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Changes in stream chemistry and nutrient export following a partial harvest in the Catskill Mountains, New York, USA

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Abstract

Clearcut forest harvesting typically results in large changes in stream water chemistry in northeastern North America. The effects of partial forest harvests on stream chemistry have not received as much attention, even though partial cutting is a more common forestry practice than clearcutting in this region. Changes in stream water chemistry following a partial cut are reported here from a 10 ha study catchment in a northern hardwood forest in the Catskill Mountains of southern New York, and are compared to those of a nearby 48 ha reference catchment. The lower two thirds of the treatment catchment was harvested in February–April 2002 by a shelterwood method, such that 33% of the basal area of the catchment was removed. Stream NO_3^-, NH_4^+, Ca^{2+}, K^+, and total dissolved aluminum (Al_{to}) concentrations increased significantly after the harvest. Stream Ca^{2+}, Mg^{2+} and NH_4^+ concentrations peaked 5 months after the initiation of the harvest, NO_3^- and K^+ concentrations peaked 6 months after cutting, and Al_{to} concentrations peaked 1 year after cutting. Streamflow was not significantly affected by the harvest when compared to the flow of three nearby streams. Export of NO_3^- in stream water increased five-fold the year after the cut, and briefly exceeded atmospheric inputs of inorganic nitrogen during 4 months in the fall of 2002. Changes in stream NO_3^- and K^+ concentrations were less than predicted by the relative basal area removed compared with those of a recent nearby clearcut. In contrast, changes in Ca^{2+}, Mg^{2+} and Al_{to} concentrations were approximately proportional to basal area removal in these two cuts. Stream chemistry returned to values close to those of the pre-cut period and to reference values by early spring of 2003, just over a year after the initiation of the harvest, except for NO_3^- concentrations, which remained elevated above background 18–20 months after completion of the cut.
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1. Introduction

Intensive forest harvesting, such as commercial clearcutting or whole-tree harvesting, can alter the physical and chemical properties of streams draining forested catchments. Although erosion and sedimentation can be minimized by the use of forestry Best Management Practices during and after harvesting operations (Binkley and Brown, 1993; Grace et al., 1998), changes in stream water chemistry are more difficult to prevent. Such changes include increased concentrations of nitrate (NO_3^-), base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), aluminum, and acidity, which persist for 3–5 years or even longer (Martin et al., 2000). These effects are largely the result of reduced uptake by vegetation, resulting changes in soil biogeochemical processes such as N-mineralization and nitrification, and subsequent leaching of excess nutrients through soils to surface waters (Hornbeck and Leak, 1992; Pierce et al., 1993; Burns and Murdoch, 2005).

Hydrological losses of nutrients are small in magnitude relative to the nutrient capital removed in harvested products (Mann et al., 1988). However, changes in stream chemistry such as acidification and increased aluminum concentrations following harvesting can be detrimental to sensitive fish species and other aquatic organisms (Baldigo et al., 2005). Additionally, high NO_3^- concentrations can degrade the quality of drinking water (Burns and Murdoch, 2005) and may contribute to eutrophication in receiving waters (Suttle and Harrison, 1988).

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Northern hardwood forests in eastern North America are particularly vulnerable to physical and chemical change following intensive harvest (Martin et al., 1984, 2000). Most forests in eastern North America developed on abandoned farms or land that was intensively harvested in the 19th century (Bolen, 1998), and are now reaching maturity. Since N retention first increases to an intermediate age and then decreases as a stand approaches maturity (Vitousek and Reiners, 1975), steady inputs of N from atmospheric deposition, which did not previously exceed biological demand, may do so as the stand reaches maturity. This phenomenon is known as nitrogen saturation and results in elevated NO_3^- concentrations in streams draining forested landscapes in parts of northeastern North America (Aber et al., 1989; Lovett et al., 2000). Long-term inputs of acidic deposition may also contribute to the depletion of soil base cations; this has been demonstrated in recent studies in the northeastern United States and Canada (Huntington et al., 2000; Watmough and Dillon, 2003), including the Catskills (Lawrence et al., 1999). The combined effects of nitrogen saturation and base cation depletion make these catchments especially sensitive to intensive harvests (Fenn et al., 1998).

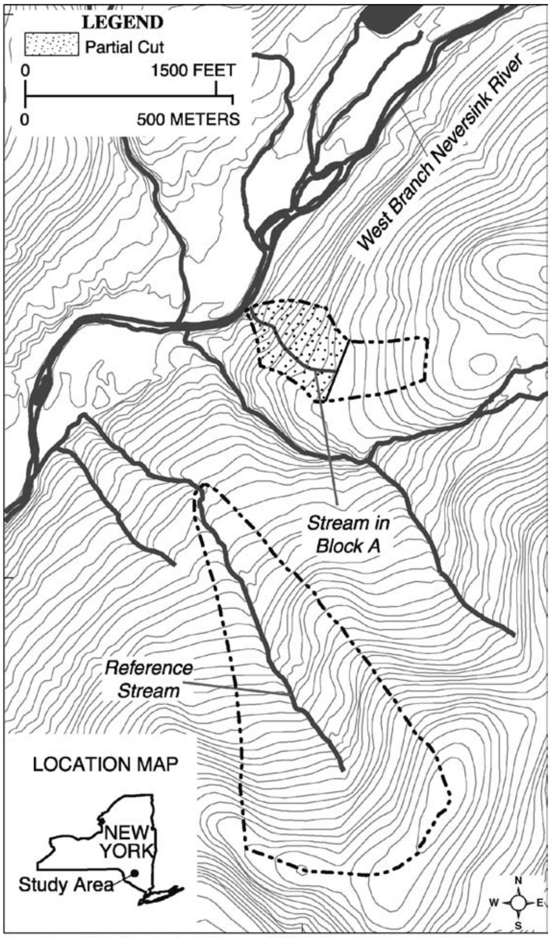
Intensive harvests are currently not as widespread as they were in the 19th and early 20th centuries, primarily due to adverse visual and environmental impacts. A growing number of local logging ordinances throughout the Northeast do not allow clearcuts (Malmsheimer and Floyd, 1998). Shelterwood cutting is a silvicultural practice aimed at establishing a new cohort of even-aged trees under the protection of residual overstory trees (Kelty and Nyland, 1981; Ray et al., 1999). In northern hardwood forests of eastern North America, foresters use the shelterwood method in places that lack abundant and well-developed advanced regeneration (Nyland, 1996). Although partial cutting is more common than clearcutting (Nyland, 1992), relatively few studies have examined the effects of partial harvests on stream quality. Some studies indicate that partial cutting, whether in the form of tending (McClurkin et al., 1987; Steele et al., 1991) or regeneration cuts (Patric, 1980; Messina et al., 1997; Wheeler et al., 2000) or selective cutting (i.e., high-grading) (Bäumler and Zech, 1999), may have less impact on stream chemistry than clearcutting.

