 years after the clearcut. The lack of a strong change in soil microclimate may be partly a reflection of the harvest method that left slash behind and used that slash to minimize soil disturbance. Methods such as a commercial clearcut or whole-tree harvest might have resulted in greater mixing of organic matter into the soil (Ryan et al. 1992), and therefore, greater soil disturbance than occurred in this Catskill study.

Can pre-harvesting nitrification rates account for increased stream export of NO_3^-?

Given that most of the inorganic N derived through N mineralization and nitrification was taken up by plants prior to the harvest, and that the rates of these processes did not change after the clearcut, these rates must be able to account for the increased export of inorganic N (mostly NO_3^-) from the watershed immediately after the harvest. During the year of greatest stream NO_3^- concentrations (August 1997 through July 1998) the potential amount of exportable NO_3^- generated through net nitrification was more than twice the measured stream export of NO_3^- for the Dry Creek watershed. Other N sinks such as vegetation uptake and immobilization by microorganisms and roots that would narrow the difference between the potential NO_3^- generated through nitrification and stream NO_3^- export were not considered in these calculations. The results of these calculations indicate, however, that nitrification rates measured in the absence of plant uptake through the *in situ* technique are sufficient to account for the measured export of NO_3^- during the year with greatest loss.

Why didn't soil warming increase N-mineralization and nitrification rates?

The question of why the measured warming of the soil after the clearcut did not result in measured increases in the rates of N-mineralization and nitrification in the Dry Creek watershed has two possible answers. First, the soil measurements had great uncertainty as evidenced by the large error bars in Figure 5; the mean relative standard deviation of O-horizon and B horizon net nitrification rates during the post-harvesting period were 1.61 and 0.91 mg N kg^{-1} day^{-1}, respectively. Evidence from previous studies indicates that the response of soil N-mineralization and nitrification rates to changes in soil temperature is highly variable, but rates typically double for every 5–10 °C increase in temperature in the range of 5–20 °C if all other factors are held constant (Powers 1990; MacDonald et al. 1995; Stark 1996). If this relation is applied to these data, the N-mineralization and nitrification rates should have increased by 10–20% for the observed 1 °C warming of the soil – clearly less than the 60% (O-horizon) and 23% (B horizon) increase that would have been necessary to detect a significant post-harvest increase in net nitrification in the clearcut plot. Second, any tendency for the rates of these N-cycling processes to increase due to soil warming may have been offset by a tendency for the rates to decrease in response to soil acidification. The pH of O-horizon soil water in the Dry Creek watershed decreased from about 4.5 to between 3.5 and 4.0 within 6 months after the harvest, and the pH of B-horizon soil water decreased from 4.5 to 4.0 during the same period (Welsch et al. in press). This acidification of soil water resulted largely from increased net nitrification in the absence of competition for N with plant roots. Nitrification and N-mineralization rates

tend to decrease as soil pH decreases to below 7, however (Focht and Verstraete 1977; Frijlink et al. 1992), and even if the nitrification process shifts from predominantly autotrophic to heterotrophic after clearcutting (Duggin et al. 1991), the rate of heterotrophic nitrification may slow as soil pH decreases below 4.0 (Stroo et al. 1986). Thus, we hypothesize that soil warming may have caused the rates of microbial N cycling processes to increase in the clearcut had soil acidification not suppressed the rates of these processes. The result is that the net rates of N-mineralization and nitrification did not change by a detectable amount.

Conclusions

The results of this study indicate that clearcutting of a mixed northern hardwood forest watershed caused rapid increases in NO_3^- concentrations of almost an order of magnitude in surface water, soil water, and soil, but did not measurably change the net rates of N-mineralization or nitrification. Therefore, the increase in stream and soil water NO_3^- transport resulted mainly from diminished plant uptake. The changes in soil temperature and soil moisture were either small or negligible; thus the rates of microbial N-cycling processes were not measurably stimulated by changes in these factors. The measured lack of change in N-mineralization and nitrification rates may reflect the relatively high background rates of these processes in this region, which receives among the greatest loads of atmospheric N in North America. The lack of a strong N-mineralization and nitrification response to the disturbance of physical conditions explains why NO_3^- export decreased markedly within the first 3 years after harvest as a new forest dominated by pin cherry (*Prunus pensylvanica)* began to establish itself. These results indicate that the lack of plant uptake of N and the consequent removal of competition with roots for available N, probably is the principal cause of the increased NO_3^- export following clearcutting of northern hardwood forests that receive large amounts of atmospheric-N deposition.

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