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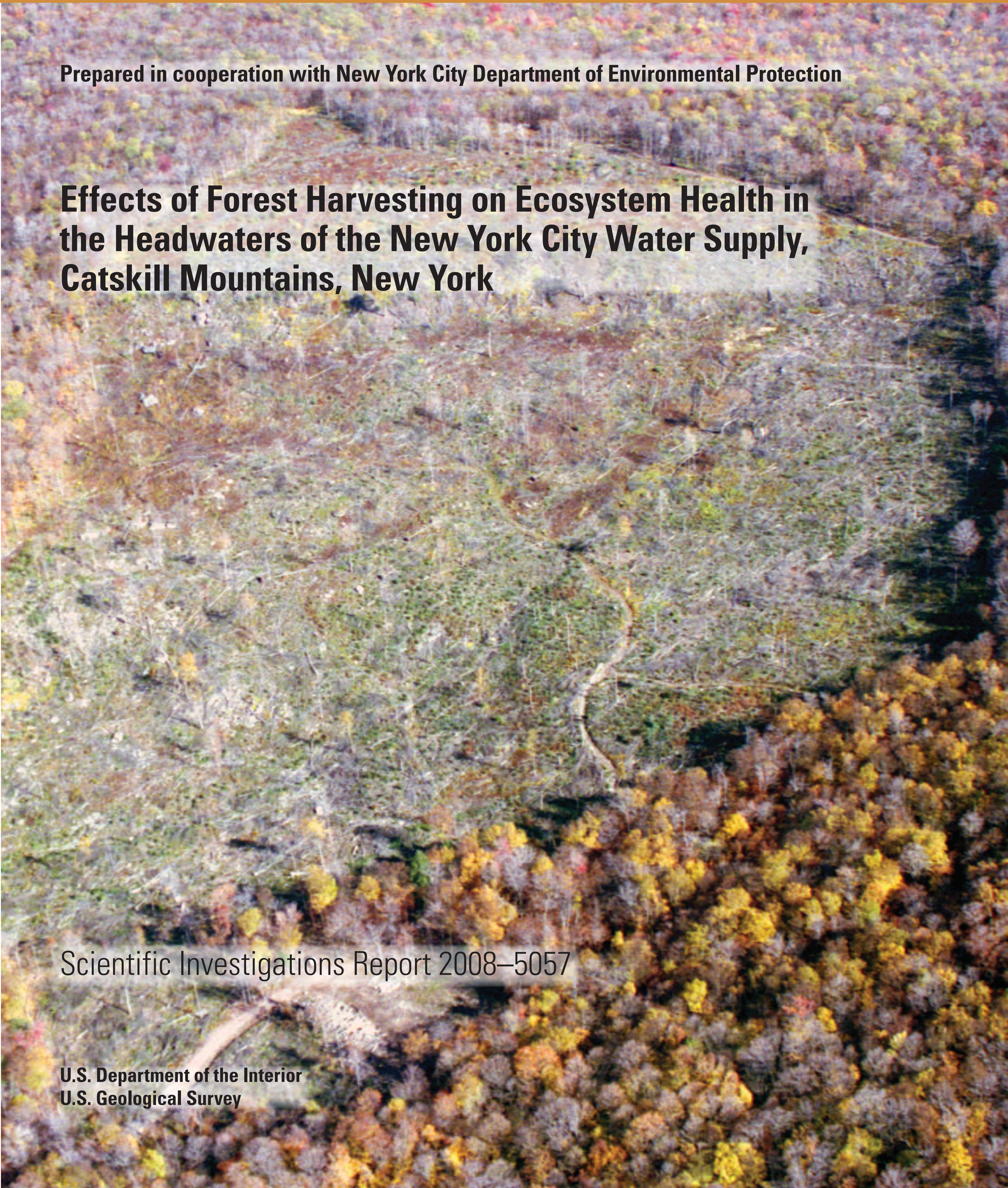
Effects of Forest Harvesting on Ecosystem Health in the Headwaters of the New York City Water Supply, Catskill Mountains, New York



Scientific Investigations Report 2008–5057

U.S. Department of the Interior
U.S. Geological Survey

Cover. Aerial view of the Dry Creek watershed during the fall of 1998, 18 months after it was clearcut. Photograph by Aerial Dimensions.

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Suggested citation:
McHale, M.R., Murdoch, P.S., Burns, D.A., and Baldigo, B.P., 2008, Effects of forest harvesting on ecosystem health in the headwaters of the New York City water supply, Catskill Mountains, New York: U.S. Geological Survey Scientific Investigations Report 2008–5057, 22 p., also available online.

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Conversion Factors, Datum, and Abbreviations

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	1.057	quart (qt)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Application rate	
kilograms per hectare	25.49	tons per square mile

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviated water-quality units used in this report

µmol/L micromoles per liter

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Effects of Forest Harvesting on Ecosystem Health in the Headwaters of the New York City Water Supply, Catskill Mountains, New York

By Michael R. McHale, Peter S. Murdoch, Douglas A. Burns, and Barry P. Baldigo

Abstract

The effects of forest clearcutting and selective harvesting on forest soils, soil and stream water chemistry, forest regrowth, and aquatic communities were studied in four small headwater catchments. This research was conducted to identify the sensitivity of forested ecosystems to forest disturbance in the northeastern United States. The study area was in the headwaters of the Neversink Reservoir watershed, part of the New York City water supply system, in the Catskill Mountains of southeastern New York. Two sub-catchments of the Shelter Creek watershed were selectively harvested, one in its northern half and one more heavily in its southern half in 1995–96, the Dry Creek watershed was clearcut in the winter of 1996–97, and the Clear Creek watershed was left undisturbed and monitored as a control site. Monitoring was conducted from 4 years before the harvests until 4 years after the harvests. Clearcutting caused a large release of nitrate (NO_3^-) from watershed soils and a concurrent release of inorganic monomeric aluminum (Al_{im}), which is toxic to some aquatic biota. The increased soil NO_3^- concentrations measured after the harvest could be completely accounted for by the decrease in nitrogen (N) uptake by watershed trees, rather than an increase in N mineralization and nitrification. The large increase in stream water NO_3^- and Al_{im} concentrations caused 100-percent mortality of caged brook trout (*Salvelinus fontinalis*) during the first year after the clearcut and adversely affected macroinvertebrate communities for 2 years after the harvest. Nutrient uptake and biomass accumulation increased in uncut mature trees after the two selective harvests. There was no increase in stream-water NO_3^- or Al_{im} concentrations, and so there were no adverse affects on macroinvertebrate or trout communities. The amount of tree biomass that can be removed without causing a sharp increase in stream-water NO_3^- and Al_{im} stream-water concentrations is unknown, but probably depends on the history of forest-disturbance and acid deposition and the level of soil acidification. Results of this study indicate that macroinvertebrate and brook trout communities were sensitive to clearcutting and that deer browsing may affect water quality by suppressing forest regeneration and nutrient uptake. Further studies of selective harvests could identify the harvesting threshold below which changes in water quality and soil chemistry are minimized, and nutrient retention is maximized, thus reducing the damage that logging can inflict on stream and aquatic communities.

Introduction

Forest-harvesting studies have indentified several variables that are directly affected by forest harvesting including: vegetation, soil chemistry, soil physical properties, soil microbial communities, and ground-water and stream-water quantity and quality (Vitousek, 1981; Hornbeck and Kropelin, 1982; Dahlgren and Driscoll, 1994). Furthermore, changes in these components can adversely affect forest regeneration and aquatic communities in surface waters that receive drainage from harvested areas. The Catskill Mountain region of southeastern New York (fig. 1) is about 85 percent forested and contains six reservoirs that are the principal drinking-water supply for New York City. Land-use managers in the region need forest-harvesting guidelines that will ensure the continued vigor of the forest-products industry while preventing water-quality degradation. The effects of harvesting on the sustainability and health of forest and aquatic ecosystems have been the subject of research for many years (Likens and others, 1969; Vitousek and others, 1979; Bormann and Likens, 1994; Reynolds and others, 1995); of particular interest have been the effects of harvesting on the nitrogen (N) cycle in forest soils and adjacent surface waters (Vitousek, 1981; Hornbeck and Kropelin, 1982).

Since 1982 the U.S. Geological Survey (USGS) has been studying stream-water quality in forested Catskill watersheds in relation to acid rain (Murdoch and Stoddard, 1992, 1993; Murdoch and Shanley, 2006), climate change (Murdoch and others, 1998; Murdoch and others, 2000; Burns and others, 2007), nitrogen cycling (Burns, 1998; Welsch and others, 2001), hillslope hydrology (Brown and others, 1999), and logging (Baldigo and Murdoch, 1997; Baldigo and others, 2005; Burns and Murdoch, 2005; McHale and others, 2007).