The objective of this study was to determine the response of stream chemistry and runoff during the first 2 years after a shelterwood cut that removed 33% of basal area in a small catchment in the Catskill Mountains. The maximum stream chemical changes are typically observed within the first 2 years following harvesting (Martin et al., 1984). We hypothesized that the residual trees remaining after the partial harvest would be sufficient to maintain nutrient retention at close to pre-harvest levels, and thus prevent the occurrence of the large chemical changes that are commonly observed in streams after clearcutting.

2. Site description

The study area is in the Catskill Mountains of Ulster County, New York (41°59′ N; 74°31′ W) at the Frost Valley Model Forest (Fig. 1). We studied two adjacent first-order streams that flow into the West Branch Neversink River, a tributary of the Delaware River, and whose catchments have similar bedrock and surficial geology. The treatment catchment, Block A, is 10 ha and ranges in elevation from 610 to 670 m. The 48 ha reference catchment ranges in elevation from 670 to 730 m. The soils are Inceptisols developed from glacial till and are classified in the Arnot-Oquaga-Lackawanna soil association (Tornes, 1979). These soils are typically medium textured with somewhat excessive to moderate drainage, and are acidic (pH range 3.3–4.2) with low cation exchange capacity ($\text{CEC} < 10\ \text{cmol}_c\ \text{kg}^{-1}$ soil). Forest floor thickness in the study catchments ranges from 3 to 6 cm (Burns and Murdoch, 2005).

The study area has a humid continental climate. At the Slide Mountain weather station, about 9 km from the study sites at an elevation of 808 m, the mean annual air temperature from 1961 to 1990 was 4.6 °C, with temperatures means of −8.6 °C in January and 16.7 °C in July (NCDC, 2004). Mean annual precipitation was 1530 mm, 20–25% of which falls as snow. Precipitation in the Catskill Mountains is among the most acidic in the United States (NADP/NTN, 2004). The mean annual pH of precipitation at a nearby station ranged from 4.43 to 4.51 during the study period (634 m elevation, NADP/NTN, 2004).



Base from U.S. Geological Survey digital data, 1:100,000, 1983

Fig. 1. Location of Block A partial cut and reference stream watersheds.

The streams we studied are fast flowing with streambeds composed of boulders and large cobbles. Some Catskill streams have low acid neutralizing capacity (ANC < 50 μequiv. L^{-1}) at baseflow, and are therefore sensitive to acidification by acid precipitation (Murdoch and Stoddard, 1992). Stream NO_3^- concentrations in the Catskills have increased since the 1960s in association with decreased pH and increased aluminum concentrations (Murdoch and Stoddard, 1992). Episodic acidification is common in Catskill Mountain streams in early spring at high flow when melt water flushes out NO_3^- accumulated in the forest floor during the winter (Wigington et al., 1996; Burns and Kendall, 2002).

The forest at the study sites is dominated by American beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), red maple (*Acer rubrum*) and yellow birch (*Betula alleghaniensis*) with lesser amounts of eastern hemlock (*Tsuga canadensis*). This second-growth northern hardwood forest is approximately 70–80 years old, with scattered large hemlocks and American beech up to 150 years old. Before about 1920, hemlock were harvested for the leather tanning industry, and hardwoods were harvested for sawmills (Kudish, 1985). In the late 1950s and early 1960s, merchantable trees were selectively cut, leaving immature trees and trees of poor quality or low value. No large fires or other major disturbances have been recorded (Kudish, 1985).

3. Materials and methods

3.1. Forest harvest

From February through April 2002, 5.7 ha in the lower portion of Block A was cut to 40% of the original basal area with the residual trees left as shelterwood. The upper portion (4.3 ha) remained uncut. Because only the lowermost part of the catchment was cut, it is likely that a greater response in stream chemistry was observed than would be expected if the cut was spread throughout the catchment. Block A lacks a distinct riparian area because the stream emerges about 100 m above the weir. No effort was made to leave a buffer of uncut trees along the water course.

Logging slash was left on the ground while merchantable stems were moved off site by skidder to a nearby landing during the subsequent month. Forestry Best Management Practices were followed to minimize physical disturbance to soils and impacts on the stream channel (Watershed Forestry Program, 2000). However, the principal road used for skidding timber off the site crossed the stream about 50 m above the weir.

After harvest, the relative density (fraction of growing space occupied by trees, USDA Forest Service, 1984), was 71%, compared to 101% before the cut. The number of trees (DBH > 2.54 cm) per hectare decreased from 1328 to 938. The overall reduction in basal area for the entire catchment was about 33% (Table 1). The cut focused on unacceptable growing stock, dominated by American beech, yellow birch and eastern hemlock. As a result, the relative abundance of sugar maple and red maple increased from 27 to 37% after cutting.

