Aquat.sci.63 (2001) 196–222
1015-1621/01/020196-27 $ 1.50+0.20/0

Aquatic Sciences

Effects of stream acidification and habitat on fish populations of a North American river

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Key words: Acidification, aluminum, habitat, fish populations, river Neversink Catskills.

ABSTRACT

Water quality, physical habitat, and fisheries at sixteen reaches in the Neversink River Basin were studied during 1991–95 to identify the effects of acidic precipitation on stream-water chemistry and on selected fish-species populations, and to test the hypothesis that the degree of stream acidification affected the spatial distribution of each fish-species population. Most sites on the East Branch Neversink were strongly to severely acidified, whereas most sites on the West Branch were minimally to moderately acidified. Mean density of fish populations ranged from 0 to 2.15 fish/m^2; biomass ranged from 0 to 17.5 g/m^2. Where brook trout were present, their population density ranged from 0.04 to 1.09 fish/m^2, biomass ranged from 0.76 to 12.2 g/m^2, and condition (K) ranged from 0.94 to 1.07. Regression analyses revealed strong relations ($r^2 \pm 0.41$ to 0.99; $p \leq 0.05$) between characteristics of the two most common species (brook trout and slimy sculpin) populations and mean concentrations of inorganic monomeric aluminum (Al_{im}), pH, Si, K^+, NO_3^-, NH_4^+, DOC, Ca^{2+}, and Na^+; acid neutralizing capacity (ANC); and water temperature. Stream acidification may have adversely affected fish populations at most East Branch sites, but in other parts of the Neversink River Basin these effects were masked or mitigated by other physical habitat, geochemical, and biological factors.

Introduction

Fish populations in acidified streams and lakes of Europe and North America have declined, and some have become extinct as a result of atmospheric deposition of acids and the resulting changes in water quality (Baker et al., 1990). Acidification and the attendant elevated concentrations of aluminum in surface waters have adversely affected fish populations and communities in parts of the Adirondack Mountains of northern New York (Colquhoun et al., 1984; Baker and Schofield, 1982; Johnson et al., 1987; Schofield and Driscoll, 1987; Kretser et al., 1989; Simonin et al., 1993) and in a few acid-sensitive streams of the Catskill Mountains of south-eastern New York (Colquhoun et al., 1984; Stoddard and Murdoch, 1991). Recent

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studies in the Neversink River Basin in the Catskills (Fig. 1) have found detrimental effects of stream acidification on fish survival and community composition in the upper parts of the basin (Murdoch et al., 1991; VanSickle et al., 1996; Baker et al., 1996; Baldigo and Murdoch, 1997; Baldigo and Lawrence, 2000), but did not thoroughly document the effects acidification on individual fish populations.

Surface-water acidification can affect fish populations by a number of mechanisms ranging from increased mortality and emigration to decreased food supplies (Baker et al., 1990). The primary reason for population decline and extinction, however, is usually the failure of a species to successfully recruit young-of-the-year fish (Mills et al., 1987; Brezonik et al., 1993). The response of aquatic communities to acidification, therefore, should appear first as decreased health of individual fish (growth and condition), then as decreased biomass and density in populations of acid-intolerant fish species (Baker et al., 1990). Parallel increases in biomass and density of acid-tolerant species populations may also occur in response to these changes. Though populations are affected by many environmental factors, decreasing populations in an otherwise constant habitat can indicate worsening affects of acidification in aquatic communities and ecosystems.

Populations reflect and integrate the responses of individual fish to many factors, including (1) stream chemistry, which is related to weathering products; (2) chemical inputs from the terrestrial environment that determine nutrient status, productivity rates, and often the degree of stream acidification; (3) physical and hydrologic characteristics such as water velocity; the area (size), depth, width, and stability of stream channel; the type of substrate; pool/riffle ratio; and amount of fish cover and shade; (4) physiographic basin characteristics such as drainage area, stream gradient, site elevation, and flow stability; (5) water temperature; (6) recruitment success (for example, rates of reproduction and emigration); (7) anthropogenic factors such as rates of fishing and stocking; and (8) natural ecological factors such as competition, predation, and the quality and quantity of food resources (Baker et al., 1990; Beauchamp et al., 1992; Baldigo and Lawrence, 2000). All hydrologic, physical, and physiographic factors not directly related to acid-base chemistry are referred to herein as "habitat" characteristics. Many habitat and water-chemistry factors are difficult to quantify in lotic systems because large spatial and temporal (hourly, daily, seasonal, and annual) variations occur in response to frequent changes in stream-water stage and discharge.

The U.S. Geological Survey, in cooperation with the New York City Department of Environmental Protection, began an intensive long-term study in 1991 to quantify the relations among soil- and stream-water quality, hydrology, stream biology, and atmospheric inputs of acidifying agents in the Neversink River Basin (Lawrence et al., 1995a). This paper evaluates (1) the effect of stream acidification on several fish-species populations, (2) the extent to which each fish population may have been affected by stream acidification, and (3) the chemical and physical factors that are most strongly correlated to density, biomass and condition of brook trout (*Salvelinus fontinalis* (Mitch.)) populations and to density and biomass of slimy sculpin (*Cottus cognatus* (Rich.)) populations in the basin. Findings from this study enhance our understanding of the effects that stream acidification has on fish populations and will help assess the effects of the revised Clean Air Act of 1990 on water quality and fish populations of small streams in the Northeastern United States.

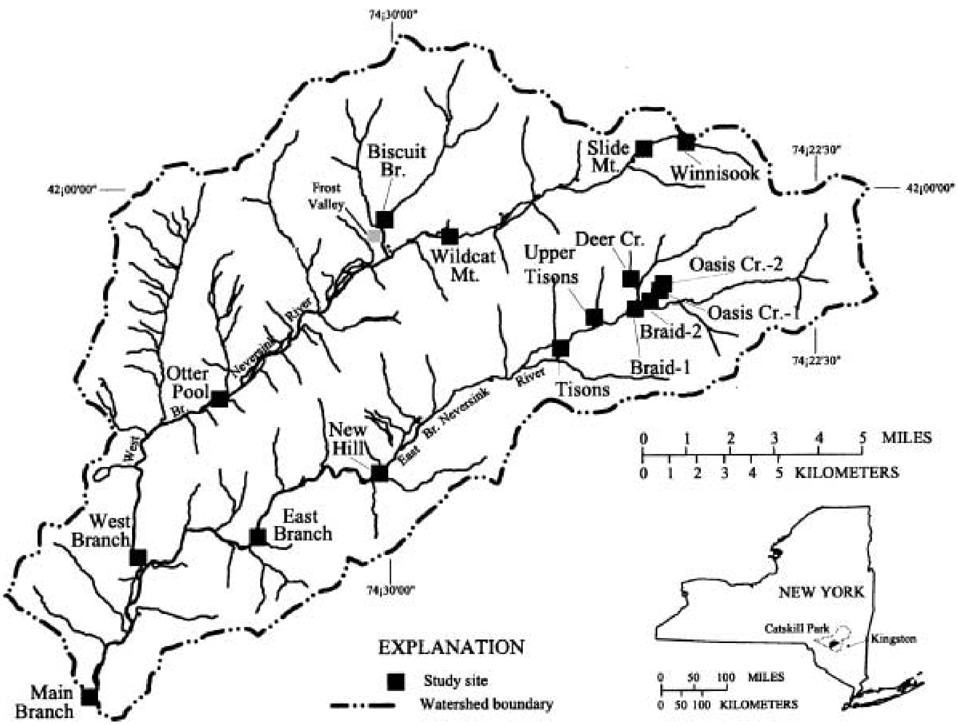

Figure 1. Location of the Neversink River Basin and study sites in the Catskill Mountain region of southeastern New York. [From Baldigo and Lawrence, 2000]

Study sites

Sixteen sites in the Neversink River Basin were selected for study; stage and discharge were monitored continuously (15-minute intervals) at 10 stations (Fig. 1). Annual wet precipitation at a precipitation gage near the Winnisook site (Fig. 1) during 1990–94 averaged 175 cm (U.S. Geological Survey, unpublished data). Average volume-weighted pH of precipitation at a precipitation gage near the Biscuit Brook site (Fig. 1) during 1984–90 was 4.3 (Murdoch et al., 1991). Additional information on climate, precipitation, physiography, bedrock geology, soils, and land uses in the region are summarized in Stoddard and Murdoch (1991) and Baldigo and Lawrence (2000).

Methods

Procedures for stream-water sampling, chemical analyses, discharge measurements, physical-habitat evaluations, and fish population surveys are described in detail by Baldigo and Lawrence (2000) and are summarized briefly below.

Water sampling and chemical analyses

Routine water samples (monthly or biweekly grabs) were collected at all discharge-gaged sites (Fig. 1) from July 1991 to July 1994 and at ungaged sites (Fig. 1) from July 1992 to January 1994. The number of routine samples from each site ranged from 19 to 39, except at two ungaged sites, Oasis-1 and Braid-1, where only 8 to 14 samples were collected. Additional samples were obtained at gaged sites during periods of high flow by stage-activated automated water samplers. Water samples were analyzed for pH, ANC, SO_4^{2-}, NO_3^-, NH_4^+, Cl^-, Ca^{2+}, Mg^{2+}, Na^+, Si, K^+, dissolved organic carbon (DOC), total Al (Al_t), total monomeric Al (Al_{tm}), organic monomeric Al (Al_{om}), and inorganic monomeric Al (Al_{im}) by methods described in Lawrence et al., (1995b). Mean and median concentrations for each constituent were calculated from routine samples collected from July 1992 to December 1993; maximum and minimum concentrations were determined from all water samples collected from each site during that period.