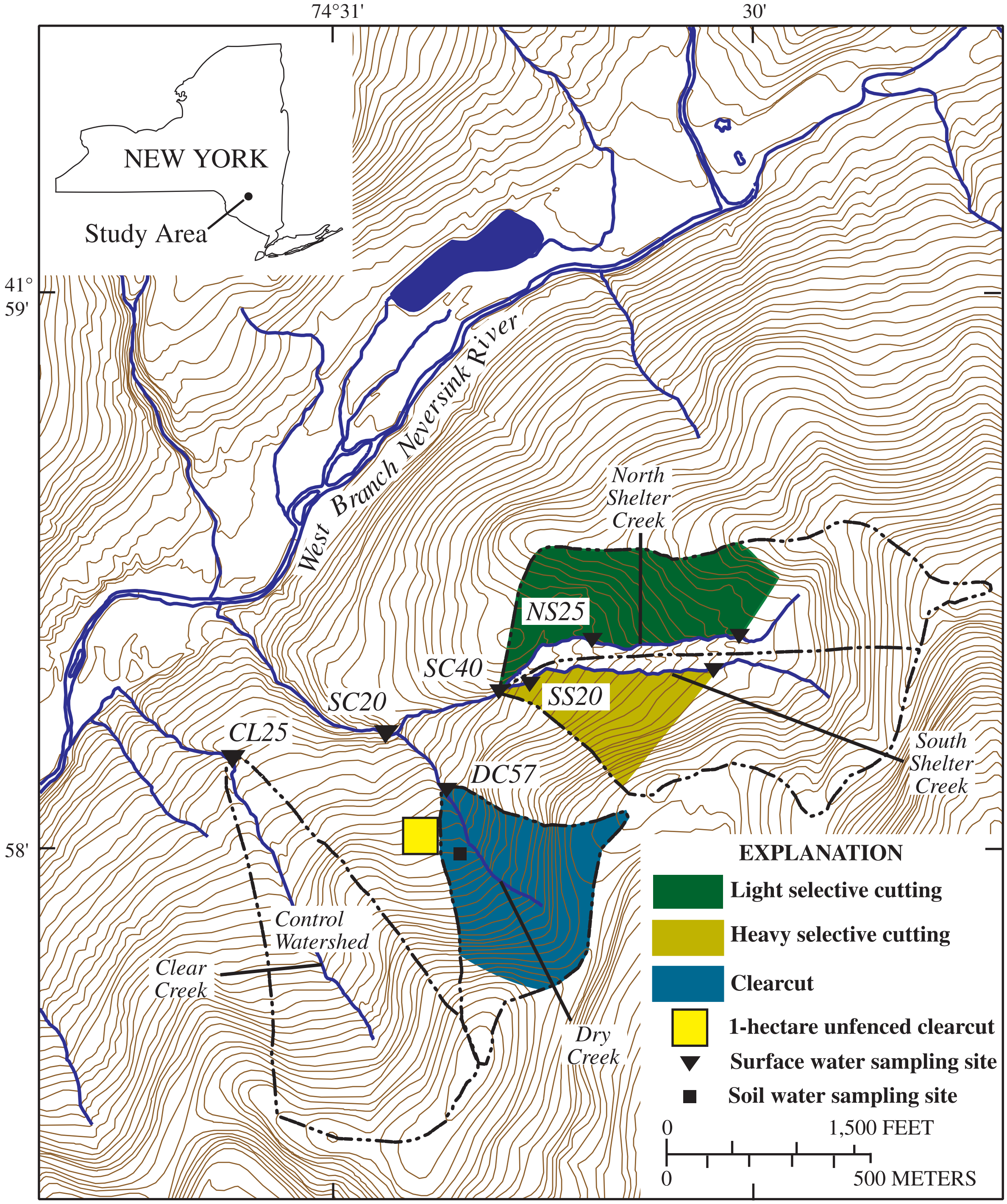

Figure 1. Location of the four study watersheds in the Catskill Mountains of southeastern New York.

In 1992, the USGS, in cooperation with the New York City Department of Environmental Protection, began a 9-year study of the ecological effects of two forest-harvesting methods—a clearcut and a selective harvest (timber stand improvement) in the headwaters of the Neversink Reservoir watershed in the Catskill Mountains of southeastern New York (fig. 1). The harvests were conducted during the winters of 1995–96 and 1996–97; stream-water and soil-water chemistry were monitored for 4 years before and after the harvests, and tree regrowth, macroinvertebrate communities, and brook-trout (*Salvelinus fontinalis*) mortality were used as indicators of the ecological effects of forest harvesting. This report describes the harvesting and monitoring methods used and summarizes the effects of the harvests on soil chemistry, soil- and stream-water chemistry, macroinvertebrate communities, and brook-trout mortality. More detailed findings from this study, published in peer-reviewed scientific journals, are referenced throughout this report.

A Changing Approach to Forest Management

Traditionally, forest-management decisions have been based mainly on the observed physical condition of trees in a forest stand. A new, broader perspective on forest management has emerged in recent years from the field of watershed biogeochemistry, the study of biological and geochemical processes and element cycling within a given drainage basin (fig. 2). A biogeochemical approach to forest management takes into account a suite of interrelated indicators of ecosystem health. These include the rate of atmospheric deposition (wet and dry chemical deposition), climatic conditions, chemical and physical properties of the soil, stream-water and ground-water quality, and the possible effects of changes in these factors on stream biota in addition to traditional silvicultural considerations such as the physical condition of the forest. For example, if logging were conducted in an area where soils had been depleted of

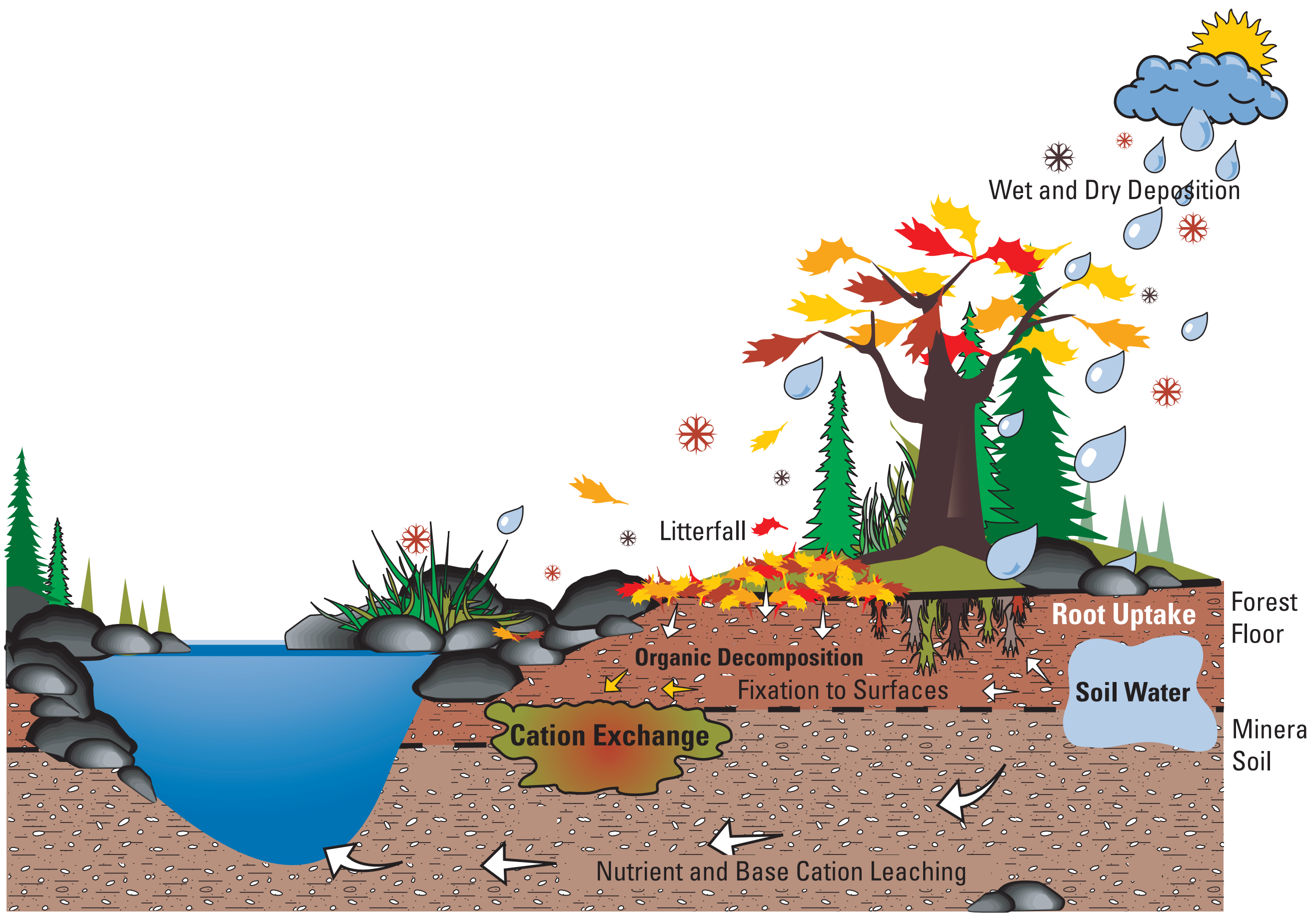

Figure 2. Interaction of biogeochemical components of a forested landscape. (Modified from Lawrence and Huntington, 1999, fig. 1.)

base cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}), a biogeochemical assessment might indicate a lighter harvest to minimize the ecological effects of harvesting, than would be suggested by standard silvicultural methods.

