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[Article]

Response of Fish Populations to Natural Channel Design Restoration in Streams of the Catskill Mountains, New York

BARRY P. BALDIGO*
U.S. Geological Survey, New York Water Science Center, 425 Jordan Road, Troy, New York 12180, USA

DANA R. WARREN
Department of Natural Resources, Cornell University, Fernow Hall, Ithaca, New York 14853, USA

ANNE G. ERNST AND CHRISTIANE I. MULVIHILL
U.S. Geological Survey, New York Water Science Center, 425 Jordan Road, Troy, New York 12180, USA

Abstract.—Many streams and rivers throughout North America have been extensively straightened, widened, and hardened since the middle 1800s, but related effects on aquatic ecosystems have seldom been monitored, described, or published. Beginning in the early 1990s, reach-level restoration efforts began to base projects on natural channel design (NCD) techniques and Rosgen's (1994b, 1996) river classification system in an effort to duplicate or mimic stable reference reach geomorphology. Four reaches in three streams of the Catskill Mountains, New York, were restored from 2000 to 2002 using NCD techniques to decrease bed and bank erosion rates, decrease sediment loads, and improve water quality. The effects of restoration on the health of fish assemblages were assessed through a before–after, control–impact (BACI) study design to quantify the net changes in population and community indices at treatment reaches relative to index changes at unaltered reference reaches from 1999 to 2004. After restoration, community richness and biomass at treatment reaches increased by more than one-third. Changes in fish communities were caused mainly by shifts in dominant species populations; fish community biomass and total fish abundance were generally dominated by daces or daces and sculpins before restoration and by one or more salmonid species after restoration. Density and biomass of eastern blacknose dace *Rhinichthys atratulus*, longnose dace *R. cataractae*, and slimy sculpin *Cottus cognatus* did not change appreciably, whereas net salmonid density and biomass increased substantially after restoration. These changes were driven primarily by large increases in populations of brown trout *Salmo trutta*. The findings demonstrate that the structure, function, and ultimately the health of resident fish populations and communities can be improved, at least over the short term, through NCD restoration in perturbed streams of the Catskill Mountains.

Streams and rivers across the United States have been extensively altered and stabilized since the mid-1800s, but few studies have examined resultant effects on aquatic ecosystems (Bernhardt et al. 2005). During the past two decades, many stream restoration programs have based project designs on natural stream channel morphology and fluvial processes to recreate stable channel geometry and normal ecosystem structure and function (Rosgen 1994a; Doll et al. 2003). The terms "stable" and "unstable" refer to the state of dynamic equilibrium rather than to the static or frequently changing geometry of streambeds and banks and are used in that sense throughout this paper. Some common goals of stream restoration projects include increased channel stability, decreased erosion and sediment transport, recovery of natural flows or water temperatures, improved habitat, and more abundant game fish populations. Earlier stream stabilization efforts, which were often termed restoration, rarely incorporated broad geomorphic and ecological principles and simply hardened stream channels and banks either to minimize localized bed and bank erosion or to mitigate flooding. Some stream stabilization efforts could be considered ecological restoration because they act to lower water temperatures or increase habitat heterogeneity, and high temperatures and homogeneous habitat have been shown to produce abridged aquatic food webs and unbalanced ecosystems (Rosgen 1994a; Scott and Hall 1997; Pretty et al. 2003). Even so, very few studies have evaluated the short-term effects of channel restoration on local fish populations and communities, instream processes, or collateral effects within contiguous reaches (Roni et al. 2002; Pretty et al. 2003). In general, studies in which habitat heterogeneity was increased have reported that fish communities shifted from an overabundance of a few species that were tolerant of high sediment loads

* Corresponding author: bbaldigo@usgs.gov

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toward more-balanced assemblages with a greater number of species that were generally larger and less tolerant of high sediment loads (Riley and Fausch 1995; Shields et al. 1995, 1998, 2000; Flebbe 1999; Dethloff et al. 2001; Roni and Quinn 2001). The effects of stream restoration on channel morphology, habitat, bed erosion and bank erosion rates, and biological integrity have only rarely been documented (Palmer et al. 2005). This general lack of information prohibits designers of subsequent restoration projects from learning from and improving upon the successes and failures of earlier restoration efforts (Bernhardt et al. 2005).

The New York City Department of Environmental Protection (NYCDEP) and the Greene County Soil and Water Conservation District (GCSWCD) recently implemented several natural channel design (NCD) restoration demonstration projects in streams of the Catskill Mountains to address water quality, flood hazard, aquatic habitat condition, fisheries, and property protection issues west of the Hudson River watershed (i.e., water supply for New York City). Restoration was performed at selected reaches that were found to be highly unstable (losing large quantities of bed and bank sediment) during basinwide geomorphic assessments. Channel restoration relied on slightly modified NCD principles and Rosgen's (1994b, 1996) system for classifying streams according to bank-full discharge hydraulic geometry. Natural channel design does not refer to engineering or construction methods but rather to a design concept that relies on data from relatively stable reference reaches nearby to recreate dimensions, patterns, and profiles in similar streams requiring restoration, given the restoration goals and existing site constraints (Rosgen 1994a; Doll et al. 2003). A primary goal of NCD restoration designs is to reestablish stable reaches that essentially exist in a state of dynamic equilibrium, in which sediment transport is characterized by balanced or equal rates of deposition and erosion; thus, bed aggradation, bed degradation, and lateral channel migration rates of restored streams should remain within the regional norms for stable streams. Restoration designs obviously differ slightly from stream to stream, but they generally decrease channel gradients and use lateral rock veins and weirs to decrease water velocity, shear stresses, and bed and bank erosion, especially at flows near and above bank-full stages. Restored channels also tend to have higher pool : riffle ratios and are deeper and narrower on average than unstable channels. Habitat heterogeneity and instream cover often increase considerably after restoration, and water temperatures may be affected initially by increased interaction between surface and hyporheic waters through the creation of more and deeper pools. Temperatures may be increasingly affected through time by riparian conditions as bank vegetation becomes reestablished and shade increases. By stabilizing channel geometry, the structure and function of stream channels (instream processes) become more natural and in turn promote the reconstitution of natural aquatic ecosystems (Doll et al. 2003).