Habitat Characteristics

Habitat characteristics were measured in 100- to 200-m-long reaches that overlapped fish-sampling locations at each site. Reaches were generally divided into four or eight, 25-m-long sections. Most habitat characteristics were measured once during base-flow conditions in April 1995. Channel, bank, riparian, and hydrologic features in each 25-m section were characterized by a combination of visual and measured approximations of areal extent and measures at points on transects using methods similar to those described by Meador et al. (1993). Hydrologic characteristics (mean stream velocity, mean annual discharge, and mean annual base flow) were generally estimated from continuous-stage records at 10 gaged sites (Main Branch, East Branch, New Hill, Tisons, Upper Tisons, West Branch, Otter Pool, Wildcat Mt., Biscuit Brook, and Winnisook) and from periodic discharge measurements at six ungaged sites (Braid-1, Braid-2, Oasis Creek-1, Oasis Creek-2, Deer Creek, and Slide Mountain). Mean, minimum, maximum, and total (or a proportion of total) values for each habitat characteristic at each site were calculated from the sum for all sections. Mean, median, minimum, and maximum water temperatures were measured during water sampling. Physiographic data, such as site elevation, watershed area, and stream gradient were obtained from a Geographic Information System (GIS) database (Lawrence et al., 1995a).

Fish Populations

Fish populations were inventoried twice at each site, once during July and August 1991 and once during August of 1992 or 1993. Fish were collected from seine-blocked, 50- to 100-m reaches in three or four successive passes with a gas-powered backpack electroshocker and two or three fish netters. The number of fish obtained from each pass was used to estimate mean population sizes and 95% confidence intervals (CI) for each fish species by the Moran-Zippin method of proportional reduction (Zippin, 1958). Total density (number/m^2) and biomass (g/m^2) for each species population at each site were calculated as the total estimated number or biomass of each species divided by the area of the sampled reach. Mean condition was estimated for brook trout, brown trout (*Salmo trutta* L.), and slimy sculpin (combined age classes) at all sites using Fulton's Condition Factor: $K = (\text{weight}/\text{length}^3) \cdot 10^5$ (Cone, 1989). Other fish species were not collected in sufficient numbers or at enough sites to estimate condition or to analyze the relations among density or biomass and water-quality or habitat factors. Population indices from the two sampling efforts were averaged by species for all evaluations.

Relations among population indices and environmental characteristics

Density, biomass, and condition of brook trout and density and biomass of slimy sculpin populations were initially associated with water-quality and habitat characteristics through Pearson correlation analyses. The potential effects of acidification on fish populations and on species distributions in the basin were evaluated in terms of the strength of their linear associations (coefficients of correlation) and by published acid- and Al-tolerance levels. Chemical constituents (Al_{td}, Cl^-, and NH_4^+) and habitat characteristics (stream gradient, maximum reach width, mean thalweg depth, bank stability, and several substrate types) that were either (1) poorly correlated to density and biomass estimates for brook trout and slimy sculpin populations, or (2) multicorrelated with other variables, are not presented here.

Habitat and chemical constituents that were moderately to strongly correlated ($p < 0.1$) with one or more of the population indices were evaluated further through simple and multiple stepwise linear regression to develop empirical models that describe the relations among the population indices, the degree of stream acidification, and habitat and physiographic characteristics. Explanatory variables that exhibited multicollinearity with others were excluded from regression analyses if their correlation with the residuals for the population index became insignificant after other highly related explanatory variables were added to the regression model.

From five to nine models (regression equations), using 1 to 4 explanatory variables, were evaluated for each population index. Explanatory variables were considered potentially important to the index if, after inclusion in the model, the standard deviation of the residuals (SDR) decreased by 1 point, and the slope-t and regression-F values remained significant ($P \leq 0.05$). The rank or importance of each constituent to each index was estimated by (1) the amount of variability in the index that an individual factor could explain alone (R^2), and in combination with other factors (adjusted R^2), (2) the probability of a legitimate association; $P \leq 0.05$ (significant t and F-values), and (3) the SDR value. The absence of controlled manipulations (where a cause can be attributed to a specific effect), require that our equations be treated only as empirical models specific to the Neversink system. The strength of these relations, however, can be used to rank the importance of stream acidification and habitat on fish populations of the Neversink. The coefficients of correlation and regression are provided here to rank the importance of the measured environmental variables on each index. A comparison of the amount of variability that acid-base chemistry and that habitat and physiography account for in population indices can partly discriminate the effects of stream acidification on fish populations from those related to differences in habitat.

Results

Results of water-quality and habitat characterizations for Neversink sites are discussed in detail by Baldigo and Lawrence (2000), and summarized in the following sections.

Water Quality

Water-chemistry data (Table 1) indicate varying degrees of stream acidification among the 16 sites. For purposes of analysis, sites were arranged into 4 groups (minimally, moderately, strongly, and severely acidified) on the basis of mean ANC, pH, and Al_{im} concentrations in routine water samples (Table 1). Mean ANC was ≥ 46.4 µeq/L, mean pH was ≥ 6.31, and mean Al_{im} concentrations were < 0.3 µmol/L at minimally acidified sites, such as Main Branch, West Branch, Otter Pool, and Oasis Creek-2. Mean ANC ranged from 11.2 to 25.4 µeq/L, mean pH ranged from 5.69 to 6.04, and mean Al_{im} ranged from 0.21 to about 1.2 µmol/L at moderately acidified sites, such as Biscuit Brook, Slide Mt., Wildcat Mt., and East Branch. Mean ANC ranged from –8.6 to 2.7 µeq/L, mean pH ranged from 4.97 to 5.39, and mean Al_{im} ranged from 1.54 to 3.71 µmol/L at strongly acidified sites, such as New Hill, Braid-1, Tisons, Deer Creek, and Oasis Creek-1. Mean ANC ranged from –27.7 to –14.6 µeq/L, mean pH was < 4.77, and mean Al_{im} concentrations were > 5.47 µmol/L at severely acidified sites, such as Upper Tisons, Braid-2, and Winnisook (Table 1).

Fluctuations in Al_{im} concentrations tended to be largest at severely acidified sites and decreased with the degree of acidification at other sites. Both pH and Al_{im} concentrations at many headwater sites on both branches and at many of the East Branch sites frequently surpassed thresholds that are acutely toxic to many fish species (Baldigo and Lawrence, 2000).

Habitat Characteristics

Habitat and hydrologic characteristics of Neversink River sites generally varied among sites with high-, middle-, and low-elevations and among sites with small to large drainage areas (Table 1). Many hydrologic- and physical-habitat characteristics for sites of similar drainage area generally did not differ significantly between the two sub-basins. Site elevations range from 819 m at Winnisook to 471 m at the Main Branch; drainage areas vary from 0.27 km^2 at Oasis Creek-2 to 172 km^2 at the Main Branch site. Mean water temperatures range from 4.2 to 7.4 °C; mean thalweg depths range from 8 to 65 cm; mean channel widths vary from 1.6 to 27 m; pool/riffle ratios vary from 0.08 to 0.64; and the ratio of mean base/annual flows range from 14 to 38 percent. A more detailed discussion of habitat variations among study sites is presented by Baldigo and Lawrence (2000).

Table 1. Selected physiographic, hydrologic, and mean chemical and physical characteristics, and the degree of stream-water acidification, for study sites in the Neversink River Basin, N.Y., 1991–95. [Site locations are shown in Figure 1. Data modified from Baldigo and Lawrence, 2000]