Study Area

The study area (fig. 1) is characterized by steep slopes interrupted by flat terraces. Thin soils overlie thin till (1–3 m or ~3–10 ft thick) that was deposited by glaciers about 14,000 years ago on sandstone and conglomerate interbedded with siltstone and shale. Forests are mixed northern hardwoods of primarily *Fagus grandifolia* (American beech), *Betula alleghaniensis* (yellow birch), *Acer saccharum* (sugar maple), and *Acer rubrum* (red maple); *Tsuga canadiensis* (L.) Car. (eastern hemlock) dominates in many riparian zones. Mean annual air temperature is 5°C (41°F), and annual precipitation averages 1.6 m (63 inches).

Methods

Three watersheds were harvested during the study, and a fourth was used as a control in which no harvesting was done (fig. 1). The North Shelter Creek (NS25, 33 ha) and South Shelter Creek (SS20, 51 ha) catchments form the Shelter Creek watershed (109 ha), which is monitored at site SC40 (fig. 1). The combined areas of the NS25 and SS20 catchments are less than the entire area of the Shelter Creek watershed at SC40 because the catchment gages are well upstream from the SC40 gage (fig. 1). The Dry Creek watershed (DC57, 24 ha) lies just south of the Shelter Creek watershed; Dry Creek flows into Shelter Creek upstream from gaging station SC20 (161 ha). The Clear Creek watershed (CL25, 48 ha) was used as a control and is located just west of the Dry Creek watershed (fig. 1).

Several environmental indicators such as atmospheric-deposition chemistry, soil chemistry, soil-water chemistry, stream-water and ground-water chemistry, tree biomass and leaf chemistry, and biological nitrogen transformations (mineralization, nitrification, and denitrification) were monitored during 1992–97 before the experimental harvests. A “Timber Stand Improvement” (selective removal of sick or unmarketable trees to increase the growth rate of remaining trees) was done in parts of the Shelter Creek watershed (SC40) in two phases. Phase 1, termed the “light selective harvest,” entailed selective logging of the North Shelter Creek catchment (NS25, fig. 1) during the winter of 1995–96 to provide a 7-percent decrease in tree basal area within the logged area; this resulted in a 2-percent decrease in basal area within the entire North Shelter Creek catchment. Phase 2, termed the “heavy selective harvest,” entailed logging of the South Shelter Creek catchment in the fall of 1996 to provide a 29-percent decrease in tree basal area within the logged area; this resulted in an 8-percent decrease in basal area within the entire SS20 catchment. About 5.6-percent of the basal area was removed from the entire Shelter Creek watershed (SC40), 68 ha of the Shelter Creek watershed was left untouched because it is part of the New York State forest preserve. During the following winter (1996–97), 18 ha of the 24-ha Dry Creek watershed (DC57, fig. 1) was clearcut, leaving only a few scattered seed trees for regeneration; 6 hectares in the southwestern portion of the watershed were left undisturbed because that area is also part of the New York State forest preserve (fig.1). Slash (branches and tree tops) was left on the ground and arranged along temporary skidder trails to create a “corduroy” surface to minimize soil disturbance. The clearcut decreased the basal area of the harvested area by 97 percent and amounted to an 80-percent decrease in the basal area of the entire watershed. The fourth watershed (CL25, 48 ha) was monitored as an untreated reference site. The heavy selective harvest in the South Shelter Creek watershed and the clearcut area of the Dry Creek watershed were enclosed with 2.5 m high game fence to prevent deer browsing which can inhibit forest regrowth. One additional 1-ha forest plot, adjacent to the Dry Creek watershed, was clearcut and left unfenced to assess the effect of deer browsing on forest regeneration (fig. 1). Monitoring at all sites continued from October 1, 1992 through September 30, 2001 (water years 1993–2001).

Effects of Forest Harvesting on Ecosystem Health

The effects of forest harvesting on soils and soil microbial communities, soil-, stream-, and ground-water chemistry, and stream aquatic communities are often used as indicators of the effects of a tree harvest on ecosystem health. The following sections describe the effects of the experimental harvests on soils and soil-water chemistry, stream-water chemistry, macroinvertebrate communities, caged brook trout, and tree regrowth after the harvests.

Forest Soils and Soil Water

Soil samples and soil-water samples were collected in the Dry Creek watershed to evaluate the effects of harvesting on watershed soils. Soil samples were collected from several depths at each of 43 locations and were air-dried, sieved, and analyzed with standard soil-analysis methods. Soil-water samples were collected monthly from zero-tension lysimeters, also referred to as “gravity lysimeters,” because they collect water that drains through the soil by gravity (as opposed to suction lysimeters, which use negative pressure to collect soil water). Additional samples were collected during storms and spring snowmelt with sequential lysimeters. This technique linked zero-tension lysimeters to an automated sampler to allow frequent sampling and provide more detailed data on changes in soil-water chemistry than would be possible with monthly, biweekly, or even weekly fixed-interval sampling.

Soil Chemistry

Soils provide the nutrients and water that trees and other vegetation require to survive and host the macro- and microorganisms that cycle those nutrients and make them available to plants. Soils are also the medium through which rain and snowmelt percolate and through which shallow ground water flows. Soil water is a significant component of stream flow and so changes in the chemistry of soil water can have a direct affect on stream-water chemistry. An assessment of soil chemistry prior to forest harvesting can indicate how harvesting may affect soil chemical pools, nutrient cycling, soil- and stream-water chemistry and ultimately the rate of forest regrowth.

Forest harvesting typically results in soil acidification because tree removal decreases N uptake creating an excess of N in the soil; that N is then transformed to nitrate (NO_3^-) through a microbial process known as nitrification. The NO_3^- then passes through the soil as nitric acid (HNO_3), which can deplete neutralizing cations such as Ca^{2+}, Mg^{2+}, sodium (Na^+), and potassium, (K^+) (collectively referred to as base cations). This leaching of soil base cations causes a decrease in soil pH and is often accompanied by a release of soil aluminum (as Al^{3+}) (McHale and others, 2007), which is detrimental to tree growth and toxic to some fish and other aquatic biota (Schofield and Trojnar, 1980; Shortle and Smith, 1988; Cronan and Grigal, 1995; Baldigo and Murdoch, 1997; Baldigo and others, 2005).

Changes in soil chemistry can be difficult to detect at time scales shorter than a decade because the pool of chemicals held in the soil greatly exceeds the amount that is cycled by biota annually. Nonetheless, the clearcut was followed by a decrease in the amount of exchangeable base cations (positively charged ions attached to negatively charged soil particles) in the upper part of the forest floor (the Oi horizon), which is rich in organic matter (table 1) (McHale and others, 2007). This decrease was insignificant at greater depths. Percent base saturation—the amount of exchangeable base cations relative to the amount of all exchangeable cations (hydrogen and aluminum plus base cations)–decreased within the Oa horizon (the organic soil layer) after the clearcut. Exchangeable base cation concentrations and percent base saturation are important measures of the base cation pool available in the soil and base cations are essential nutrients for forest regrowth.

In general, the concentrations of exchangeable base cations in the study area were low, even before the clearcut, relative to those of forests elsewhere in the northeastern United States (David and Lawrence, 1996); this is because the sandstone bedrock from which Catskill soils are derived has a relatively slow weathering rate and consists largely of silica (Rich, 1934). These soils were highly acidic even before the forest harvest as a result of natural soil-forming processes and several decades of acidic atmospheric deposition (Lawrence and Huntington, 1999). The clearcut resulted in a further decrease in exchangeable base cations and a coincident increase in exchangeable Al concentration within the soil (table 1).

Soil Microbial Processes

The N cycle in forest soils reflects the competition among plant roots and microbes for available ammonium (NH_4^+) and NO_3^-. Plants need soil microorganisms to convert N stored in organic matter into inorganic forms that they can assimilate through their roots (although recent research has shown that some plants take up organic forms of N directly). The effects of forest disturbances such as tree harvesting, soil freezing, and insect infestations can shift the balance between roots and microorganisms and thereby alter the rate of N accumulation and movement in soils (Likens and others, 1969; Groffman and others, 2001; Lovett and others, 2002). Forest harvesting causes an increase in NO_3^- concentrations in soil water, stream water, and ground water. What is unclear is whether the increase is caused primarily by tree removal and the consequent decrease in N uptake or increased rates of microbial N cycling that result from higher soil moisture and temperature. To investigate this question, net N-mineralization and nitrification rates (the processes by which N is converted from organically bound N to NH_4^+ and NO_3^-) were measured before and after the clearcut and compared to estimates of N uptake by vegetation before the clearcut and stream-water N export after the clearcut. Net N-mineralization and nitrification rates in Catskill soils before the clearcut were among the highest recorded in northeastern forests and did not change significantly as a result of the clearcut (Burns and Murdoch, 2005). Rather, the increase in stream-water N export in Dry Creek after the clearcut roughly equaled the preharvest uptake of N by trees in the watershed; therefore, the increase in stream-water N export is attributed mostly to a decrease in uptake by trees, rather than to a temperature- or moisture-stimulated increase in rates of N mineralization and nitrification. This conclusion may also apply to other forested watersheds that receive N deposition in amounts greater than required by watershed biota. Previous studies have documented significant increases in N-mineralization and nitrification rates after forest harvesting in other northeastern watersheds, however, those watersheds were leaching much less inorganic N to streams than the Dry Creek watershed was prior to harvesting (Matson and Vitousek, 1981; Gordon and Van Cleve, 1983; Vitousek and Matson, 1985; Frazer and others, 1990; Pierce and others, 1993).