Table 1
Basal area by tree species in Block A before and after harvest (m^2 ha^{-1})

Tree species	Pre-cut	Post-cut	Reduction (%)
American beech (*Fagus grandifolia*)	9.9	5.1	49
Yellow birch (*Betula alleghaniensis*)	7.8	5.5	29
Eastern hemlock (*Tsuga canadensis*)	4.6	2.3	50
Sugar maple (*Acer saccharum*)	3.4	3.2	7
Red maple (*Acer rubrum*)	5.1	4.6	9
Other	0.9	0.7	25
Total	31.7	21.4	33

3.2. Streamflow measurement, stream sampling and chemical analysis

A 90° sharp-crested V-notch weir was constructed at the outlet of Block A in May 2001. Stream stage was recorded every 15 min by a transducer/data logger system installed beside the weir. Streamflow was estimated from the stage value through a theoretical rating curve for a 90° V-notch weir, $Q = KH^{2.5}$, where Q is the estimated stream discharge, H the height of the water column above the bottom of the V-notch, and K a constant dependent on the angle of the weir opening and the units of measurement. The rating curve was checked by nine volumetric measurements of streamflow collected at various flow conditions. These measurements were compared to those predicted by the theoretical rating curve through a Mann–Whitney rank sum statistical test for data pairs that are not normally distributed, and the hypothesis that the pairs of values were equal could not be rejected at $\alpha = 0.05$, indicating that the theoretical rating curve provided a good estimate of flow in this stream.

The stream in Block A was sampled just upstream of the weir manually biweekly, and during high flow with an automated sampler, from December 2000 to December 2003. Stream chemistry at the reference site has been monitored by the US Geological Survey since 1991 (Burns and Murdoch, 2005), and here data are reported for December 2000 through December 2003. Samples are collected manually biweekly. All samples were analyzed for pH, NO_3^-, NH_4^+, Ca^{2+}, Mg^{2+}, K^+, Na^+ and total dissolved Al (Al_{to}). Samples collected from Block A before June 2002 (mainly during the pre-cut period) were analyzed at the State University of New York College of Environmental Science and Forestry (ESF) in Syracuse, New York. All samples from Block A thereafter and those from the reference stream throughout the study period were analyzed at the US Geological Survey Water Analysis Laboratory in Troy, New York.

In the ESF laboratory, pH was measured electrometrically. Samples were filtered through 0.4 μm polycarbonate membrane filters prior to chemical analysis. Nitrate was measured by a cadmium reduction method and NH_4^+ was measured by an automated phenate method (Eaton et al., 1995). Base cations and Al_{to} were determined by inductively coupled plasma (ICP) emission spectroscopy (Perkin-Elmer, 1996).

In the USGS laboratory, chemical constituents were measured according to procedures described in Lawrence et al. (1995). Stream pH was measured electrometrically on an unfiltered aliquot. Calcium, Mg^{2+} and Al_{to} were measured by

ICP spectrometry, and K^+ and Na^+ were measured by flame atomic absorption spectroscopy. After filtration, nitrate was measured by ion chromatography and NH_4^+ was measured by an automated indophenol blue method.

All biweekly samples collected from July 2001 to June 2002 were analyzed in both laboratories and the results were compared using a paired *t*-test. The ESF lab tended to report lower values than the USGS lab for Ca^{2+}, Mg^{2+} and higher values for NH_4^+ for samples during the growing season, and lower year-round values for Al_{to} and Na^+ (Table 2). No significant between-lab differences were found in pH, NO_3^- or K^+ at $\alpha = 0.05$.

3.3. Data from other sources

Precipitation data were obtained from the National Climate Data Center web site (NCDC, 2004) for the Slide Mountain Climatologic Station. Atmospheric deposition data were obtained from the National Atmospheric Deposition Program web site for the Biscuit Brook station (NADP/NTN, 2004), which is 2.4 km northeast of the Block A stream gage. Because the reference stream did not have a stream gage, three nearby streams (Biscuit Brook, West Branch Neversink River at Winnisook, and Shelter Creek, which are located at distances of 9.3, 3.2, and 1.0 km, respectively, from the Block A stream gage) with undisturbed catchments at a similar elevation and with similar forest cover were used as references for streamflow. The cutting effects in Block A were also compared to a clearcut conducted in nearby Dry Creek, where 80% of the 24 ha catchment was harvested in 1997. Streamflow data for the three reference streams were calculated using standard USGS gaging methods (Rantz et al., 1982), and stream chemical analyses at the clearcut were determined according to methods described previously for the USGS laboratory in Troy, NY.

3.4. Data analysis

Monthly mean runoff in Block A was compared with the three nearby tributaries of the West Branch Neversink River basin described above during the pre- and post-harvest periods using a Mann–Whitney rank sum test because these data failed a test for normality. Stream chemistry (concentrations and loads) was compared qualitatively and descriptively within Block A before and after harvest, and among sites with different treatments (partial cut, clearcut and reference). These pre- and post-cut comparisons among the treatment and reference streams included examining differences in concentrations among event and biweekly samples collected during the dormant (November–April) and growing (May–October) seasons. Differences were reported as statistically significant using $\alpha = 0.05$.

Table 2
Seasonal mean and standard error of major chemical constituents at low flow in the reference stream (July 2001–June 2002) ($n = 19$)

Constituent	Dormant (November–April)		Growing (May–October)	
	ESF	USGS	ESF	USGS
pH	5.9 (0.1)	6.0 (0.1)	6.2 (0.1)	6.2 (0.1)
NO_3^-	13.1 (2.8)	14.3 (2.0)	10.8 (2.2)	8.0 (1.1)
NH_4^+	2.5 (1.2)*	1.3 (0.2)*	4.1 (1.8)*	1.1 (0.3)*
Al_{to}	0.5 (0.1)*	1.7 (0.1)*	0.8 (0.2)*	2.1 (0.2)*
Ca^{2+}	48.5 (2.7)	45.1 (1.1)	41.7 (3.1)*	51.0 (2.0)*
Mg^{2+}	28.8 (1.2)	28.3 (0.8)	25.1 (0.8)*	30.6 (1.1)*
K^+	6.2 (0.6)	6.6 (0.3)	4.6 (0.5)	4.3 (0.2)
Na^+	8.0 (0.3)*	9.5 (1.4)*	14.2 (0.5)*	14.9 (1.0)*

Note: All values except pH are in units of $\mu mol\ L^{-1}$.