Site name and degree of acidification	Elevation (m)	Watershed area (km^2)	Mean base/annual flow[g] (%)	pH	Al_{im} (µmol/L)	ANC[f] (µeq/L)	K^+ (µmol/L)	DIC[e] (µmol C/L)	Si (µmol/L)	Ca^{2+} (µmol/L)	Mg^{2+} (µmol/L)	Water temperature (°C)	Water velocity (m/s)	Percent fines (%)	Percent med. gravel (%)	Percent undercut banks (%)	Channel width (m)	Channel width/depth ratio	Channel pool/riffle ratio	Percent trees (%)
West Branch																				
Winnisook[d]	819	2.13	26	4.75	9.74	– 17.7	4.9	117.0	37.1	23.9	19.5	6	0.75	4	8	2	4.0	0.23	0.42	33
Slide Mountain[b]	747	3.15	19	5.82	1.16	15.8	5.2	79.0	36.4	54.8	21.6	7	0.35	6	13	5	4.1	0.32	0.32	49
Biscuit Brook[b]	630	9.59	36	6.04	0.24	25.4	5.2	96.8	38.0	59.1	22.7	7.5	1.06	8	14	4	6.5	0.35	0.18	50
Wildcat Mt.[b]	628	20.45	18	5.99	0.21	19.0	5.7	60.9	36.8	51.2	26.4	8	1.16	4	11	5	13.3	0.62	0.16	37
Otter Pool[a]	556	65.04	23	6.38	0.28	50.1	6.4	72.3	38.0	68.2	25.5	8.5	1.04	6	11	0	10.6	0.27	0.30	28
West Branch[a]	494	87.57	24	6.59	0.29	66.2	6.8	68.3	38.5	78.3	26.9	9	1.72	5	12	2	15.5	0.47	0.18	23
East Branch																				
Oasis Creek-2[a]	686	0.27	35	6.22	0.60	44.0	6.8	76.4	48.3	51.9	33.9	5.5	0.43	13	13	13	2.6	0.14	0.41	6
Upper Tisons[d]	683	0.65	14	4.59	6.83	– 27.7	4.4	163.2	40.4	26.1	20.7	7	0.85	10	12	3	1.6	0.11	0.10	23
Deer Creek[c]	695	5.46	20	5.02	3.27	– 6.2	5.7	103.6	40.6	33.6	27.6	6	0.59	3	13	2	4.1	0.18	0.10	30
Braid-2[d]	684	15.18	20	4.77	5.47	– 14.6	4.9	109.5	39.2	25.1	21.8	6.5	0.62	11	5	8	4.1	0.19	0.32	25
Oasis Creek-1[c]	683	15.44	25	5.26	1.80	– 0.7	5.3	111.3	43.0	31.5	25.4	6.5	0.51	15	21	17	3.3	0.16	0.64	5
Braid-1[c]	683	20.93	30	4.97	3.71	– 7.3	5.5	103.6	42.5	32.0	24.7	6.5	1.3	8	12	7	4.9	0.15	0.30	13
Tisons[c]	653	23.52	27	4.97	3.55	– 8.6	5.5	110.6	40.3	29.4	24.1	6.6	0.7	7	8	3	11.3	0.44	0.14	55
New Hill[c]	579	45.21	27	5.39	1.54	2.7	6.3	99.7	41.8	39.1	26.0	7.5	1.05	13	10	2	18.8	0.75	0.14	33
East Branch[b]	530	59.63	27	5.69	0.81	11.3	6.9	90.8	42.3	44.8	26.7	8	0.98	7	12	3	13.3	0.51	0.08	8
Main Branch site[a]	471	172.47	38	6.36	0.21	46.5	7.6	66.9	41.0	65.6	27.9	10	0.84	9	14	2	26.7	0.91	0.20	6

[a] Minimally acidified, [b] moderately acidified, [c] strongly acidified, [d] severely acidified, [e] DOC = dissolved organic carbon, [f] ANC = acid-neutralizing capacity, [g] ratio of mean annual base flow to mean annual flow.

Fish Populations

Fish populations at West Branch sites were apparently affected by environmental factors that differed from those that affected populations in the more acidic East Branch. The density of sculpin and brown trout populations in the West Branch were generally intermediate in most reaches and decreased to zero with increasing elevation (Tables 1, 2, Fig. 2A); blacknose dace (*Rhinichthys atratulus* (Hermann)) and longnose dace (*R. cataractae* (Val.)) only occurred at the most downstream sites; brook trout densities were highest in small streams of intermediate elevation and absent or low at high and low elevations; (Tables 1, 2, Fig. 2A). Fish populations in the East Branch followed a different pattern (Fig. 2A); blacknose dace were absent; longnose dace and brown trout were absent at all but the most downstream site; sculpin densities were absent or small in larger reaches of low to high elevation; and brook trout densities were generally intermediate at most sites but low (Braid-2), zero (Upper Tisons), or very high (Oasis Creek-2) at the headwater sites in the East Branch (Tables 1, 2, Fig. 2A). Except for brook trout, biomass trends for most species' populations were similar to density patterns (Tables 1, 2, Fig. 2B). Biomass of brook trout populations tended to be either very high or zero in small, high-elevation streams and low in intermediate to large streams. The trend of increasing brook trout biomass with increasing elevation was observed in both subbasins.

The data in Figure 2 and Tables 1 and 2 generally indicate that (1) in small watersheds (< 6 km^2), either no fish species or only mature brook trout occur at strongly to severely acidified sites, and only brook trout and sculpin occur at minimally acidified sites, (2) in intermediate-size watersheds (6–50 km^2), only brook trout and relatively few or no sculpin or brown trout occur at moderately to strongly acidified sites, and (3) in large watersheds (> 50 km^2), brook trout, brown trout, sculpin, and longnose dace occur at minimally and moderately acidified sites, and, blacknose dace, and Atlantic salmon (*Salmo salar* L.) occur only at minimally acidified sites.

The distribution of fish species (Fig. 2) and mean pH values for all sites (Table 1) illustrate the relative acid-tolerance level for each fish species. Brook trout were observed only at sites where mean pH exceeded 4.77, slimy sculpin at sites where mean pH exceeded 5.26, brown trout and longnose dace at sites where mean pH exceeded 5.69, and blacknose dace and Atlantic salmon at sites where mean pH exceeded 6.36. Stream pHs, lower than these mean values occurred during acidic episodes at each of the sites, thus, the pH values may be considered relative thresholds for each species in the upper Neversink Basin. This order does not take into consideration other toxic constituents, such as Al_{im}, which may affect species' distributions, more than acidity. A similar ranking of species by tolerance to Al_{im} may be pertinent here because Al_{im} has been identified as the primary determinant of brook trout mortality during toxicity tests in the basin (Baldigo and Murdoch, 1997). The order of Al_{im} tolerance and corresponding mean Al_{im} concentration, from most- to least-tolerant species, appears to be: brook trout (5.5 µmol/L), slimy sculpin (1.8 µmol/L), brown trout and longnose dace (0.8 µmol/L), blacknose dace (0.3 µmol/L), and Atlantic salmon (0.2 µmol/L). Like the pH-tolerance thresholds, these Al_{im} thresholds are relative to other species in the basin because they are averages and higher Al_{im} concentrations occur during acidic-Al_{im} episodes.

Table 2. Estimated density, biomass, and mean condition (K) for brook trout and other species populations from 16 sampling sites in the Neversink River, 1991–93. [Condition factors for populations with slopes of the length-to-weight relation that differ from 3.0 and (or) with slopes of the K-to-length relation that differ from 0 are identified by an asterisk. Locations are shown in Fig. 1. NA, not available]

Site name and degree of acidification	Population density (No. of fish/m^2)						Population biomass (g/m^2)						Mean condition factor (K)		
	Atlantic salmon	Black-nose dace	Long-nose dace	Brook trout	Brown trout	Slimy sculpin	Atlantic salmon	Black-nose dace	Long-nose dace	Brook trout	Brown trout	Slimy sculpin	Brook trout	Brown trout	Slimy sculpin
West Branch															
Winnisook [d]	0	0	0	0	0	0	0	0	0	0	0	0	NA	NA	NA
Slide Mountain [b]	0	0	0	0.18	0	0.01	0	0	0	3.39	0	0.08	1.01	NA	1.33*
Biscuit Brook [b]	0	0	0	0.27	0.07	0.31	0	0	0	2.85	0.70	1.32	1.02	0.93	1.11
Wildcat Mt. [b]	0	0	0	0.12	0.01	0.37	0	0	0	2.89	0.81	1.21	0.97	0.95	1.24*
Otter Pool [a]	0	0.03	0	0.06	0.02	0.57	0	0.05	0	1.56	1.60	1.19	NA	NA	NA
West Branch [a]	0	0.31	0.18	0.01	0.05	0.61	0	0.99	1.82	0.27	0.93	1.58	1.07*	1.00	1.16*
East Branch															
Oasis Creek-2 [a]	0	0	0	1.06	0	0.67	0	0	0	12.16	0	2.57	1.00	NA	1.09
Upper Tisons [d]	0	0	0	0	0	0	0	0	0	0	0	0	NA	NA	NA
Deer Creek [c]	0	0	0	0.14	0	0	0	0	0	5.59	0	0	1.05	NA	NA
Braid-2 [d]	0	0	0	0.05	0	0	0	0	0	1.15	0	0	1.06	NA	NA
Oasis Creek-1 [c]	0	0	0	0.40	0	0.07	0	0	0	9.66	0	0.42	1.06	NA	1.21*
Braid-1 [c]	0	0	0	0.28	0	0	0	0	0	4.77	0	0	1.03	NA	NA
Tisons [c]	0	0	0	0.06	0	0	0	0	0	0.84	0	0	1.05	NA	NA
New Hill [c]	0	0	0	0.11	< 0.01	0.01	0	0	0	1.07	0.01	0.07	0.94*	0.85*	1.22*
East Branch [b]	0	< 0.01	0.06	0.09	0.01	0.35	0	0.01	0.79	1.07	0.08	1.74	0.98*	0.95*	1.12
Main Branch site [a]	0.01	0.21	0.12	0.04	0.04	1.08	0.45	0.65	0.92	0.76	0.54	2.93	0.97	1.00	1.16*

[a] Minimally acidified, [b] moderately acidified, [c] strongly acidified, [d] severely acidified.