Table 1. Mean chemical properties of soil horizons in Dry Creek watershed before and after clearcut of 1996–97.

[Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; Al, aluminum; H^+, hydrogen ion; m, meter. Site location is shown in fig. 1]

Soil horizon[a]	No. of samples (*n*)[b]	Soil properties					Exchangeable-cations, in centimoles of charge per kilogram							Percent base saturation	Ca:Al ratio
		Soil-water pH	Soil pH (as $CaCl_2$)[c]	Percent LOI[d]	Percent carbon	Percent nitrogen	Ca	Mg	K	Na	Al	H^+	Cation-exchange capacity		
A. Preharvest—12 samples collected at 0.1-m depth increments and 31 bulk samples from each horizon during 1996															
Oi	11	4.50	3.88	88	47.8	2.69	23.55	4.70	3.83	0.09					
Oa	16	3.83	3.21	34	17.7	1.03	3.53	0.87	0.63	.03	4.73	4.09	13.87	35.79	0.75
B	79	3.90	3.38	5	2.5	0.18	0.38	.12	.11	.02	5.34	1.74	7.72	7.98	.07
C	47	4.40	3.78	2	0.9	.14	.15	.04	.06	.01	3.53	0.48	4.27	6.11	.04
B. Postharvest—27 samples collected from soil pits at 0.1-m depth increments during 1998															
Oi	27	4.06	3.38	78	41.9	2.23	13.88	2.69	1.63	.05					
Oa	26	3.77	3.13	43	24.2	1.38	3.96	.82	.71	.04	7.82	4.80	18.15	29.73	.51
B	98	4.13	3.46	4	3.7	.25	.26	.08	.12	.01	5.48	1.54	7.49	6.66	.05
C	34	4.40	3.71	2	.9	.07	.11	.03	.07	.01	3.65	0.42	4.29	5.19	.03

[a] Oi, Organic material that shows little decomposition, mostly leaves.

[a] Oa, Organic material that is well decomposed.

[a] B, Mineral soil that shows little or no evidence of the original sediment or rock structure and has a low organic matter content.

[a] C, Undeveloped soil composed of the material from which the soil is formed; includes materials in various stages of weathering.

[b] Differences in n values between horizons reflect the number of 0.1-m depth intervals within each horizon.

[c] Soil pH after extraction with a 0.02 M $CaCl_2$ (calcium chloride) solution.

[d] Percent Weight Loss on Ignition (LOI) gives a measure of the organic matter in the sample; it denotes the percent weight lost when the sample is combusted.

Soil-Water Chemistry

Water enters forest soils as dilute rainwater, snowmelt, or throughfall (precipitation that has passed through the forest canopy). Upon entering the soil, the water percolates downward where it can be taken up by plants, recharge ground water, or drain to streams. The chemistry of the water changes considerably as it interacts with the soil mainly through exchange reactions with ions bound to soil particles; as a result soil water chemistry reflects conditions in the soil. Soil water chemistry can be a more sensitive indicator of changes in soil chemistry than stream water or ground water because stream water is composed of soil water, groundwater, and (during storms) precipitation and changes in ground water chemistry occur over much longer time periods than soil water. Soil water was sampled as a part of this study to measure changes in the soil caused by the harvests.

Nitrate and Sulfate

Previous studies of forest harvesting have documented a large increase in soil-water NO_3^- concentrations and have attributed that change to decreased uptake by trees and to increased rates of N mineralization and nitrification (Vitousek and Melillo, 1979; Matson and Vitousek, 1981; Vitousek, 1981; Hornbeck and Kropelin, 1982). Within a few years soil-water NO_3^- concentrations typically decrease to preharvest concentrations or lower as the demand for N by vegetation increases during the early stages of forest regrowth. Soil water in the Dry Creek watershed before the 1996–97 clearcut was acidic and contained measurable amounts of sulfate (SO_4^{2-}) and NO_3^- throughout the year. Soil-water chemistry did not change immediately after the clearcut, which was completed in April 1997; rather, it remained at preharvest levels for 3 months until mid-July, when it changed sharply

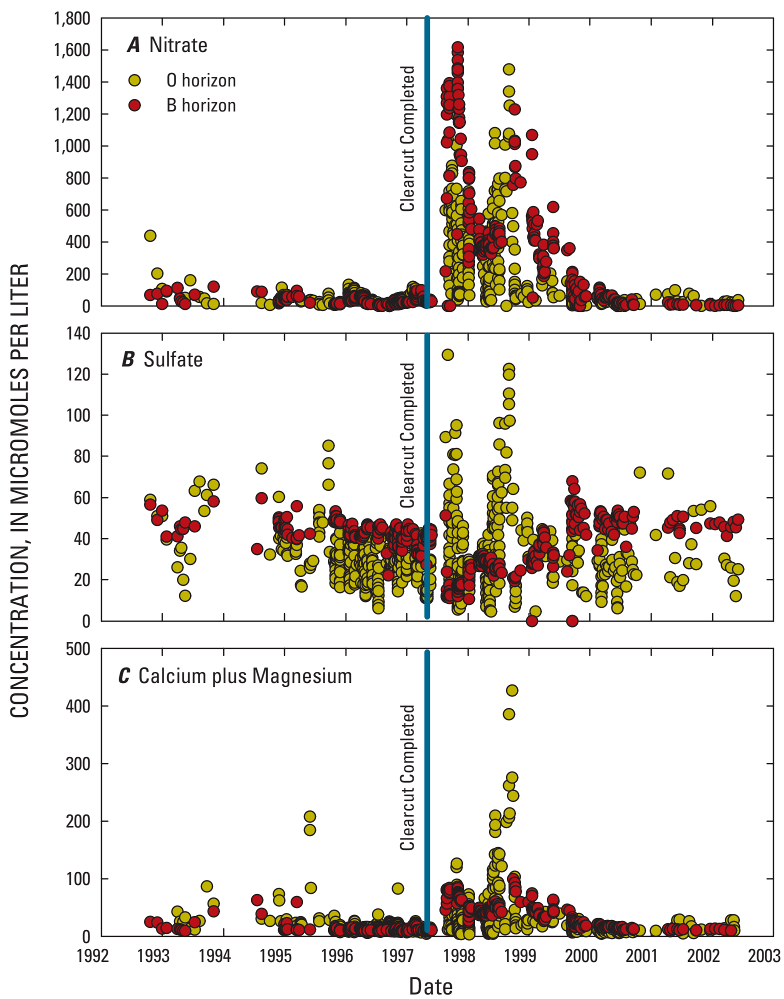

Figure 3. Concentrations of *(A)* nitrate, *(B)* sulfate, and *(C)* calcium plus Magnesium in O- and B-horizon soil water in the Dry Creek watershed (DC57) in response to the clearcut of 1996–97. (Location is shown in fig. 1.)

(fig. 3). During the fall of 1997 NO_3^- concentrations exceeded 1,100 µmol/L in O horizon soil water, 1,600 µmol/L in B horizon soil water, and were as high as 1,390 µmol/L in stream water (McHale and others, 2007). Those concentrations were much higher than NO_3^- concentrations measured after clearcuts in other northeastern watersheds with lower rates of atmospheric N deposition, for example the whole-tree harvest at Hubbard Brook, N.H. in 1983–84 produced maximum soil-water NO_3^- concentrations of ~825 µmol/L (Dahlgren and Driscoll, 1994). In contrast to the Hubbard Brook study there was still measurable NO_3^- in soil water during the growing season as long as 4 years after the Dry Creek clearcut. Sulfate concentrations in B-horizon soil water decreased from 45 µmol/L to 20 µmol/L during the first 8 months after the clearcut because a decrease in soil pH increased the adsorption of sulfate onto soil particles (fig. 3) (Welsch and others, 2004).

After the clearcut, soil-water samples from the sequential lysimeters often showed 2 peaks in NO_3^- concentration during storms, the first peak typically occurred early in the storm, the second after the storm hydrograph peak. Water table elevation data collected at a shallow well located adjacent to the sequential lysimeters revealed that the first peak in NO_3^- occurred when the water table was below the lysimeters as soil water was percolating down through the soil column. The second peak in NO_3^- concentration occurred when the water table had risen above the elevation of the lysimeters and shallow ground water was flowing laterally into the lysimeters. This dual peak in NO_3^- concentrations only occurred during storms in which the water table overtopped the lysimeters. Storms that occurred after long, dry periods resulted in high NO_3^- and NH_4^+ concentrations because, in the absence of vegetative uptake, those dry periods allowed NO_3^- to buildup in the soil through N mineralization and nitrification. When storms occurred in rapid succession there was a dilution of NO_3^- and NH_4^+ in soil water from one storm to the next. Thus, the moisture conditions in the watershed before storms had a large effect on the release of NO_3^- from watershed soils.

Calcium and Magnesium

Concentrations of Ca^{2+} and Mg^{2+} in soil water increased sharply after the clearcut and returned to preharvest levels within 4 years (fig. 3). Clearcutting in these Ca-poor soils resulted in a decrease in the exchangeable-base-cation pool and the percent base saturation, both of which are indicators of the amount of base cations available to support forest regrowth (table 1). Continued monitoring of soil-water chemistry and tree regrowth is expected to reveal the long-term effect of decreased exchangeable Ca^{2+} and Mg^{2+} on forest regeneration in these Catskill watersheds.