* Statistically significant difference between ESF and USGS labs (within a season).

Harvest effects on stream chemistry were also analyzed with repeated measures ANOVA, with time and cutting treatment as class variables. The effects of time and treatment and their interaction were tested for significance using the Type III sum of square tests. There is a possibility of mistakenly interpreting differences due to the two labs as treatment effects when comparing pH and concentrations of Ca^{2+}, Mg^{2+}, NH_4^+, Na^+ and Al_{to}, which is noted in the text where both a treatment and a time effect were present. All statistical analyses were conducted in SAS (2000).

Net chemical loads in the partially cut catchment were calculated for each month by subtracting atmospheric input (wet deposition only) from hydrologic loss. These losses were computed as the product of flow-weighted monthly mean concentration and monthly discharge. Atmospheric inputs were from the NADP/NTN Biscuit Brook site. Loads were calculated for a pre-cut year from June 2001 to May 2002, which ended 1 month after the harvest was completed, but before measurable effects on stream chemistry were evident. The post-cut year for the purposes of load calculations was from June 2002 to May 2003. This definition of pre- and post-cut years allowed us to compare periods with the same component months.

4. Results

4.1. Precipitation and streamflow

Precipitation amount at the Biscuit Brook NADP/NTN site during the 2001–2003 hydrologic years (October–September) was 1140, 1134, and 1653 mm, respectively, compared to a long-term mean (1984–2003) of 1355 mm. Hydrologic years 2001 and 2002 each received about 16% less precipitation than normal, and were the second and third driest years recorded during 1984–2003 at the Biscuit Brook site. Monthly precipitation varied from 24 mm (April, 2001) to 304 mm (August, 2003). Late spring (May and June) and autumn (September through December) were generally the rainiest periods.

Stream runoff from Block A was 722 mm during 2002 and 1387 mm during 2003. Stream runoff was 64% of annual precipitation in 2002 and 87% in 2003, suggesting that water yield may have been increased by harvesting during 2003. Stream runoff from Block A was generally lowest in summer (July through September) due to a combination of high evapotranspiration and low rainfall, and increased in the fall (October and November) when the growing season ended and rainfall increased. Maximum stream runoff occurred in the late winter when the snow pack melted.

Catchments that have been clearcut typically show increased water yields due to reduced evapotranspiration (Patric, 1980; Martin et al., 2000). Because water yields can vary considerably from year to year, we tested the effect of the partial harvest by comparing monthly stream runoff in Block A with that of three nearby streams. During the pre-harvest period, stream runoff in Block A was strongly related to that of the other three streams (Fig. 2; $r^2 = 0.79$, $p < 0.001$), and a Mann–Whitney rank sum test indicated no significant difference ($p = 0.41$) among pair wise comparisons of the Block A stream with the three other three streams. In the year following the harvest, Block A stream runoff continued to be strongly related to runoff from the other three streams ($r^2 = 0.66$, $p < 0.001$) though the slope and intercept of the linear regression changed such that Block A flow was greater than the other streams at flows <75 mm month^{-1}, and less than the others at greater flows. The post-harvest regression relation, however, was highly leveraged by an outlier month, when one stream had a runoff value more than double that of the Block A stream. Neither of the other two streams showed a similarly high runoff value during that month, and daily runoff data shows that the stream with the exceptionally high monthly runoff value was strongly influenced by two storms that appeared to affect this stream to a greater extent than the others. When this high monthly value was removed and the regression relation was re-calculated, the slope and intercept (1.06 and 2.3, respectively) differed little from the pre-harvest regression values (0.98 and −2.3, respectively), suggesting little change in runoff at Block A resulting from the harvest. Indeed a pair wise comparison of these data sets with a Mann–Whitney rank sum test indicates that runoff in Block A was not significantly different ($p = 0.49$) than runoff in the three nearby streams during the post-harvest period. In this case, decreased evapotranspiration from the partial harvest was not sufficient to significantly affect monthly water yield of the Block A stream.

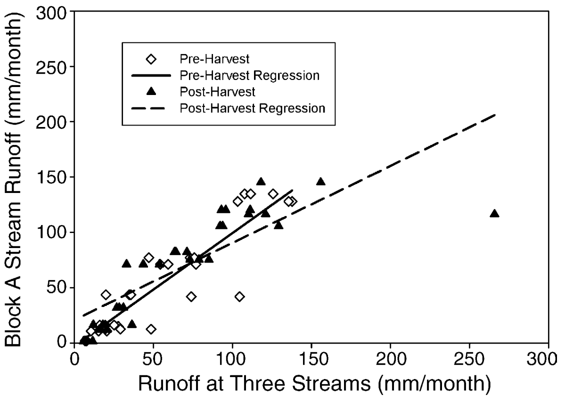


Fig. 2. Monthly runoff in Block A as a function of monthly runoff in each of three nearby streams in the Neversink River Basin during the June 2001 to April 2002 pre-harvest period and the May 2002–April 2003 first year after harvest. Linear regression relations for the pre- and post-harvest data are shown. Biscuit Brook, West Branch Neversink River at Winnisook, Shelter Creek and the Block A stream have drainage areas of 963, 199, 161 and 10 ha, respectively.

4.2. Stream chemistry before partial cutting

Mean annual Ca^{2+}, Na^{+} and Al$_{to}$ concentrations were similar between Block A and the reference stream before cutting (Fig. 3). Prior to harvest, the stream in Block A was more acidic than the reference stream (pH 5.68 versus 6.08), and both streams showed a one-unit variation around the mean annual pH values (Fig. 3). Mean annual stream NO$_3^-$ concentration was 12 μmol L^{-1} in Block A, less than that in the reference (18 μmol L^{-1}). Both streams, however, were within the range of NO$_3^-$ concentrations found in 39 forested headwater streams in the Catskills and less than the mean value of 23 μmol L^{-1} (Lovett et al., 2000). Block A had higher mean annual NH$_4^+$ concentrations than the reference (4.6 versus 2.4 μmol L^{-1}) but lower K^{+} (5.0 versus 6.4 μmol L^{-1}) and Mg^{2+} concentrations (22 versus 28 μmol L^{-1}).