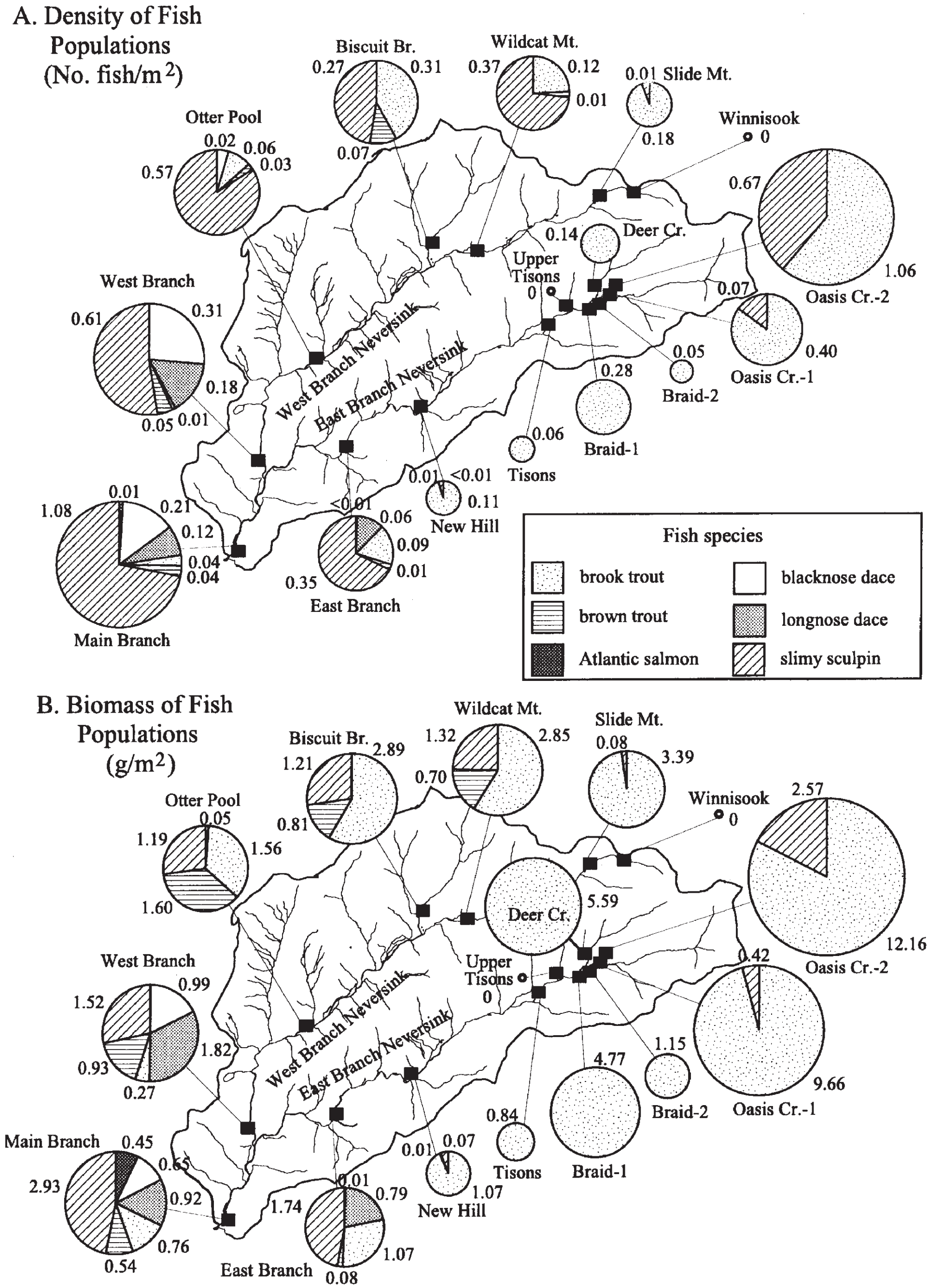

Figure 2. Estimates of density (A) and biomass (B) for fish species populations at 16 sites in the Neversink River, 1991–93. [Modified from Baldigo and Lawrence, 2000]

Brook trout-condition (K) and water-quality data (Tables 1, 2) indicate that (1) brook trout condition was relatively similar among sites (K = 0.94–1.07), and (2) individual brook trout were slightly larger and more robust at moderately to strongly acidified sites than at most minimally acidified sites. Brown trout condition was lower (0.85 for 1 individual) at the strongly acidified New Hill site than at the other five minimally to moderately acidified sites (K = 0.93–1.00; Table 2). Slimy sculpin condition ranged from 1.09 to 1.33 among nine sites (Table 2).

Analysis and interpretation of fish-condition factors assume that the growth rate of each fish species is similar among test groups and uniform across age classes (isometric); this means that the slope of the length-to-weight relation (*ln*-transformed data) for test groups should not depart from 3.0 and that the slope of the K-to-length relation for each species population is not significantly different from 0 (Cone, 1989). Slopes of the length-to-weight relations for brook trout populations range from 2.94 to 3.07 at all but three of the study sites and average 2.99. For the East Branch and New Hill sites the slopes for brook trout length-to-weight relations ranged from 2.86 to 2.87 and the slopes for the K-to-length relations were significant (negative). For the West Branch site, the slope for the length-to-weight relation was 2.62 (only six brook trout were sampled). These findings indicate that condition of brook trout in the Neversink Basin does not generally change with length or age (growth rates are isometric), but growth rates decrease slightly with increasing length at two sites. The small number of sampled fish probably skews the K estimate for the brook trout population at the West Branch site. Therefore, brook trout K data from these three sites are not used in further analyses. Minor differences in brook trout condition among study sites probably are not due to differing growth rates or to mean trout length, but to other biotic and abiotic factors. Slopes of the length-to-weight relations for brown trout populations at five sites range from 2.82 to 3.10 and average 3.06, which indicates that condition generally increases with length and age. The K-to-length relations for brown trout populations were not significant (+ or –) at any site. The range of slopes for the length-to-weight relations, both above and below 3.0, indicate that growth rates are not equal (isometric) across age classes at all sites; thus, differing mean lengths for brown trout populations among sites could account for the observed variations in their condition. This finding, combined with the small number of sites with brown trout populations, preclude further analysis of the relations between brown trout K and predictor variables. Slopes of the length-to-weight relations for slimy sculpin populations range from 2.20 to 3.56 and average 2.78 at nine sites, which indicates that condition generally decreases with increased length and age. Thus, site-to-site differences in sculpin condition may be attributed to differences in water quality or habitat and (or) to non-isometric growth rates. The K-to-length relations for sculpin populations were significantly ($p \leq 0.05$) negative at minimally to moderately acidified sites. This, combined with positive but nonsignificant K-to-length relations at acidified sites, suggest that site-to-site differences in sculpin growth rates and condition could reflect severity of stream acidification. The wide range in slopes of length-to-weight relations means that the small differences in mean sculpin length among sites could produce the observed differences in mean K values; thus, analyses of the relations between sculpin condition and predictor factors is subject to bias and is not pursued further. Populations whose slopes for their length-to-weight relation that

Table 3. Results of correlation and regression analyses relating mean brook trout density (N = 16), biomass (N = 16), and condition (N = 10) to selected characteristics at 16 sites on the Neversink River, 1991–95. [Significant correlations ($p \leq 0.1$) of each index in the top row with the explanatory variables in the first column are denoted by a + or – coefficient of correlation (r) in the first column under each index. Explanatory variables that contribute to the strongest conceptual models (regression equations using 1 to 4 variables) are denoted by "x" in the variable row; the *SDR* and the R^2 or adjusted R^2 values, which identify the amount of variability in the index model that the variable(s) can explain, are listed at the bottom of each column. Other explanatory variables that can be used in each index model and explain nearly as much variability in the index as the primary model are also identified by a "o" in the variable row for each model. NS, not significant; NA, not applicable.]

Explanatory variable	Brook trout density						Brook trout biomass							Brook trout condition						
		Model						Model							Model					
	r	1	2	3	4	5	*r*	1	2	3	4	5	6	*r*	1	2	3	4	5	6
pH, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	– 0.86	o	–	–	o	–	x
Al_{im}[a], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	+ 0.78	–	–	–	–	–	–
Al_{tm}[b], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	+ 0.85	o	–	–	–	–	o
Al_{om}[c], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	+ 0.96	o	–	–	o	o	–
NO_3[d], mean	+ 0.57	–	x	–	–	x	+ 0.44	–	–	–	–	–	o	NS	–	–	–	–	–	–
DOC[e], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	+ 0.97	x	–	–	x	x	x
ANC[f], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	– 0.83	–	–	–	–	–	–
Si, mean	+ 0.74	x	x	–	–	–	+ 0.69	x	–	–	–	–	–	NS	–	–	–	–	–	–
Ca, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	– 0.85	o	–	–	–	–	–
Mg, mean	+ 0.65	–	–	–	–	x	+ 0.60	–	–	–	x	x	x	NS	–	–	–	–	–	–
K, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	– 0.66	–	–	–	–	–	–
Na, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	– 0.68	–	–	–	–	–	–
temp., max.	– 0.50	–	–	–	–	–	– 0.56	–	–	–	–	–	o	– 0.68	–	–	–	–	–	–
temp., mean	NS	–	–	–	–	–	+ 0.53	–	–	–	o	o	–	– 0.66	–	–	–	–	–	–
D.O., minimum	+ 0.54	–	–	–	–	–	+ 0.59	–	–	x	o	–	x	0.65	–	–	–	–	–	–
velocity, mean	– 0.44	–	–	–	–	–	– 0.50	–	–	–	–	o	–	NS	–	–	–	o	–	x
width, mean	NS	–	–	–	–	–	– 0.44	–	–	–	–	x	o	– 0.63	–	–	o	o	–	–
thalweg depth, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–	NS	–	–	–	x	x	–

[a] Al_{im} = Inorganic monomeric aluminum, [b] Al_{tm} = Total monomeric aluminum, [c] Al_{om} = Organic monomeric aluminum, [d] NO_3 = nitrate,
[e] DOC = dissolved organic carbon, [f] ANC = acid neutralizing capacity.