Stream-Water Chemistry

Stream-water chemistry reflects all of the watershed processes discussed thus far and is often used to represent the response of an entire watershed to natural disturbances as well as to forest-management activities. The study was divided into three time periods for water-quality comparisons among watersheds—the preharvest period (1993–96), the harvest period (1997–99), and the postharvest period (2000–01). The NO_3^- and base-cation concentrations in Dry Creek increased sharply after the clearcut, but there was only a small response in Shelter Creek after the two selective harvests (fig. 4). This is consistent with results of previous studies, which have also documented the leaching of NO_3^- and base cations after forest harvests (Vitousek and Melillo, 1979; Hornbeck and Kropelin, 1982; Dahlgren and Driscoll, 1994). As NO_3^- passes through the soil th cidity it produces is neutralized first by base cations and then by inorganic monomeric Al (Al_{im}), as a result Al_{im} concentrations in Dry Creek also increased markedly after the clearcut, but not in Shelter Creek after the selective harvests (gaging stations NS25, SS20, or SC40) (fig. 4, table 2). In general, NO_3^- and Al_{im} concentrations in Dry Creek were much higher than those reported for the whole-tree harvest at Hubbard Brook (Hornbeck and Kropelin, 1982; Lawrence and others, 1987; Dahlgren and Driscoll, 1994). High Al_{im} concentrations are toxic to some fish species, including brook trout (Schofield and Trojnar, 1980; Baker and Schofield, 1982; Baldigo and Murdoch, 1997; Kaeser and Sharpe, 2001; Baldigo and others, 2005); they also can inhibit the uptake of calcium by tree roots (Shortle and Smith, 1988; Cronan and Grigal, 1995) and thereby increase forest vulnerability to disease, insect infestation, and mortality from other stresses such as drought.

Ground-water seepage into Dry Creek mitigated the effect of the clearcut on stream-water chemistry to a degree, in that the high base-cation concentrations in ground water neutralized some of the stream acidity produced by soil-water HNO_3. Nonetheless, the large amount of NO_3^- released from watershed soils after the clearcut overwhelmed the neutralizing capacity of the ground water and the sharp decrease in soil-water and stream-water pH coincided with a large release of Al_{im} from O- and especially B-horizon soils to the stream (fig. 4, table 2) (McHale and others, 2007). Forest regeneration began during the first year after the clearcut (fencing around the clearcut area prevented deer browsing on young trees), and stream-water NO_3^-, Al_{im}, and base-cation concentrations returned to or fell below pre-harvest concentrations by the fifth year after the clearcut.

The large release of NO_3^- and the coincident release of Al_{im} from watershed soils after the clearcut, produced stream-water Al_{im} concentrations well above the 3.7 µmol/L threshold that is considered toxic to some aquatic biota (fig. 4, table 2). In contrast, the selective harvests in the north and south Shelter Creek catchments did not cause an increase in the concentrations of stream-water NO_3^- or Al_{im} (fig. 4, table 2). Further research is needed, however, to define the harvesting threshold above which nutrient and base-cation losses greatly increase, and below which nutrient retention is maximized, to ensure minimal effects on stream-water quality and aquatic biota (fig. 5).

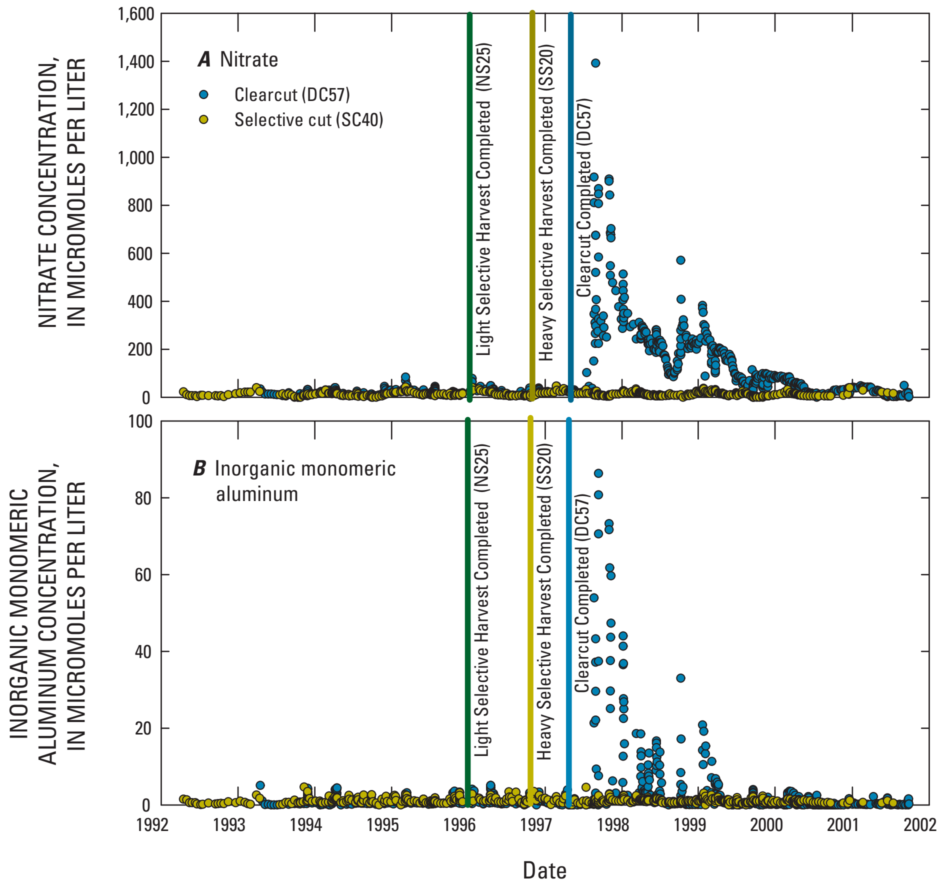

Figure 4. *(A)* Nitrate and *(B)* inorganic monomeric aluminum concentrations in stream water before, during, and after the harvests in the Dry Creek - DC57 (clearcut) and Shelter Creek - SC40 (selectively harvested) watersheds in southeastern New York, 1992–2001. (Locations are shown in fig. 1.)

Forest Regrowth and Aquatic Communities after the Harvests

Soil chemistry and microbial processes are the principal factors that affect the rate of forest regrowth while stream-water quality and flow conditions are the principal factors that affect the health of stream aquatic communities. As discussed in the previous section, stream water quality integrates the effects of soil chemistry, soil microbial activity, and soil-water chemistry as well as other factors such as atmospheric deposition, soil- and ground-water flowpaths, and the effects of vegetation and, therefore, is often used to represent the response of the entire watershed to an ecosystem disturbance such as forest harvesting. An increase in stream-water acidity and Al concentrations can affect the survival of individual organisms, species distribution, and the structure and function of aquatic communities. Many of these factors can be represented by biological indicators which are used to quantify the severity of a disturbance within an affected stream ecosystem. Therefore, part of this study entailed monitoring of forest regrowth, macroinvertebrate communities, and mortality of brook trout as indicators of the effects of forest harvesting on biological communities.

Nutrient Uptake and Tree Regrowth

From a forest management perspective the critical question regarding forest regrowth is whether the physical, chemical, and hydrologic conditions in the watershed after the harvest will sustain healthy regeneration. Those conditions determine the rate and vigor of forest regrowth and they depend on the pre-harvest state of the watershed and the severity of the disturbance. For this study forest regrowth was assessed by measuring nutrient uptake and biomass

Table 2. Stream-water chemistry in Dry Creek (clearcut, DC57), Shelter Creek (selectively harvested watersheds, SC40), and Clear Creek (the control watershed, CL25) before, during, and after forest harvests conducted from 1995–97.

[Concentrations are means, in micromoles per liter. pH is given in pH units, ANC given in microequivalents per liter. ANC, acid-neutralizing capacity; Ca, calcium; Mg, magnesium; K, potassium; Na, sodium; Cl, chloride; NO_3, nitrate; SO_4, sulfate; DOC, dissolved inorganic carbon; SiO_4, silica; Al_{mon}, monomeric aluminum; Al_{org}, organic momomeric aluminum, Al_{im}, inorganic monomeric aluminum, ND = not detected. Watershed locations are shown in fig. 1]

Watershed	pH	ANC	Ca	Mg	K	Na	Cl	NO_3	SO_4	DOC	SiO_2	Al_{mon}	Al_{org}	Al_{im}
Preharvest (1993–96)														
Clearcut	5.91	28.22	55.86	25.87	8.48	16.29	15.83	22.85	55.23	192.77	35.95	1.97	0.79	1.18
Selective cut	5.40	2.75	41.49	24.95	6.97	13.84	16.09	12.33	55.20	299.93	40.31	3.00	1.58	1.40
Control	5.97	20.02	47.81	29.28	6.50	13.57	16.05	12.24	60.37	150.66	44.94	1.34	.61	0.74
Harvest (1997–99)														
Clearcut	5.59	6.34	85.47	53.17	17.37	17.20	16.07	206.85	41.73	162.81	35.26	7.76	.71	6.99
Selective cut	5.46	6.52	41.03	24.06	7.36	12.63	12.77	13.73	49.63	312.66	36.16	2.88	1.63	1.25
Control	6.04	20.14	49.29	29.92	6.53	14.33	13.54	27.27	53.66	146.76	39.57	1.17	.37	.72
Postharvest (2000–01)														
Clearcut	6.17	42.34	56.48	26.52	13.62	15.72	13.03	24.97	52.28	202.84	37.34	0.88	.15	.56
Selective cut	5.63	11.65	40.05	24.32	6.29	15.24	15.53	13.95	51.00	184.77	38.47	1.22	.39	.79
Control	6.14	27.67	47.05	29.03	6.24	14.55	14.54	16.45	53.28	141.43	40.27	.45	ND	.38