Stream acidity (pH) was inversely correlated with streamflow in Block A ($r = -0.09$, $p < 0.0001$), similar to observations in other Catskill streams (Murdoch and Stoddard, 1993). Nitrate concentrations increased with stream discharge ($r = 0.48$, $p < 0.0001$), as did K^{+} ($r = 0.49$, $p < 0.0001$), and Al$_{to}$ ($r = 0.15$, $p = 0.042$) concentrations. The relation between streamflow and either stream NH$_4^+$ or base cation concentrations in Block A was not significant, though event samples tended to have higher Ca^{2+} and Mg^{2+} concentrations, and lower Na^{+} concentrations than non-event samples. The effect of streamflow on stream chemistry in Block A was stronger during the dormant season than during the growing season. These relations between streamflow and stream chemistry in Block A are consistent with those of other headwater catchments in the Catskill Mountains (Murdoch and Stoddard, 1992).

Stream nutrient concentrations varied seasonally (Fig. 3). Stream NO$_3^-$ and K^{+} concentrations were higher in the dormant season than the growing season. Nitrate concentrations were generally less than 10 μmol L^{-1} during the growing season but greater than 20 μmol L^{-1} during winter and early spring. High K^{+} concentrations were also observed in the Block A stream in late summer at extremely low streamflow. No significant seasonal trend was found for stream Ca^{2+}, Mg^{2+} and Al$_{to}$ concentrations in either Block A or the reference stream. Solute concentrations in the Block A stream showed greater variation than the reference stream, probably reflecting the flashy nature of stream hydrology in Block A due to its smaller size. Additionally, event samples were not collected by an automated sampler in the reference stream. Concentrations of chemical constituents of samples collected at high flow by automated samplers tend to have greater variation than those of samples collected at baseflow.

4.3. Stream chemistry after partial cutting

In spite of the low intensity of harvest, nutrient concentrations increased in the Block A stream after a time lag (Fig. 3). The first indication of a response was the increase in Ca^{2+} concentrations at high flow during and soon after snowmelt in April and May, 2002, 2 months after cutting began. Since this response was not associated with increased NO$_3^-$ concentra-

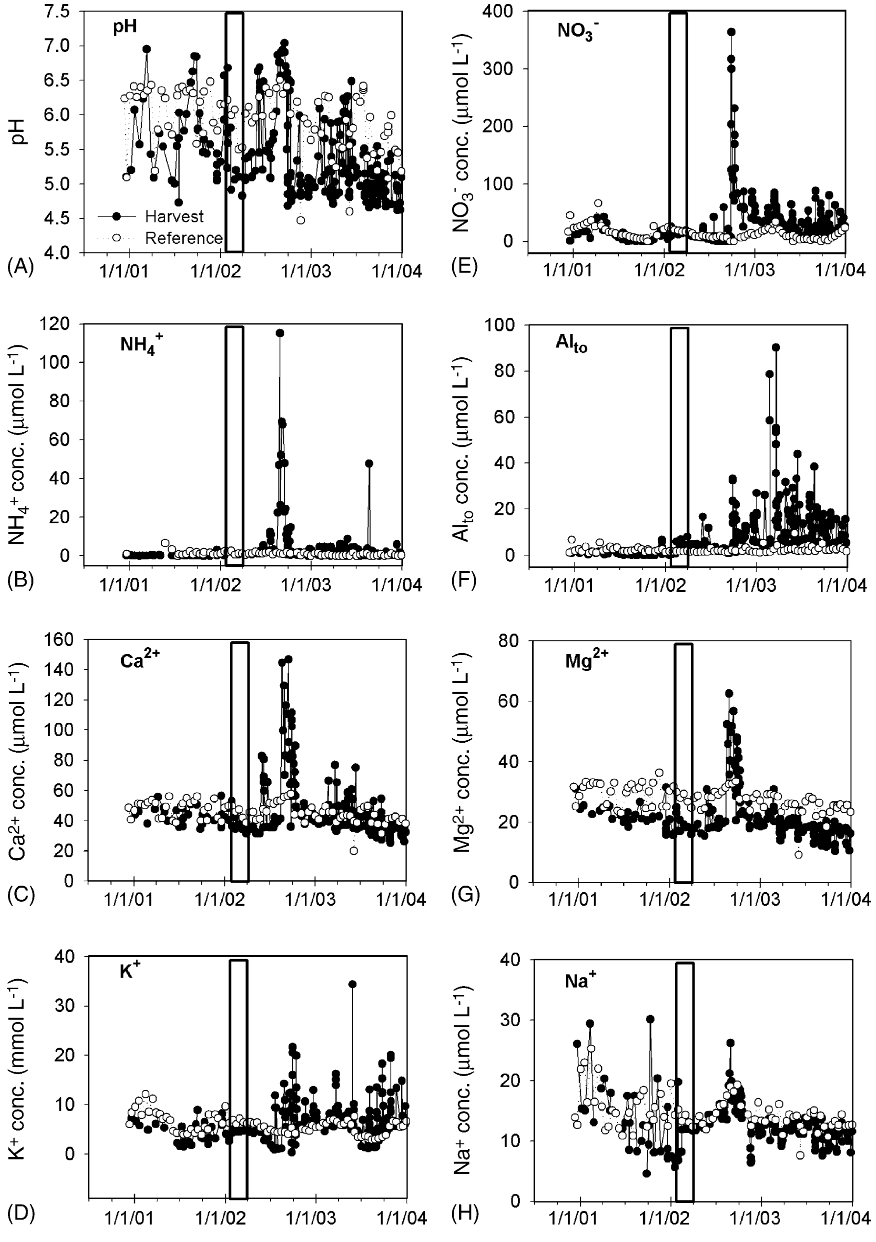


Fig. 3. Time series of stream chemistry at Block A partial cut and reference site during December 2000–December 2003. (A) pH, (B) NH_4^+, (C) Ca^{2+}, (D) K^+, (E) NO_3^-, (F) Al_{to}, (G) Mg^{2+}, and (H) Na^+. The vertical rectangle in each graph denotes the February 2002–April 2002 harvest period.