Table 3 *(continued)*

Explanatory variable	Brook trout density						Brook trout biomass							Brook trout condition						
		Model						Model							Model					
	r	1	2	3	4	5	*r*	1	2	3	4	5	6	*r*	1	2	3	4	5	6
depth/width ratio	NS	–	–	–	–	–	– 0.43	–	–	–	–	–	–	– 0.71	–	o	x	–	–	–
pool/riffle ratio	+ 0.47	–	–	–	–	–	+ 0.59	–	–	–	–	o	x	NS	–	–	–	–	–	–
percent small gravel	NS	–	–	–	–	–	NS	–	–	–	–	–	–	NS	–	–	–	–	x	–
percent md. gravel	NS	–	–	–	–	–	+ 0.60	–	–	x	o	–	x	NS	–	–	–	–	–	o
percent lg. cobble	– 0.46	–	–	–	–	–	– 0.48	–	–	–	–	–	–	NS	–	–	–	–	–	–
percent fines	+ 0.49	–	–	–	–	–	+ 0.44	–	–	–	–	–	–	NS	–	–	–	–	–	–
percent undercut bank	+ 0.72	–	–	x	x	x	+ 0.81	–	x	x	x	x	o	NS	–	–	–	–	–	–
percent bare ground	NS	–	–	–	–	–	NS	–	–	–	–	–	–	NS	–	–	x	–	–	–
percent grasses	+ 0.63	–	–	–	–	–	+ 0.61	–	–	–	–	–	–	NS	–	–	–	–	–	–
percent shrubs	NS	–	–	–	–	–	– 0.47	–	–	–	–	–	–	– 0.79	–	x	–	–	–	–
percent shade	NS	–	–	–	–	–	NS	–	–	–	–	–	–	NS	–	–	–	–	–	o
percent submerged	NS	–	–	–	–	–	NS	–	–	–	–	–	–	NS	–	–	–	–	–	o
percent base/ann flow	+ 0.43	–	–	–	–	–	NS	–	–	–	–	–	–	NS	–	–	–	–	–	–
R^2	NA	0.55	0.67	0.52	0.70	0.76	NA	0.45	0.66	0.75	0.79	0.89	0.94	NA	0.94	0.62	0.76	0.97	0.98	0.99
SDR[g]	NA	0.18	0.15	0.19	0.14	0.13	NA	2.71	2.12	1.78	1.62	1.19	0.84	NA	0.01	0.02	0.02	0.01	0.005	0.003

[g] *SDR* = standard deviation of residual.

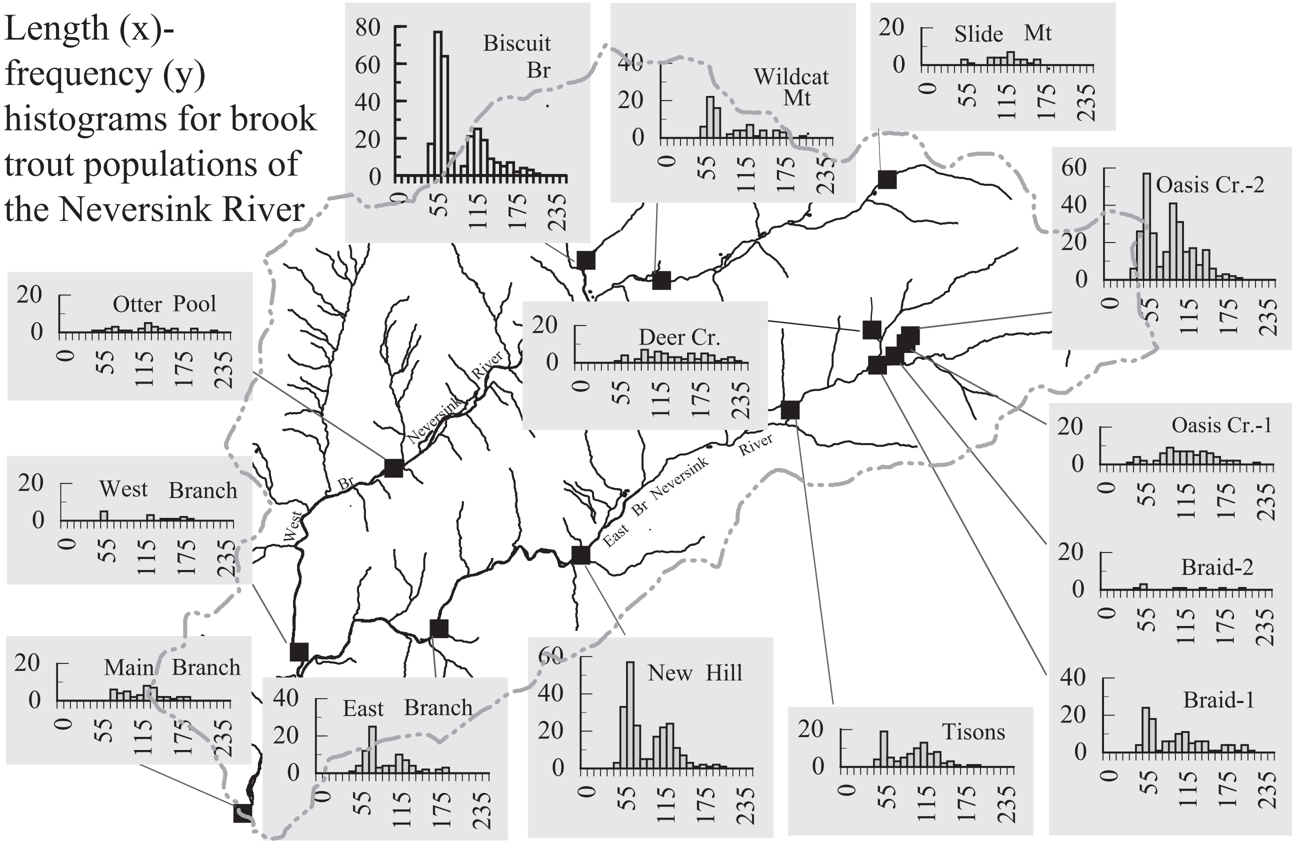

Figure 3. Length-frequency histograms for brook trout collected at 14 sites in the Neversink River, 1991–93. [the bars depict The total number and frequency of trout on the y axis for each 10 mm length category on the x axis]

are not equal to 3.0, or whose slopes for the K-to-length relation differ significantly from 0, are indicated in Table 2.

Comparison of length-frequency distributions of brook trout among sites (Fig. 3) indicates that age classes are unbalanced and their populations appear to be unstable at many strongly acidified sites. For example, the low numbers of young-of-year (YOY) and the shift in median brook trout lengths from about 75 mm at minimally to moderately acidified Oasis Creek-2, Biscuit Brook, and Wildcat sites to at least 115 mm at strongly acidified Deer Creek, Braid-2, and Oasis Creek-1 sites indicate that young (acid-intolerant) brook trout are poorly recruited to the local populations at the latter sites. The large, mature brook trout and a few YOY collected at most strongly acidified sites probably migrated from nearby minimally acidified stream reaches.

Relations among population indices and environmental characteristics

Significant correlations ($p \leq 0.05$ and r values of $\pm$ 0.44 to $\pm$ 0.85) were identified between environmental characteristics and (1) mean density, biomass, and condition of brook trout populations (Table 3), and (2) mean density and biomass of slimy sculpin populations (Table 4). Results of regression analysis show that multiple chemical and habitat variables can account for as much as 76, 94, and 97 % of the variability in density, biomass, and condition of brook trout populations, respectively (Table 3), and as much as 86 and 92 % of the variability in density and biomass of slimy sculpin populations (Table 4).

Brook trout – Biomass and density of brook trout populations were significantly, but weakly, related to a few acidification constituents and strongly related to several physiographic and habitat characteristics (Table 3). Individually, mean Si, Mg^{2+}, and NO_3^- accounted for 30 to 55 % of the variability in density of brook trout populations, whereas minimum D.O., percent undercut bank, percent grasses, and percent fines accounted for 29 to 51 %; and combinations of mean Mg^{2+}, NO_3^-, and percent undercut banks accounted for 70 to 76 % of the variability in density (Table 3). Individually, mean Mg^{2+} and Si accounted for 36 to 45 % of variability in biomass of brook trout populations, whereas, minimum DO, percent undercut bank, or percent medium gravel could account for as much as 75 % of the variability in biomass (Table 3). In various combinations, mean Mg^{2+}, NO_3^-, maximum and mean water temperature, mean water velocity and channel width, percent medium gravel, minimum DO, pool/riffle ratio, and percent undercut bank could account for 79 to 94 % of the variability in biomass of brook trout populations (Table 3). Thus, habitat factors appear to be primary determinants of density and biomass of brook trout populations throughout the Neversink River, except at two severely acidified sites (Winnisook and Upper Tisons).