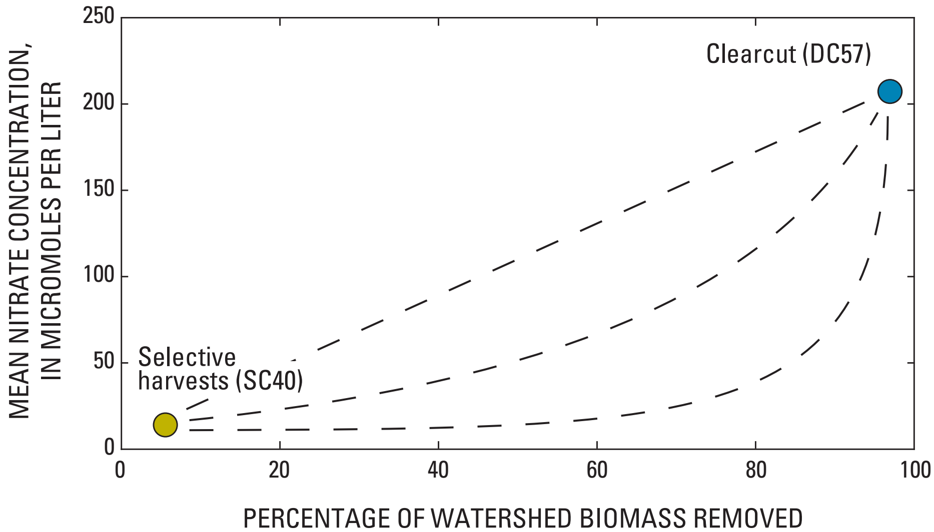

Figure 5. Three hypothetical relations (dotted lines) between mean stream water nitrate concentration and percentage of watershed biomass harvested during the first year after the clearcut (DC57) and the selective harvests (SC40) in southeastern New York. The actual relation is unknown. (Locations shown in fig. 1.)

accumulation in 20 x 20-m plots established throughout the clearcut watershed (DC57), the selectively harvested watersheds (SS20 and NS25), and the reference watershed (CL25) (Yorks, 2001; Yorks and others, 2003) (fig. 1). In addition, the effects of deer browsing on vegetation regrowth was assessed by comparing regrowth in a 1-ha unfenced clearcut area established outside of the Dry Creek watershed to the fenced 18-ha clearcut area within the Dry Creek watershed.

Biomass and nutrient accumulation were greater in the Shelter Creek selectively harvested catchments than in the Dry Creek clearcut during the first 2 years after the harvests, but this pattern reversed during the next 2 years (Yorks, 2001). Trees with a diameter-at-breast-height greater than 5 cm showed the greatest amount of nutrient and biomass accumulation in the selectively harvested areas, whereas in the Dry Creek clearcut the greatest amount of nutrient and biomass accumulation initially occurred in woody stems less than 1.4 m tall, and later in saplings, as regeneration progressed (Yorks, 2001). Biomass accumulation and nutrient uptake increased after the harvests in uncut mature trees in the selectively harvested watersheds and stream-water chemistry indicated that light tree thinning can be done without adversely affecting stream-water quality (Yorks, 2001).

The two selectively harvested areas showed minimal new growth of striped maple (*Acer pensylvanicum*) and American beech (*Fagus grandifolia*), whereas the clearcut watershed showed substantial regeneration of pin cherry (*Prunus pensylvanica*), sugar maple (*Acer sacharum*), yellow birch (*Betula alleghaniensis*), and several shrub species (Yorks, 2001). Deer browsing suppressed regeneration, biomass accumulation, and nutrient uptake by vegetation in the 1-ha unfenced clearcut area; N uptake in the unfenced area 4 years after the clearcut was only 6.3 kg/ha—one-fifth of that measured in the fenced clearcut where N uptake totaled 30.4 kg/ha (Yorks, 2001). These results confirm that deer browsing suppresses forest regeneration and nutrient uptake in Catskill forests and imply that deer browsing may affect soil- and stream-water quality.

Macroinvertebrate Communities

Benthic macroinvertebrates are reliable indicators of stream-water quality because many species are fairly immobile and vary widely in their sensitivity to common toxins; also their moderately long life span generally allows exposure to rare or episodic toxic disturbances (Bode and others, 1991, 1996; Lazorchak and others, 2003). Nevertheless, no recent studies have documented the effects of forest harvesting on macroinvertebrate communities despite evidence that it can alter the chemistry of soil and stream water (Driscoll and others, 1989; Dahlgren and Driscoll, 1994; Burns and others, 1997). For this study macroinvertebrate communities were sampled at four sites—the Dry Creek gage (DC57) at the outlet of the clearcut watershed, the upper Shelter Creek gage (SC40) at the confluence of the two streams that drain the selectively harvested catchments, the lower Shelter Creek gage (SC20) downstream from the confluence of Dry Creek and Shelter Creek, and the outlet of the control watershed (CL25) (fig. 1).

Sampling was done in the late summer 1 or 2 years before and 4 or 5 years after each harvest to evaluate the resulting changes in macroinvertebrate communities. Macroinvertebrates were sampled by the method of Surber (1970). Six indices were used to represent the response of macroinvertebrates to the effects of forest harvesting:

1. Total species richness, the total number of species or taxa found in the sample.
2. EPT richness, the number of species of mayflies (Ephemeroptera), stoneflies (Plecoptera), and caddisflies (Tricoptera) found in an average 100 organism subsample; these are considered clean-water organisms.
3. The Hilsenhoff Biotic Index (HBI), a measure of the tolerance of organisms in a sample to organic pollution such as sewage effluent or animal waste.
4. Percent gatherer feeding groups, the percentage of macroinvertebrate species that feed on items found on surface deposits. Percent gatherer feeding groups are sometimes lower in toxic conditions.
5. Percent shredder feeding groups, the percentage of macroinvertebrate species that shred organic material. The percentage of shredder feeding groups usually increases when organic matter in the water increases which would be typical immediately after a clearcut.
6. MTI, the metals-tolerance index which is an index of the number of species present that are tolerant of high metals concentrations in water (Bode and others, 2002).

Three of these indices—total species richness, EPT richness, and HBI—exceeded the New York State Department of Environmental Conservation thresholds that denote "slight impairment" of the site after the clearcut during 1998 or 1999 (fig. 6) (Bode and others, 1996; Smith and Bode, 2004). In addition, there was a decrease in the HBI and the percent of gatherer feeding groups and an increase in the percent of shredder feeding groups and the MTI after the clearcut (figs. 6, 7). None of the indices were affected by the selective harvests at Shelter Creek (SC40) or downstream from the clearcut and selective harvests at lower Shelter Creek (SC20) (fig. 6). The low index values for Clear Creek (CL25) during 1996 were probably caused by a highly acidic snowmelt during a thaw in January. The decrease in the HBI and the increase in the MTI, at Dry Creek after the clearcut reflect a large decrease in the numbers of metal-sensitive *Microspectra sp.* and an increase in the numbers of other metals-tolerant species (figs. 6, 7). Most of the indices at Dry Creek had returned to near preharvest conditions by August 2000 (figs. 6, 7).

Fish Communities

While other studies have shown that forest harvesting can affect the chemical quality of stream water (Likens and others, 1970; Dahlgren and Driscoll, 1994; Burns and others, 1997), the effects of forest harvesting on fish survival (or mortality) and fish communities in acid-sensitive streams have not been well documented. For this study young-of-the-year brook trout from the New York State Department of Environmental Conservation hatchery in Rome, N.Y., were exposed (in cages) to stream water in Dry Creek (DC57), Shelter Creek (at the SC40 gage), lower Shelter Creek (at the SC20 gage), and the reference stream (CL25) for 30-day periods during each spring from 1995 through 2000 to evaluate the effects of the selective harvests and the clearcut on this acid-tolerant species (Baldigo and Lawrence, 2001). As discussed previously the clearcut in the Dry Creek watershed caused a sharp increase in stream-water Al_{im} concentrations to levels that are toxic to brook trout and many other fish species (fig. 4, table 2) (Baker and others, 1990; Baker and Christensen, 1991; Baldigo and Murdoch, 1997).