tions, this early increase in Ca^{2+} concentrations may have been due to soil disturbance and sediment movement associated with the road used for skidding. This road crosses the stream via a culvert about 50 m upstream from the gage. Little further departure from pre-cut stream chemistry was evident until late in the growing season, 6 months after the partial cutting began. The peak concentrations of Mg^{2+} (63 $\mu mol\ L^{-1}$) and Na^+ (26 $\mu mol\ L^{-1}$) were observed in late August, and NH_4^+ (64 $\mu mol\ L^{-1}$) and Ca^{2+} (147 $\mu mol\ L^{-1}$) concentrations peaked in mid September. In late September, NO_3^- (364 $\mu mol\ L^{-1}$) and K^+ (22 $\mu mol\ L^{-1}$) concentrations peaked.

The peak Al_{to} concentration (211 $\mu mol\ L^{-1}$) was observed in February, 2003 following a rain-on-snow event. Stream pH in Block A was one unit lower than the reference during most of the post-cut period, except in August, 2002 when base cation concentrations reached their highest low flow values. No chemical changes were evident in the reference stream during the post-cut period relative to pre-cut observations (Fig. 3).

The persistence of elevated stream concentrations after partial cutting varied with the solute. Base cations and NH_4^+ concentrations remained elevated for 2 months following peak values (September and October 2002) and then returned to pre-cut levels in non-event samples (Fig. 3). Stream Ca^{2+}, K^+ and NH_4^+ concentrations remained elevated above the reference stream during events in the spring of 2003 (Fig. 3). Stream NO_3^- concentrations decreased gradually, but the mean NO_3^- concentration was still 30 $\mu mol\ L^{-1}$ during October–December 2003, 18–20 months after the cut compared to a mean value of 6.5 $\mu mol\ L^{-1}$ during the same period in 2001 before the cut. Additionally, stream NO_3^- concentrations continued to peak during events in October–December 2003 at values 50–100% higher than during the comparable period in 2001 (Fig. 3). High $\mathrm{Al_{to}}$ concentrations exceeding pre-cut levels were repeatedly observed during high flow events beginning in September, 2002. Stream pH in Block A remained at about 5 throughout the second growing season due to the asynchronous recovery of $\mathrm{NO_3}^-$ and base cations (Fig. 3).

A comparison of pre-cut and post-cut stream chemistry in Block A to the reference stream using repeated measures ANOVA indicates that cutting effects were significant for $\mathrm{NO_3}^-$ concentrations ($p = 0.02$) as well as $\mathrm{NH_4}^+$ ($p = 0.02$), Ca^{2+} ($p = 0.03$), K^+ ($p < 0.001$) and $\mathrm{Al_{to}}$ ($p < 0.001$) concentrations. Concentrations of $\mathrm{NH_4}^+$ and $\mathrm{Al_{to}}$ were also related to sampling date, which was associated with a change in laboratories; the post-cut changes of these two constituents are partly explained by between-lab analytical differences. Neither a cut nor a time effect was found for stream pH, Mg^{2+} or Na^+.

4.4. Nutrient export before and after partial cutting

The input/output balance of major nutrients in Block A changed after the partial cut, particularly for $\mathrm{NO_3}^-$ and some of the base cations (Table 3). Prior to the cut, the atmospheric input of $\mathrm{NO_3}^-$ in wet deposition exceeded the hydrological losses in stream, indicating strong catchment retention of $\mathrm{NO_3}^-$. Nitrate retention declined about 7 months after the cut, beginning in September 2002, as reflected in elevated stream $\mathrm{NO_3}^-$ concentrations. During the 4 months from September to December 2002, the catchment showed positive net export of $\mathrm{NO_3}^-$. Ammonium, in contrast, was consistently retained. The post-cut spikes of stream $\mathrm{NH_4}^+$ concentrations in the first growing season occurred at low flow and thus did not greatly affect the total $\mathrm{NH_4}^+$ balance. Base cations showed consistently high net losses from the catchment, because atmospheric deposition provides little input compared to stream water export. Wet deposition was about 5–10% of stream Ca^{2+} and Mg^{2+} losses, 10–20% of stream K^+ losses, and about half of Na^+ losses.

Stream export of Ca^{2+} represented more than 60% of the total base cation losses from Block A. Increased export of base cations after partial cutting was modest; the net loss of Ca^{2+} was 9.5 kg ha^{-1} in the pre-cut year and 12.9 kg ha^{-1} in the post-cut year (Table 3). The pre-cut export was higher than the reported level of 6.0 kg $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$ at Hubbard Brook, but close to values reported from other harvested sites in the Northeast (Hornbeck et al., 1997). The increase in base cation export can be explained mainly by the increase in precipitation and resulting increase in stream runoff during the post-cut period (699 mm during the pre-cut year and 965 mm during the post-cut year). Hydrologic losses per unit of runoff were slightly lower for Ca^{2+} and Mg^{2+} during the post-cut than the pre-cut periods, whereas values for K^+ and Na^+ were 38% and 21% higher, respectively (Table 3).

Table 3
Atmospheric input and hydrological loss of nutrients in Block A during the year (June 2001–May 2002) before and after (June 2002–May 2003) completion of the partial cut

Constituent	Pre-cut			Post-cut		
	Input	Loss	Loss mm^{-1} runoff	Input	Loss	Loss mm^{-1} runoff
$\mathrm{NO_3}^-$	21.5	5.4	0.0077	29.8	26.9	0.0279
$\mathrm{NH_4}^+$	3.7	0.2	0.0003	5.1	0.1	0.0001
Ca^{2+}	1.1	10.6	0.0152	1.5	14.4	0.0149
Mg^{2+}	0.2	3.2	0.0046	0.3	4.3	0.0045
K^+	0.2	1.1	0.0016	0.2	2.1	0.0022
Na^+	0.9	1.7	0.0024	1.2	2.8	0.0029

Units for input and loss are kg ha^{-1}, and loss mm^{-1} runoff is in units of kg $\mathrm{ha}^{-1}\,\mathrm{mm}^{-1}$.