Analysis of acid-base chemistry and mean brook trout condition (K) indicate that brook trout were larger and slightly more robust at moderately to strongly acidified sites than at minimally acidified sites (Table 3). Individually, mean pH, log Al_{im}, Al_{im}, Al_{tm}, Al_{om}, Ca^{2+}, DOC, ANC, Na^+, and K^+, mean and maximum water temperature, minimum DO, percent shrubs, width/depth ratio, and mean channel

Table 4. Results of correlation and regression analyses relating slimy sculpin density and biomass to selected characteristics at 16 sites on the Neversink River, 1991–95. [Significant correlations ($p \leq 0.1$, N = 16) of each slimy sculpin population index in the top row with the explanatory variables in the first column are denoted by a + or – coefficient of correlation (r) in the first column under each index. Explanatory variables that contribute to the strongest empirical models (regression equations using 1 to 4 variables) are denoted by "x" in the variable row; the *SDR* and the R^2 or adjusted R^2 values, which identify the amount of variability in the index model that the variable(s) can explain are listed at the bottom of each column. Other explanatory variables that can be used in each index model and explain almost as much variability in the index as the primary model are also identified by a "o" in the variable row for each model. NS, not significant; NA, not applicable.]

Explanatory variables	Slimy sculpin density						Slimy sculpin biomass						
		Model						Model					
	r	1	2	3	4	5	r	1	2	3	4	5	6
pH, mean	+ 0.81	o	o	–	–	o	+ 0.75	–	o	–	–	o	o
Al_{im}[a], mean	– 0.51	–	–	–	–	–	– 0.54	–	–	–	–	–	–
$\log_{10} Al_{im}$, mean	– 0.75	–	x	–	x	–	– 0.71	–	x	–	–	o	o
Al_{tm}[b], mean	– 0.55	–	–	–	–	–	– 0.57	–	–	–	–	–	–
Al_{om}[c], mean	– 0.73	–	–	–	–	–	– 0.66	–	–	–	–	–	–
SO_4[d], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–
NO_3[e], mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–
DOC[f], mean	– 0.73	–	–	–	–	x	– 0.64	–	–	–	–	x	x
ANC[g], mean	+ 0.83	x	o	–	–	–	+ 0.74	–	–	–	–	o	–
Si, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–
Ca, mean	+ 0.73	–	o	–	o	–	+ 0.61	–	–	–	–	–	–
Mg, mean	+ 0.55	–	–	–	o	–	+ 0.64	–	–	–	–	–	–
K, mean	+ 0.82	o	x	–	–	–	+ 0.79	x	x	–	–	–	–
Na, mean	NS	–	–	–	–	–	NS	–	–	–	–	–	–
temp., mean	+ 0.65	–	–	–	o	–	NS	–	–	–	–	–	–
D.O., minimum	– 0.61	–	–	–	o	–	NS	–	–	–	–	–	–
velocity, mean	+ 0.60	–	–	x	–	–	NS	–	–	–	–	–	–

[a] Al_{im} = Inorganic monomeric aluminum, [b] Al_{tm} = Total monomeric aluminum, [c] Al_{om} = Organic monomeric aluminum, [d] SO_4 = sulfate, [e] NO_3 = nitrate, [f] DOC = dissolved organic carbon, [g] ANC = acid neutrailizing capacity.

Table 4 *(continued)*

Explanatory Variables	Slimy sculpin density						Slimy sculpin biomass						
		Model						Model					
	r	1	2	3	4	5	*r*	1	2	3	4	5	6
width, mean	+ 0.58	–	–	–	–	–	NS	–	–	–	–	–	–
depth/width ratio	NS	–	–	–	–	–	NS	–	–	–	–	–	–
pool/riffle ratio	NS	–	–	–	–	–	NS	–	–	–	–	–	–
percent med. gravel	NS	–	–	–	–	–	+ 0.53	–	–	–	x	–	–
percent lg. cobble	NS	–	–	–	–	–	– 0.54	–	–	–	–	–	x
percent fines	NS	–	–	–	–	–	+ 0.58	–	–	–	–	–	–
percent undercut bank	NS	–	–	–	–	–	NS	–	–	–	–	–	–
percent grasses	NS	–	–	–	–	–	NS	–	–	–	–	–	–
percent trees	NS	–	–	–	–	–	– 0.56	–	–	–	–	o	o
percent shade	– 0.68	–	–	–	–	–	– 0.70	–	–	x	–	–	–
percent base/ann flow	+ 0.57	–	–	x	o	x	+ 0.67	–	–	o	x	x	x
elevation	– 0.69	–	–	–	–	–	– 0.62	–	–	–	–	–	–
watershed area	+ 0.76	–	–	–	x	o	+ 0.62	–	–	–	–	–	–
R^2	NA	0.67	0.86	0.51	0.69	0.82	NA	0.62	0.68	0.48	0.60	0.83	0.92
SDR [h]	NA	0.39	0.13	0.24	0.19	0.15	NA	0.65	0.57	0.76	0.64	0.42	0.23

[h] *SDR* = standard deviation of residuals.

width accounted for 40 to 94% of the variability in brook trout K (Table 3). Multiples of mean channel width, width/depth ratio, percent bare ground, and percent shrubs accounted for 62 to 76% of the variability. Multiples of chemical and physical factors, such as mean pH, Al_{im}, Al_{om}, DOC, thalweg depth, water velocity, channel width, percent shrubs, percent shade, percent submerged vegetation, and percent small gravel accounted for 82 to 99% of the variability in brook trout K. The strong correlations between brook trout K and acidification factors and the strong influence of habitat variables on brook trout K in regression analyses indicate that stream acidification and habitat characteristics are equally important predictors of brook trout condition in the Neversink River.

Slimy sculpin – The density of slimy sculpin populations was strongly correlated with several acidification variables and moderately correlated with other chemical and habitat characteristics. Individually, mean K^+, pH, ANC, Al_{im}, Al_{om}, $\log Al_{im}$, DOC, and Ca^{2+} accounted for 53 to 69% of the variability in sculpin density, whereas, mean water temperature, minimum DO, water velocity, percent shade, site elevation, and watershed area, accounted for 36–58%, and multiples of mean pH, $\log Al_{im}$, ANC, Ca^{2+}, K^+, DOC, watershed area, and percent base annual flow, accounted for 76–86% of the variability in density (Table 4). Thus, the degree of stream acidification appears to be primary determinant, and habitat characteristics the secondary determinants of sculpin population density in the Neversink River.

The biomass of slimy sculpin populations, like brook trout biomass is correlated with habitat characteristics, but, unlike brook trout, sculpin biomass is strongly related to acidification factors such as pH and ANC (Table 4). Individually, mean K^+, pH, $\log Al_{im}$, ANC accounted for 50 to 62% of the variability in sculpin biomass, and combinations of mean K^+, pH, and $\log Al_{im}$ accounted for 66 to 68% of the variability in biomass (Table 4). Individual habitat characteristics accounted for less than 50% of the variability in sculpin biomass (e.g., percent shade), but in multiples, accounted for as much as 60% of the variability in biomass (Table 4). Combinations of acidification and habitat variables – mean DOC, $\log Al_{im}$, pH, ANC, percent trees, and percent base annual flow – accounted for 69 to 83% of the variability in sculpin biomass, and multiples of these constituents together with mean K^+, and percent small boulders accounted for 80 to 92% of the variability (Table 4). Biomass of slimy sculpin populations appeared to be affected primarily by acidification characteristics, although, several habitat variables, such as percent base/annual flow and percent trees accounted for an additional 13 to 26% of the variability in biomass.

Discussion

The absence of all fish species in several headwater reaches and of most fish species in much of the East Branch is not typical of streams in the Catskill region (Colquhoun et al., 1984) and indicates that factors, other than habitat, have affected their populations. The estimated acid-tolerance thresholds for fish species in the Neversink, except for Atlantic salmon and sculpin did not differ greatly from those observed in the wild by other investigators. Using data from many studies, Baker and Christensen (1991) estimated that same species found in the Neversink are typically lost when pH of natural waters decreases to the range of 4.7 to 5.2 (brook trout), 5.5 to 5.9 (slimy sculpin), 4.7 to 5.7 (brown trout), 5.6 to 6.2 (blacknose dace), and 4.9 to 5.3 (Atlantic salmon). No acid-tolerance information is available for the longnose dace, but its distribution in the Neversink River indicates that it is more acid tolerant than blacknose dace and as tolerant as brown trout. Though pH tolerance levels offer a general ranking of each species' sensitivity in acidified systems, many studies have shown that other factors such as Al_{im}, DOC, and Ca^{2+}, along with the timing and magnitude of episodic fluctuations in toxic acid and Al_{im} concentrations, are strongly related to the degree of stream acidification and influence fish survival in natural systems (Baker et al., 1990; Gagen et al., 1993; Simonin et al., 1993; Van Sickle et al., 1996; Baldigo and Murdoch, 1997). Aluminum fractionation and Al_{im} concentration are also directly dependent upon pH levels (Driscoll, 1985) and both acidity and Al_{im} act in a similar manner to affect fish survival (Wood et al., 1990). These findings imply that the degree of stream acidification and related differences in stream-water chemistry may be primarily responsible for the restricted distributions of most fish-species' populations in the Neversink river, and in other similarly acidified riverine systems.

Atlantic salmon

The small population of Atlantic salmon in the Neversink River is a result of a 1970's stocking program in the upper Neversink Basin and an ongoing stocking effort in the Neversink Reservoir, 5 km downstream from the Main Branch site. Atlantic salmon juveniles, found only at the Main Branch site, may be a result of the species' limited natural reproduction in the basin's middle reaches.