A small percentage of brook trout mortality was measured at Dry Creek (DC57), Shelter Creek (SC40), and Clear Creek (CL25) during the spring of 1996 (fig. 8) as a result of unusually high and acidic stream flow during spring melt that mobilized some Al_{im}, however, that was the only year mortality occurred at the control watershed. Dry Creek (DC57) was the only site where there was mortality of brook trout as a result of the forest harvest (fig. 8). Trout mortality at this site ranged from 0 to 15 percent in the spring of 1995 and 1996 (before the clearcut) and during the first spring after the clearcut (1997), but all caged brook trout died during the first 7 days of the test in the spring of 1998, and 85 percent died during the 30-day test in 1999. No mortality occurred during the 30-day test in 2000. Although exposure tests were not conducted during the fall, stream water Al_{im} concentrations in Dry Creek during the fall of 1997 indicate that toxicity was greater and trout mortality would have occurred sooner than in the spring test of 1998 (fig. 4). The brook-trout mortality appears to have been caused by the Al_{im} concentrations that reached toxic levels during the first year after the clearcut as the lack of N uptake by trees allowed excess N to become nitrified and increase the soil-water acidity, which in turn mobilized soil Al_{im} which was transported to the stream (Burns and Murdoch, 2005; McHale and others, 2007).

Findings from this study and related investigations in the Northeast (Gagen and others, 1993; Simonin and others, 1993; Van Sickle and others, 1996; Baldigo and Murdoch, 1997) confirm that Al_{im} in stream water is acutely toxic to juvenile brook trout when concentrations exceed 3.7 μmol/L. Several laboratory and field investigations have found brook trout to be more tolerant of acidic, high-Al_{im} conditions than many other fish species that inhabit headwater streams of the Northeast (Johnson and others, 1987; Baker and Christensen, 1991; Gagen and others, 1993; Simonin and others, 1993; Baldigo and Lawrence, 2001). Therefore, the toxic conditions produced by the clearcut would probably have killed other fish species that may have been present, such as slimy sculpin (*Cottus cognatus*), and the brook-trout mortality reported here may represent only some of the detrimental effects that clearcutting could have on fish communities and the downstream ecosystem.

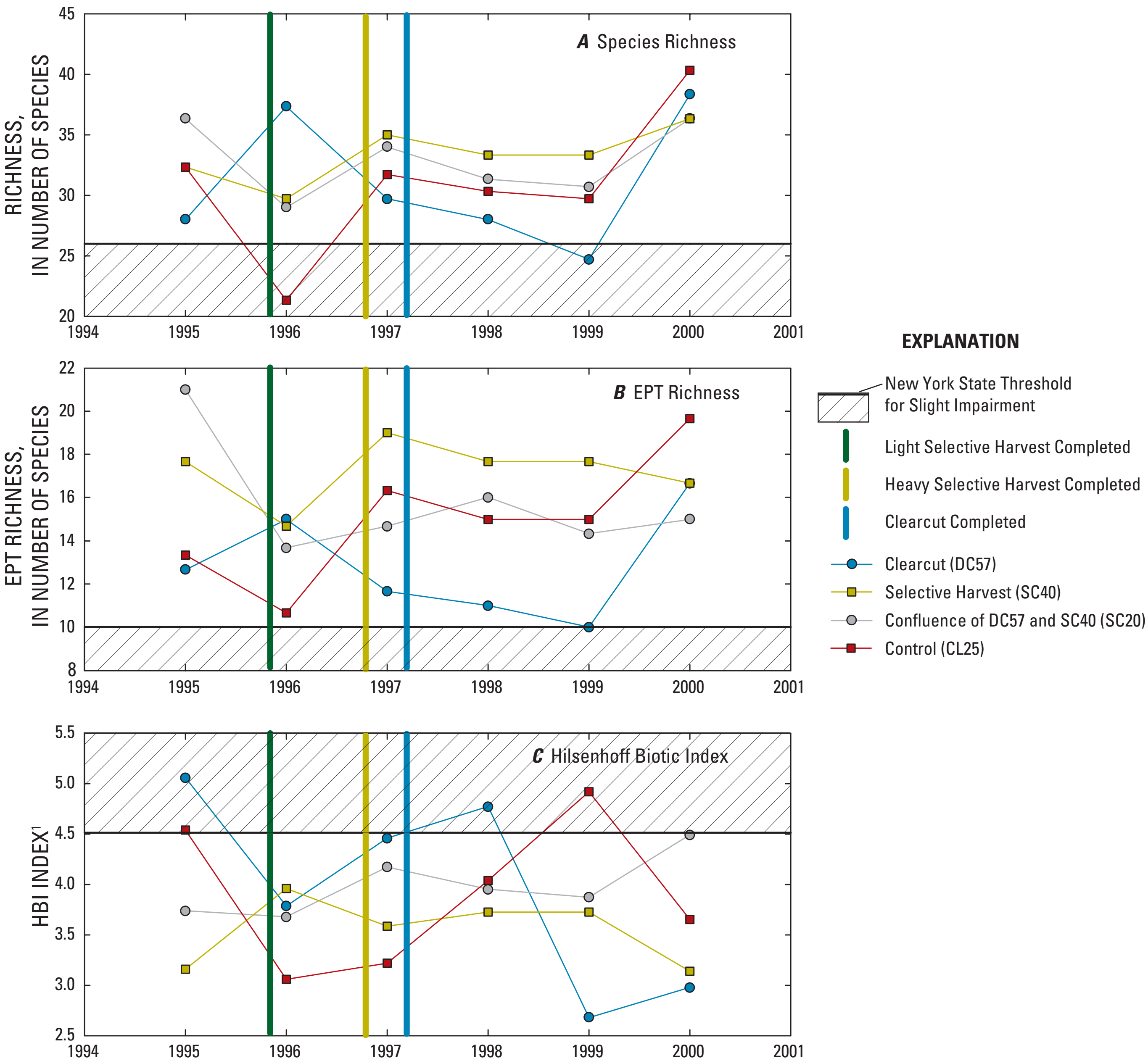

Figure 6. *(A)* Species richness, *(B)* EPT richness, and *(C)* Hilsenhoff Biotic Index in relation to New York State thresholds for "slightly impaired" site conditions as defined by Smith and Bode (2004) at four stream sites in the study area before, during, and after experimental tree harvests. (Locations are shown in fig. 1.)

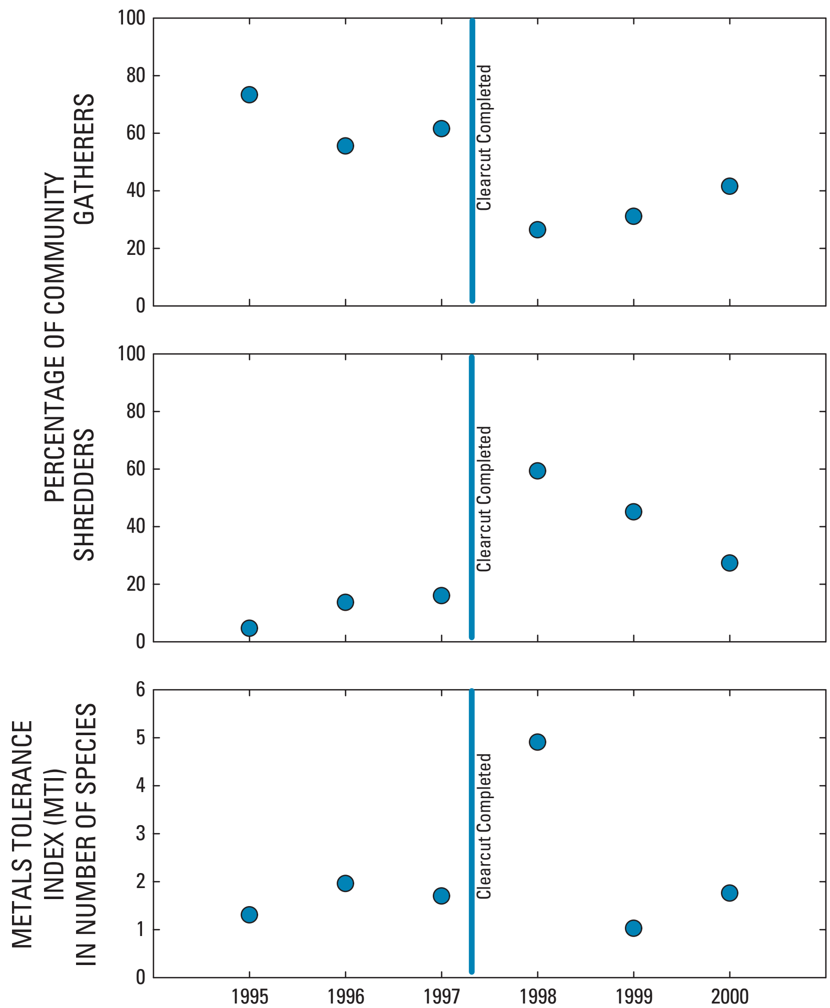

Figure 7. Mean sample values for (A) Percent Gatherers, *(B)* Percent Shredders, and *(C)* Metals Tolerance Index at the Dry Creek gage (DC57) before and after the clearcut. (Location is shown in fig. 1.)