4.5. Effect of harvest intensity on stream chemistry

Changes in stream chemistry were generally less than those observed in a 1997 clearcut in the nearby Dry Creek catchment, and elevated post-cut nutrient concentrations persisted for a shorter duration than in the clearcut. Stream $\mathrm{NO_3}^-$ concentrations increased to about 1400 μmol L^{-1} within 5 months after completion of the clearcut in the first growing season and remained above 200 μmol L^{-1} for 4 years after the cut (Burns and Murdoch, 2005). In contrast, $\mathrm{NO_3}^-$ concentrations after the partial cut peaked at 360 μmol L^{-1} and declined to <50 μmol L^{-1} within 2 months after the occurrence of the peak value.

To better understand the relations between harvest intensity and stream chemistry, post-cut changes in stream chemistry were plotted as a function of the proportion of basal area removed from Block A and Dry Creek (Fig. 4). Changes in stream concentrations were determined as the mean value during the year after the harvest minus the mean value during the year preceding the harvest in each catchment. We chose not to compare chemical fluxes before and after harvest, because such a comparison would be confounded by changes in precipitation and stream runoff during the study period.

Stream chemical constituents showed various patterns in response to harvest intensity (Fig. 4). Total Al showed a proportional response as harvest intensity increased from the 33% of basal area removed by partial cutting in this study to the 80% of basal area removed in the clearcut in Dry Creek. Nitrate, K^+, Ca^{2+}, and Mg^{2+}concentrations increased less after partial cutting than predicted by a linear relation with basal area removal. The unexpectedly low response to partial cutting was most pronounced for K^+ and $\mathrm{NO_3}^-$ and least pronounced for Ca^{2+} and Mg^{2+}. Sodium concentrations showed little if any response to either harvest.

Stream pH in the partial cut was lower than in the clearcut, especially during the second year after harvest (data not shown). Pre-harvest stream pH, however, was also lower in the partial cut than in the clearcut, indicating that much of the difference in pH is explained by natural differences in the extent to which acid precipitation is neutralized during transit through these catchments. The continued release of large amounts of base cations in the clearcut contrasted with the rapid recovery of base cation concentrations in the partial cut, which also

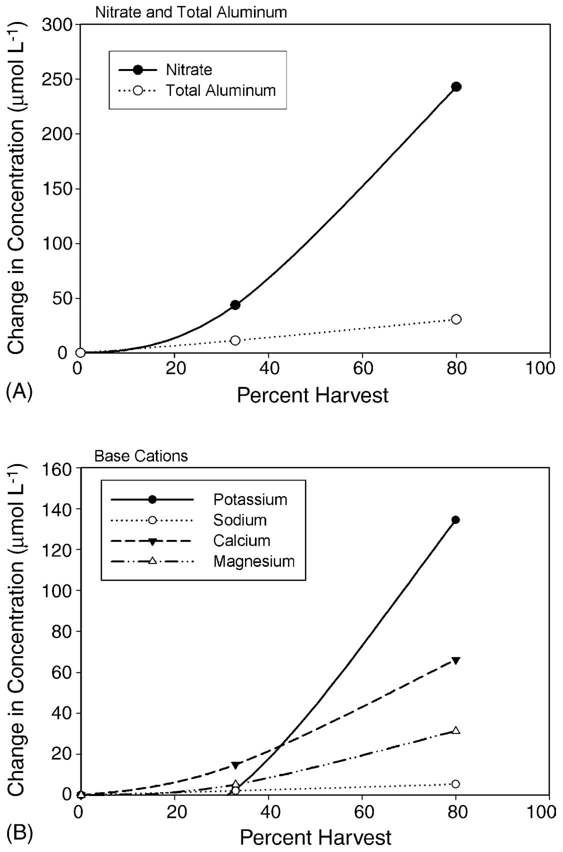


Fig. 4. Increase in mean concentrations of six chemical constituents in stream water during the year following harvest relative to the year before harvest for the partial cut (this study) and a nearby clearcut (Burns and Murdoch, 2005; Burns, unpublished data). (A) NO_3^- and Al_{to}, and (B) base cations.

likely contributed to the relatively higher stream pH in the clearcut.

5. Discussion

Before harvest, both the Block A and reference streams had higher NO_3^- concentrations in winter than in summer (<10 µmol L^{-1}), typical of catchments in Stage 1 of Stoddard's (1994) classification system of catchment N status. According to this conceptual model, catchments receiving atmospheric N deposition range from Stage 0 with only small dormant-season losses of NO_3^- in stream water to Stage 3 with year-round elevated NO_3^- concentrations. Significant losses of NO_3^- in stream water during the dormant season and minimal losses during the growing seasons are considered symptomatic of systems at Stage 1 of N saturation (Stoddard, 1994). These pre-cut and reference data are consistent with the history and current rate of atmospheric N deposition in the Catskill Mountains. After harvest, NO_3^- concentrations increased sharply in the Block A stream to about 360 µmol L^{-1} for a short time. Annual export of inorganic N in stream water was 21% of the precipitation input before the cut, less than values of 28–55% reported for nearby streams with similar soil and tree species composition (Lovett et al., 2000; Campbell et al., 2004), indicating that the forest in Block A was more effective at retaining N than these nearby forested catchments. This difference may be in part related to the high-grade harvests in the Block A forest during the 1950s and 1960s. The pre-cut export values in Block A were also influenced by the relatively dry conditions and low runoff during 2001 and 2002, and export would likely have been higher in a year with normal flow conditions.