Stocked Atlantic salmon in the Neversink Basin may be slightly less acid tolerant than native salmon observed in other studies for several reasons: (1) they originate from a sheltered (hatchery) gene pool, (2) they are affected by other toxic constituents such as Al_{im}, or (3) they are affected by other biotic factors in the basin. Several investigators have observed lower acid-tolerance thresholds than noted in Baker and Christensen (1991) and increased mortality of Atlantic salmon exposed to low pH and slightly to moderately elevated Al_{im} concentrations. For example, Johansson et al., (1977) found that few Atlantic salmon eggs survived in waters with pH of 5.5; Kretser et al., (1989) only encountered Atlantic salmon in Adirondack lakes with a pH of 6.3 or greater. Norrgren and Degerman (1993) exposed Atlantic salmon yolk-sac fry in-situ for 77 days and noted 100% mortality at pH 5.1 and Al_{im} concentrations of 7.5 μmol/L and 64% mortality at pH 5.7 and Al_{im} concentrations of 1.2 μmol/L; they estimated the upper pH threshold for survival to be about 6.0. Hesthagen (1989) observed high mortality of Atlantic salmon in Norway streams during single and successive acidic episodes with pH less than 5.5 and Al_{im} concentrations of 1.1 to 2.6 μmol/L. If acid-tolerance thresholds indicated by the literature are accurate, the absence of salmon in the West Branch might be due to slightly elevated Al_{im} concentrations.

Acutely toxic pH and Al_{im} conditions for Atlantic salmon occur nearly continuously at most East Branch sites, at least once yearly at most West Branch sites, but rarely at the Main Branch site (Baldigo and Lawrence, 2000). This may explain why Atlantic salmon were collected only during 1991 and only at the Main Branch site. No severe acidic episodes occurred at the Main Branch during the study, but extremely high flows produced a moderate Al_{im}-acidic episode with pH of 5.0 and Al_{im} concentration of 2 μmol/L during the spring of 1993 (Baldigo and Lawrence, 2000) and may have eliminated the remnant population of juvenile Atlantic salmon. Data in the literature and findings from this study indicate that Atlantic salmon populations were probably restricted by low pH and elevated Al_{im} concentrations in the Neversink River Basin.

Slimy sculpin

Slimy sculpin populations were observed at all Neversink River sites with pH in the critical range of pH of 5.5 to 5.9, as defined by Baker and Christensen (1991), and at two sites (New Hill and Oasis Creek-1) where pH averaged 5.39 and 5.26. Thus, their populations may be slightly more acid tolerant than previously reported and (or) their distributions may be positively affected by other biotic and abiotic factors. Other investigations have also observed higher acid tolerance thresholds than indicated by Baker and Christensen (1991). For example, experimental acidification of Lake 223 and Lake 302 South, caused (1) a 60 % decline in density of slimy sculpin populations as pH decreased from 6.5 to 5.59, (2) failure of slimy sculpin recruitment when pH values decreased to the range of 5.6 to 5.9, and (3) extinction of non-reproducing sculpin populations at pH 5.1 in one lake and at pH 4.6 in the other (Schindler et al., 1985 a, 1985 b; Mills et al., 1987; Schindler et al., 1991). These results indicate that mature sculpin can survive at pH levels well below those that are toxic to, and inhibit recruitment of, early life stages, and, demonstrate that early sculpin life stages are more acid sensitive than older individuals. The presence of slimy sculpin at Neversink sites with mean pH near 5.3 may be due to the high acid tolerance of mature individuals and migration from nearby well-buffered tributaries with reproducing populations.

Observations in the Neversink indicate that slimy sculpin are less acid tolerant than brook trout, however, previous toxicity tests in northeastern streams have indicated that slimy sculpin are generally more acid tolerant than brook trout (Van Sickle et al., 1996). This apparent contradiction could be due to several factors: (1) mature sculpin may be more acid tolerant than the juvenile brook trout used in the tests of Van Sickle et al. (1996); (2) the small size, limited mobility, and presumed acid intolerance of early sculpin life stages may restrict stable populations to sites with well buffered water; and (3) only mature individuals can tolerate waters at moderately to strongly acidified reaches that are near refuges. The presence of a slimy sculpin population in some acidic reaches, but not in others where only brook trout are found, could be due to immigration of adults from nearby reaches with good water quality. For example, East Branch sites Oasis Creek-1 and New Hill (Fig. 1) likely receive mature sculpin from robust populations in adjacent well-buffered tributaries, but the long reach between New Hill and Braid-1 forms an acidic barrier that separates populations from Oasis Creek from those in the lower basin. The presence of brook trout, but not sculpin in all main stem reaches of the

East Branch, and the presence of sculpin at several (not all) moderately to strongly acidified sites, confirm that (1) brook trout are generally more tolerant of acidic conditions than sculpin and (2) refuges can play an important but limited role in the distribution of sculpin in the Neversink River Basin.

Blacknose dace

The limited distribution of blacknose dace at Main Branch, West Branch, and Otter Pool sites, where mean pH ranged from 6.36 to 6.59, indicates that they are either substantially less acid tolerant than reported, are affected by other toxic constituents such as Al_{im}, or their population is restricted by other biotic and abiotic factors in the basin. Johnson et al. (1987) estimated the threshold for blacknose dace survival in Adirondack waters to be from pH 5.9 to 6.0, and Baker and Christensen (1991) estimated it to be from pH 5.6 to 6.2. These findings indicate that blacknose dace in the Neversink would be expected to also inhabit waters at Wildcat, Biscuit, and Oasis Creek-2 sites whose mean pH ranges from 6.0 to 6.2. Habitat conditions at the two sites on the West Branch are similar to those found to be highly suitable (gravel to rocky substrate, maximum temperatures of 14 to 22° C, water velocity of 15 to 45 cm/s, and stream gradients of 11 to 23 m/km) for blacknose dace (Trial et al., 1983). The absence of blacknose dace at Oasis Creek-2 could indicate either less than optimal habitat conditions or isolation from downstream populations by the intervening acidic reaches of the East Branch. The reason for their absence at other sites may be related to their low tolerance to elevated acid and Al concentrations.

Results from several interrelated investigations of acidic-Al_{im} episodes, streamwater toxicity, and fish populations indicate that the recurrence of acidic-Al_{im} episodes in the Neversink may limit the distribution of blacknose dace. Surveys of Adirondack Mountain streams and lakes indicate that blacknose dace are among the least acid tolerant fish species; and, even though individuals have been observed in waters with pH as low as 5.6, populations were seldom encountered in waters with pH less than 6.0 (Schofield and Driscoll, 1987; Kretser et al., 1989). Johnson et al. (1987) exposed blacknose dace to stream and lake waters of the Moose River Basin in the western Adirondacks and observed more than 70% mortality for (1) egg-to-feeding fry at pH levels of 5.05 to 5.87 and Al_{im} concentrations of 0.4 to 9.3 μmol/L, (2) YOY dace at pH levels of 4.50 to 5.57 and Al_{im} concentrations of 0.4 to 7.4 μmol/L, and (3) adults at pH levels of 4.83 to 5.32 and Al_{im} concentrations of 0.7 to 6.7 μmol/L. Mortality of adult blacknose dace in other streams of the Moose River Basin were greater than 20% at all sites with median pH levels of 4.6 to 5.1 and Al_{im} concentrations of 3.9 to 13.0 μmol/L and less than 20% with median pH levels of 5.2 to 6.8 and Al_{im} concentrations of 0.7 to 3.5 μmol/L (Simonin et al., 1993). Authors of both studies conclude that median Al_{im} concentration was the primary determinant of blacknose dace mortality in their tests. Overlapping investigations in the Adirondack and Catskill Mountains and in Pennsylvania found blacknose dace only in streams that had a median pH greater than 5.2 and median Al_{im} concentrations less than 2.6 μmol/L during high flows (Baker et al., 1996). High spring and fall flows at Wildcat Mt. and Biscuit Brook commonly result in pH decreases to

5.0 and Al_{im} increases to 2.25 µmol/L or higher (Baldigo and Lawrence, 2000). The seasonal recurrence of acidic-Al_{im} episodes and coincident increases in acidity and Al_{im} concentrations are sufficient to account for the absence of blacknose dace, as well as Atlantic salmon, at several sites in the Neversink Basin.

Brown trout

Brown trout distributions in the Neversink is fairly consistent with previously reported critical pH thresholds of 4.7 to 5.7 (Baker and Christensen, 1991), and appear to be more sensitive than brook trout to stream acidification. Brown trout were collected only at Neversink sites where pH was 5.69 or greater. Several studies have shown that brown trout usually are adversely affected at pH 5.5 and below in the presence of low and intermediate concentrations of Al. For example, brown trout were unaffected at pH 5.0 in synthetic waters, but mortality increased with additions of 1.9 and 0.9 µmol Al_{td}/L (mostly Al_{im}) (Waring and Brown, 1995); mortality of aged 1+ brown trout ranged from 86 to 100% after 20 to 60 days of exposure to waters of pH 4.7 to 4.5 (Leivested et al., 1976); and all brown trout died after being stocked into soft water at pH 5.4 with 4.5 µmol Al_{td}/L (Dietrich and Schlatter, 1989).