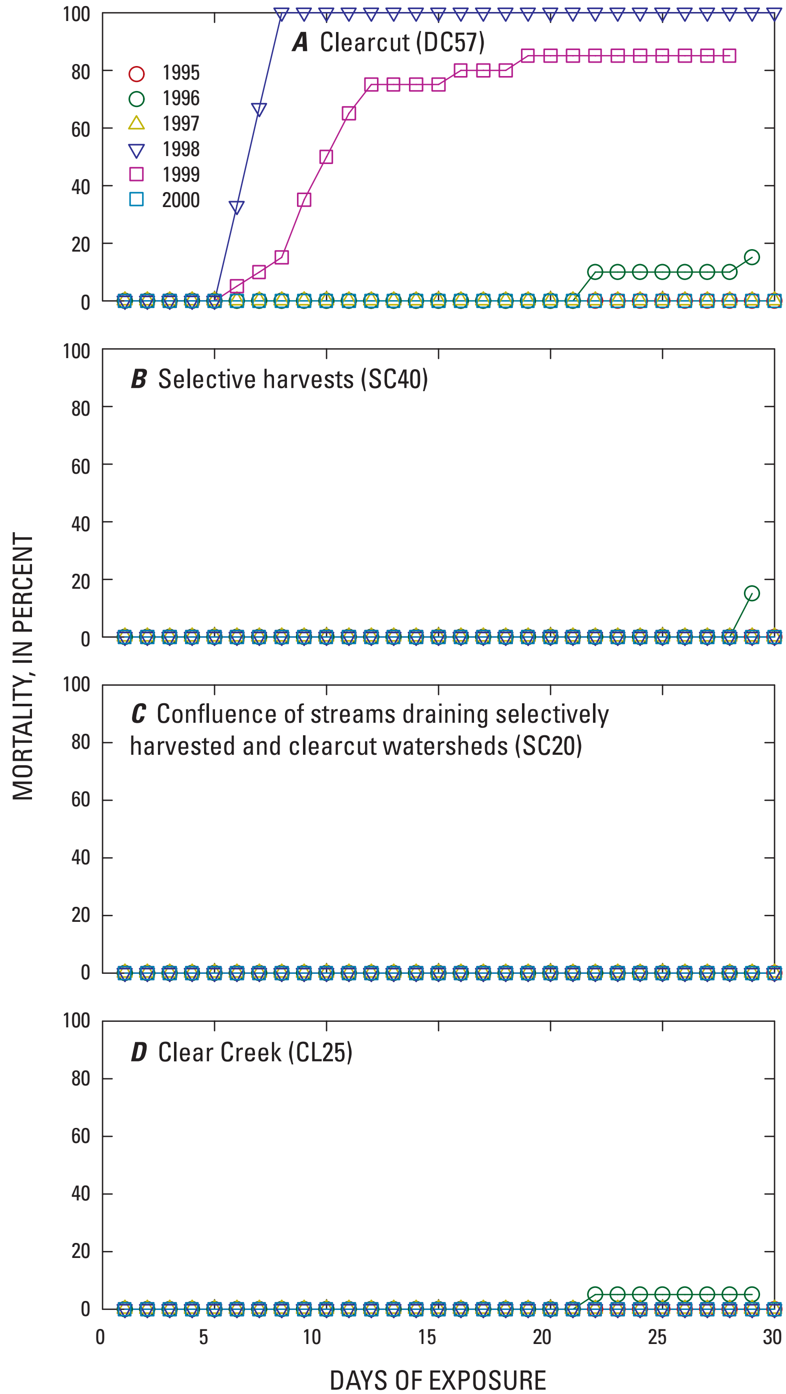

Figure 8. Brook-trout mortality during 30-day exposure experiments in the spring of each year 1995–2000 at: *(A)* the clearcut site (Dry Creek, DC57), *(B)* the selectively harvested sites (North and South Shelter Creek, SC40), *(C)* the confluence of Dry Creek and Shelter Creek (SC20), and *(D)* Clear Creek (the control stream, CL25). (Locations are shown in fig. 1.)

Conclusions

This study evaluated the effects of clearcutting and selective harvesting on nutrient retention, soil chemistry, soil-water chemistry, stream-water quality, fish and macroinvertebrate communities, and forest regrowth in three small, forested watersheds in the Catskill Mountains of southeastern New York. All of these factors were included to evaluate the effect of harvesting on the health of the ecosystem rather than focusing on one component. Several general conclusions can be drawn from this research:

- Soil chemical pools are large relative to the changes in soil chemistry that resulted from clearcutting so significant long-term changes in soil chemistry are unlikely. Nevertheless, a reduction in the base cation pool in the upper soil horizons could inhibit forest regrowth since that is where vegetation gets the majority of the nutrients it needs for growth.
- The clearcut resulted in a large release of NO_3^- from watershed soils and a coincident release of Al_{im}, which was toxic to brook trout and adversely affected macroinvertebrate communities.
- The selective harvests, which removed far fewer trees than the clearcut, did not cause an increase in stream-water NO_3^- or Al_{im} concentrations. Nutrient uptake and biomass accumulation in the uncut mature trees increased after the selective harvest, and stream water quality changed little—an indication that tree thinning can be done with minimal effect on stream-water quality.
- Deer browsing severely limited tree regrowth in the 1-ha unfenced clearcut area; a lack of regrowth can limit nutrient uptake and lead to prolonged soil N leaching and the resultant adverse effects on stream water quality.
- Selective harvesting of about 5 percent of the basal area had little effect on stream-water chemistry or on brook-trout survival.
- The percentage of tree basal area that can be harvested without a large release of NO_3^- and Al_{im} is unknown but probably is variable, depending on the amount of previous forest disturbance, the acidity of the soil, and the history of acid deposition at the site.

Results of this study indicate that brook trout and macroinvertebrates in many Catskill streams, particularly in the highly acidic Neversink River basin, are likely to be adversely affected by clearcutting. Further research is needed to define the harvesting threshold below which soil nutrient loss is minimized to limit the adverse effects of logging on stream-water quality and aquatic biota.

Acknowledgments

The authors thank Tom Suleski, James Anderson, Deborah Horan-Ross, Gretchen Wall, and Hannah Ingleston for assistance with field work and the staff at the US Geological Survey Laboratory in Troy, N.Y. for chemical analyses. Financial support for this research was provided by the New York City Department of Environmental Protection and the US Geological Survey. The Frost Valley YMCA owns the land this research was conducted on and Frost Valley foresters conducted the forest harvest; their support is greatly appreciated.

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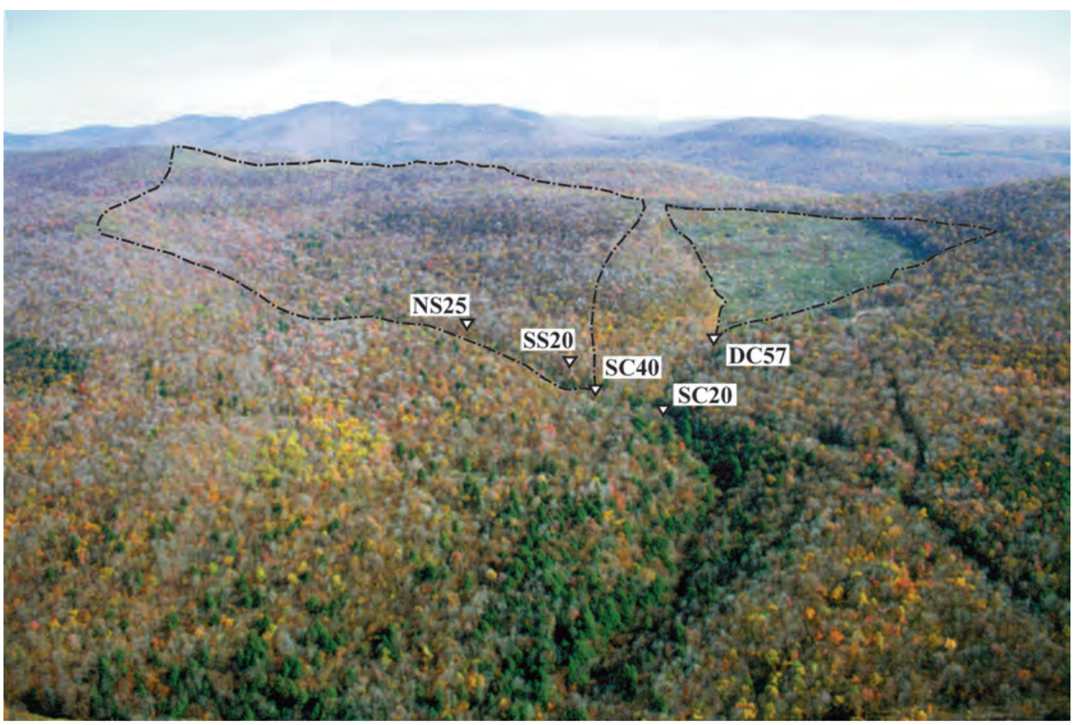
Appendix 1. Selected Photographs of the Dry Creek and Shelter Creek Forest Harvesting Study

1. The Dry Creek clearcut during October, 1998—18 months after the clearcut was completed.



2. The Dry Creek and Shelter Creek watersheds and the approximate locations of the NS25, SS20, DC57, SC40, and SC20 gaging stations.

3. View of the clearcut facing east about halfway up the Dry Creek watershed, fall 1998.

4. View of the clearcut facing east just outside the deer fence from the southwest corner of the Dry Creek watershed, fall 1998.

5. Clearcut facing north, fall 1998.

6. Clearcut facing northeast, fall 1998.

7. Clearcut facing northwest, fall 1998.

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ISBN 978-1-4113-2160-1