After the cut, annual export increased sharply to 77% of wet deposition, a decrease in N retention to a value more typical of a catchment at Stage 2 of N saturation, and exceeding the background range of nearby catchments. Stage 2 is characterized by elevated NO_3^- concentrations in groundwater resulting from excess nitrification, and therefore elevated NO_3^- concentrations in baseflow and a damping of the typical seasonal cycle of NO_3^- found in catchments at Stage I (Stoddard, 1994). We observed an increase in stream NO_3^- concentrations at baseflow during the post-cut period, however, we also observed increased "spiking" of NO_3^- concentrations during events to a greater extent than before the cut. These changes after harvest do not exactly mimic the changes expected during a normal progression of N saturation in an undisturbed forest, primarily because the sudden absence of vegetation allows a large buildup of NO_3^- in the soil during the growing season which is periodically flushed during precipitation events.

Overall, the response of stream chemistry after this partial cut was less than that of other clearcuts in the northeastern United States (Martin et al., 1984; Lawrence et al., 1987), similar to a clearcut in Pennsylvania (Patric, 1980), and greater than a selective cut in Germany (Bäumler and Zech, 1999). These varied results with different cutting practices and in different geographic regions indicate that factors such as leaving a protective buffer along the stream channel during the cut (Patric, 1980) or differences in N saturation and soil base saturation status (Bäumler and Zech, 1999) must be considered along with harvest intensity (Lawrence et al., 1987) when examining stream chemical changes from different sites. In this case, increases in NO_3^- and K^+ concentrations were less than proportional to the removal of tree basal area compared to a nearby clearcut, perhaps because the remaining vegetation increased retention of these nutrients through root and canopy expansion (Nyland, 1996). Increases in Ca^{2+} and Mg^{2+} concentrations following the partial cut were also less than proportional to basal area removal in the clearcut, though these relations were closer to linear than those of NO_3^- and K^+. This suggests that canopy expansion after the partial cut did not "draw down" the concentrations of Ca^{2+} and Mg^{2+} as greatly as those of NO_3^- and K^+, which is consistent with the large source of Ca^{2+} and $Mg^{2+}$from mineral weathering. This response does not generally support the idea that the availability of Ca^{2+} and Mg^{2+} are low enough in these Catskill soils to limit the growth of common tree species such as sugar maple (Federer et al., 1989; Lawrence et al., 1999).

Nitrate concentrations, even at the peak value of 360 µmol L^{-1} after the partial cut, were well below the EPA standard of 710 µmol L^{-1} for drinking water (10 mg L^{-1}, USEPA, 2002). Post-cut Al_{to} concentrations exceeded the

USEPA's secondary standards for drinking water (0.2 mg L^{-1}) and the pH was below the EPA requirement of 6.5 (USEPA, 1992). The environmental impact of these changes is limited, however, because the Block A stream enters the West Branch of the Neversink River about 100 m below the stream gage, where it is diluted more than 500-fold.

It seems probable that partial harvesting at an intensity similar to the current study could affect fish populations. After the clearcut at Dry Creek, inorganic monomeric aluminum concentrations reached values >7 μmol L^{-1}, which were high enough to result in complete mortality of brook trout held in bioassay cages during early spring 1 year after harvest (Baldigo et al., 2005). The peak Al_{to} concentrations of 100 μmol L^{-1} reported in this study are higher than a threshold that has been reported to cause brook trout mortality in similar streams (Gagen and Sharpe, 1987). However, the Block A stream is probably too small to support a naturally reproducing brook trout population.

6. Summary and conclusions

These findings generally support the idea that stream chemical changes can be minimized by practicing low-intensity harvest methods. The removal of 33% of basal area from the 10 ha Block A did not generate a detectable increase in stream runoff, but did result in significant short-term changes in stream chemistry, followed by a return to pre-cut levels for most constituents within 18 months. Stream water NO_3^- concentrations increased from about 20 μmol L^{-1} to about 360 μmol L^{-1} during the first growing season after the harvest and remained higher than pre-cut levels during the second year after cutting. Stream Al_{to} concentrations increased considerably in the first dormant season and spikes as high as 20 μmol L^{-1} were observed at high flows even 1 year after the cut. Stream NH_4^+ and base cation concentrations peaked late in the first post-cut growing season and soon returned to pre-cut levels. Stream Ca^{2+}, K^+ and NH_4^+ showed a different but less distinct peak period during snowmelt or late in the growing season of the second year after the cut.

Before the cut, Block A was at stage 1 (Stoddard, 1994) of catchment N saturation, but showed some characteristics of a catchment at Stage 2 after the cut. The partial cut increased stream water NO_3^- export five-fold, such that losses exceeded atmospheric inputs for 4 months. The export of other nutrients also increased considerably after cutting. Harvest effects on stream chemistry were statistically significant for NO_3^-, NH_4^+, K^+, Ca^{2+} and Al_{to} concentrations, but not for pH, Mg^{2+}, and Na^+ concentrations, and these effects were most apparent at high flow. Concentrations of NH_4^+ and Al_{to} also showed a time effect, indicating that differences in the values of these two constituents can be partly explained by a change to a different analytical laboratory soon after completion of the cut. Cut-induced stream chemical changes were not likely to have adverse effects on water quality for drinking purposes, nor on plant growth, but Al_{to} concentrations may have been high enough to affect stream biota. The magnitudes of changes in nutrient concentrations were much lower and the duration of altered nutrient concentrations was much shorter than in a neighboring catchment that was previously clearcut. Stream Al_{to} concentrations in the partial cut were comparable to those in the clearcut, which probably resulted in part from the lower pre-harvest stream pH in the partially cut catchment.

Stream Ca^{2+}, Mg^{2+} and Al_{to} concentrations showed an approximately linear relation with basal area removal, whereas stream Na^+ concentrations were insensitive to harvest intensity. Stream NO_3^- and K^+ concentration changes were less than proportional to the changes in the clearcut relative to basal area removal, suggesting a biological control that depressed losses of NO_3^- and K^+ losses in the partial cut through enhanced nutrient retention by the remaining trees. Whether this less-than-proportional relation of harvest intensity to stream nutrient concentration changes is valid for a range of harvest intensities awaits additional studies that span a wider range of cuts.

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