These findings indicate that brown trout probably could survive the acidity levels at the Oasis Creek-2 and Slide Mt. sites, but unsuitable habitat, strong interspecific competition, and high Al_{im} concentrations appear to bar them from both sites. Even though the mean Al_{im} concentration was 1.16 µmols/L at Slide Mt., the highest Al_{im} concentration during an acidic episode was 7.4 µmol/L and is toxic to most trout species (Baker et al., 1990). Similarly toxic conditions did not occur at Oasis Creek-2, but waters at all main stem reaches of East Branch between Oasis Creek and the downstream sites with brown trout (Figs. 1, 2) were continuously high in acidity and Al_{im} concentration. Unsuitable habitat at the two sites could partly account for the absence of brown trout; their channels were shallower, smaller, and more shaded; pools were less evident; water velocities were greater; water temperatures were lower; and site elevations were higher than those at sites with brown trout (Tables 1, 2). Healthy brook trout populations at both sites may also be important; competition generally favors brook trout over brown trout in headwater sites at high elevations, steep channel gradients, and fast water velocities (Fausch and White, 1981; Kozel and Hubert, 1989; Waters, 1983). In general, brown trout appear to be restricted from middle reaches of the East Branch by low pH and high Al_{im} concentrations and from upper reaches in both branches by unsuitable habitat, colder water temperatures, and acidified stream waters.

Brook trout

Brook trout are the most acid-tolerant fish species in the basin, and their wide distribution reflects critical pH thresholds of 4.7 to 5.2 estimated by Baker and Christensen (1991). Young-of-year (YOY) brook trout, however, were only present in low numbers or absent at most East Branch sites with mean pH values of 4.77 to 5.69 and mean Al_{im} concentrations of 1.54 to 5.47 µmol/L. Evidence from other investigations have indicated that the small number of YOY at these sites, and of mature brook trout at two severely acidic sites, may be directly related to acutely toxic Al_{im} concentrations. For example, the loss of brook trout populations in acidified lakes and streams was attributed mainly to the loss of acid intolerant early life stages (Mount et al., 1990); other wild brook trout populations were lost where water pH ranged from 4.3 to 5.8 (Harvey, 1975; Baker and Christensen, 1991; Tremblay and Richard, 1993). Brook trout abundance was reduced in studied streams from the Northeast where median pH values were less than 5.0 to 5.2 and median Al_{im} concentrations were greater than 3.7 to 7.4 µmol/L during high flows (Baker et al., 1996). Significant (>20%) brook trout mortality was observed in these streams when time-weighted median Al_{im} concentrations exceeded 7.4 µmol/L (Van Sickle et al., 1996). These acutely toxic conditions occurred almost continuously at the Upper Tisons and Winnisook sites and infrequently at most other East Branch sites.

The frequency distributions of successive brook trout age classes at minimally to moderately acidified sites (Biscuit Brook, Wildcat Mt., East Branch, New Hill, and Oasis Creek-2) (Fig. 3) indicate consistent year-to-year mortality rates and relatively stable populations. Brook trout populations at Tisons, Braid-1, and Braid-2 reflect fairly normal frequency distributions that are probably due to immigration of fish from nearby refuges. The low numbers of brook trout at Main Branch, West Branch, Otter Pool, and East Branch sites may result from competition with brown trout, which may be more suited than brook trout to the warm, middle-order streams.

Density and Biomass of Brook Trout Populations – Habitat characteristics appear to govern the density of brook trout populations in the Neversink, the degree of stream acidification seems to affect biomass of their populations to a lesser extent. The weak relations between acidification factors and population density and biomass are consistent with the high acid tolerance of brook trout, one of the most tolerant species in the Northeast (Baker and Christensen, 1991). Density and biomass of brook trout populations at most East Branch sites were lower than at similar-sized West Branch sites, but they were present at all main stem sites because (1) mature individuals have a high tolerance to acidity, (2) YOY recruits originate from well-buffered refuges near many of the moderately to strongly acidified reaches (Murdoch et al., 1991; Baker et al., 1996), and (3) the absence of interspecific competition allows brook trout to fully occupy many of the most acidified reaches across the Neversink Basin.

Density (and to a limited extent, biomass) of brook trout populations in the Neversink River were adversely affected only by extremely low pH and high Al_{im} concentrations. Brook trout populations were only absent from two sites, both of whose mean pH was below 4.77 and whose mean Al_{im} concentration was above 5.7 µmol/L; the ratio of adults to juveniles also was greater at several strongly acidified sites than at the minimally or moderately acidified sites. Density of brook trout populations, where present, was not related to stream pH or Al_{im} concentration, but was strongly related to percent undercut banks and moderately related to water temperature, and Si, Mg^{2+}, and NO_3^- concentrations. Two other studies have associated the presence or absence of brook trout populations in Adirondack lakes with habitat and acidification factors. Presence of brook trout populations and, thus, population density and biomass have been correlated with the level of stocking; pH, Si, and ANC concentrations; lake accessibility; and substrate characters (Beauchamp et al., 1992); the presence of reproducing brook trout populations was related to Si, Na^{+}, Cl^{-}, and Ca^{2+} concentrations; till thickness; lake-recharge rate; site elevation; and watershed area (Schofield, 1993).

Stream acidification had moderate beneficial and detrimental affects (depending upon its severity), whereas habitat had strong affects on the biomass of brook trout populations in the Neversink Basin. Biomass was more highly related to habitat features, and more weakly related to acidification characteristics, than was density. Biomass was moderately related to pH, Al_{im}, and Si concentrations, and site elevation, but strongly related to percent undercut banks and medium-sized gravel, mean water temperature, minimum DO, and magnesium (Mg^{2+}) concentrations (Table 3). Many of these constituents (e.g., Mg^{2+}, Si, temperature, DO, and elevation) reflect stream order and the degree of buffering. Population biomass was substantially greater in moderately to strongly acidified reaches than at minimally acidified sites, probably due to reduced competition and predation. Intraspecific (juvenile brook trout) and interspecific (brown trout and dace) competitors and potential predators (brown trout) are generally absent from sites with mean pH values below 6.0 and mean Al_{im} concentrations greater than 1.0 µmol/L; brook trout comprise all or most of the fish biomass at these sites. This finding was predictable because acid-tolerant species have often replaced acid-sensitive fish species in acidified lakes and streams of North America and Europe during the past 3 decades (Baker et al., 1990).

Brook Trout Condition – Brook trout condition in the Neversink River appears to be affected equally by stream acidification and habitat factors. Combinations of acidification and habitat factors could account for as much as 99% of the variability in brook trout condition. Differences in brook trout condition throughout the Neversink River Basin indicate that stream acidification, in conjunction with favorable habitat, had a slightly positive affect on condition, and, thus a beneficial affect on individuals given that condition can reflect relative health (Tremblay and Richard, 1993). Mature brook trout that inhabit acidified reaches have little competition for available food and may thereby grow stouter than those at comparable minimally acidified sites with diverse fish communities. Individual brook trout, therefore, are expected be healthier at moderately to strongly acidified sites with optimal habitat conditions – high elevation, cold water, steep gradients, small channels, and fast water velocities (Kozel and Hubert, 1989) – and with little competition from juveniles or other acid-intolerant fish species. Severe acidification at the two Neversink sites uninhabited by brook trout, however, must have a strong adverse affect on brook trout condition. Other studies have documented positive, density-compensatory changes in growth and condition of several fish species related to acidification (Baker et al., 1990). Brown trout condition improved during 1969–79 as their population density declined by about 90% in 3 Norwegian lakes undergoing acidification (Rosseland et al., 1980). Condition of white sucker and lake trout were stable or increased after moderate decreases in pH and decreased only after loss of the food web during experimental acidification of Lake 223 between 1975 and 1981 (Schindler et al., 1985a; Mills et al., 1987). High densities of stocked brook trout increased intraspecific competition for food and resulted in decreased growth rates and condition of older age classes during maintenance liming of an acidic Adirondack Mt. lake between 1985 and 1989 (Schofield et al., 1991). Decreased competition at strongly acidified sites may positively affect growth and condition of mature brook trout in the Neversink River.

Conclusions

The absence of brook trout populations in poorly buffered headwater reaches of the East and West Branch Neversink, and the lack of acid-intolerant fish species in most reaches of the East Branch, indicate that fish populations have been adversely affected by stream acidification. The presence of relatively healthy brook trout populations at several strongly acidified sites indicates, however, that fish-community structure can be partly sustained even in a strongly acidified riverine system. These findings further indicate that fish populations and communities in other rivers and streams of the Northeast may be resilient to the effects of acidification as long as acid-tolerant species inhabit the systems, stream habitat is diverse, and (or) well-buffered refugia are available. If projected decreases in the atmospheric deposition of acids result in decreased stream-water acidity, recovery of fish populations and communities would be expected in affected rivers of northeastern North America. If acidic deposition does not decrease and continues to cause surface-water acidification, however, the health of fish populations would be expected to decline further in the Neversink and in similar streams of the Northeast.

ACKNOWLEDGEMENTS

The authors extend their thanks to R. Scutt, T. Suleski, P. Davis, D. Horan-Ross, T. Lincoln, M. Olson, R. Eckret, and G. Lester for technical support; the Frost Valley YMCA for use of their facilities; and the Frost Valley YMCA, the New York State Department of Environmental Conservation, the Tison family, and the Connell family for access to streams on their properties. This research was partially funded by the New York City, Department of Environmental Protection.

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Received 13 March;
revised manuscript accepted 31 January 2001.