In 1999, the U.S. Geological Survey (USGS), in cooperation with NYCDEP and GCSWCD, began an 8-year study to evaluate the effects of NCD restoration projects on fish populations and communities at six unstable stream reaches. This paper is one of four articles and uses data from four treatment reaches (and reference reaches) that were restored before 2004 to assess hypotheses that NCD restoration (1) decreases the density and biomass of small forage species (e.g., daces and sculpins), (2) increases the density and biomass of salmonids, and (3) improves the general health (or indices commonly correlated with health) of overall fish communities. Changes in population and community indices in each of the four treatment (restored) reaches were adjusted for changes in corresponding indices at reference reaches before and after restoration to account for normal year-to-year variation in respective indices. The other three articles assess related effects of NCD restoration on biodiversity of fish communities (Baldigo et al. 2008) and stream habitat (A. G. Ernst, U.S. Geological Survey, unpublished data) and the sampling strategies and analytical methods used to detect the effects of restoration on fish assemblages (Baldigo and Warren 2008, this issue).

Methods

Study scope and area.—Fish and habitat surveys were conducted at the reach scale in three streams where large NCD restoration projects (0.4–3.0 km long) were implemented over the course of the study (Figure 1). Fish and habitat surveys were done annually at four small (87–112 m long) treatment reaches and three reference reaches 1–2 years before restoration and 2–3 years after treatment reach restoration; sampling years differed among streams. Surveys were done at treatment reaches that were located entirely within the larger restoration project reaches and at stable references reaches that were located upstream from the restoration project reaches. Study reaches were about 20 mean stream widths (MSWs) long and covered one or two complete geomorphic channel sequences (Meador et al. 1993). The reaches were relatively short and therefore might not accurately represent habitat, community, and population conditions existing across

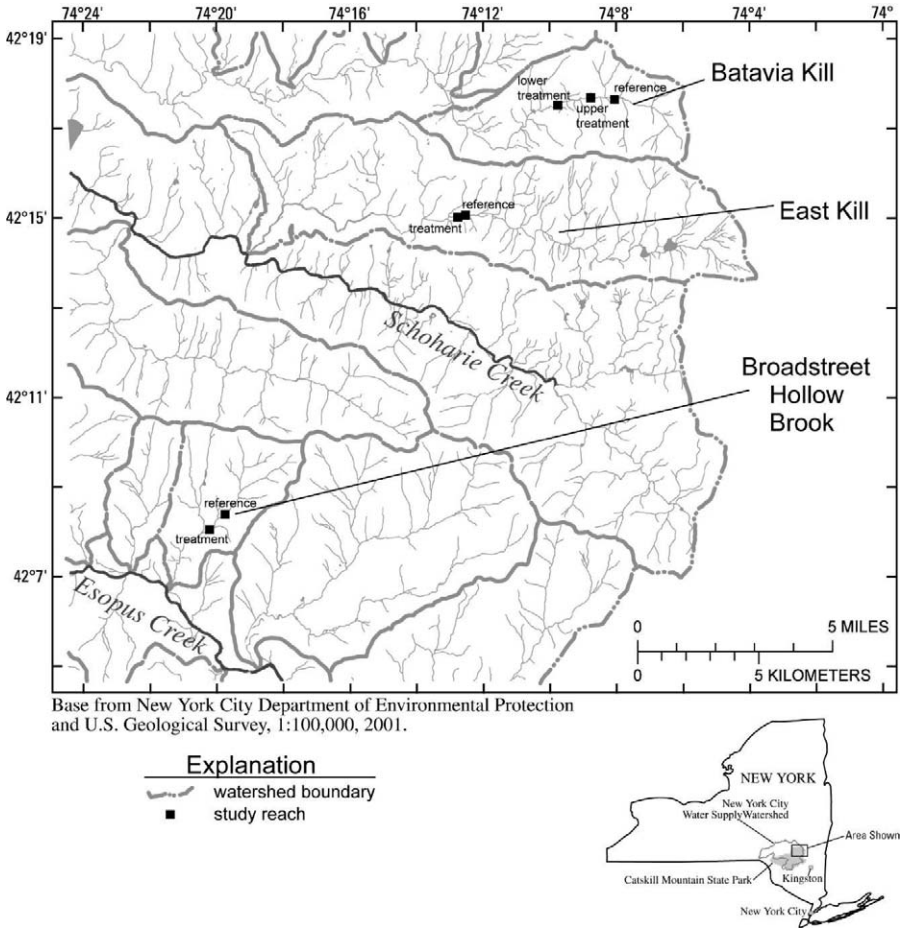

FIGURE 1.—Locations of stream restoration demonstration projects in three streams of the Catskill Mountains, southeastern New York.

larger stream segments (Simonson et al. 1993); however, that was not their main purpose. The permanent study reaches were selected to characterize prerestoration (baseline) conditions, provide a way to adjust indices for normal year-to-year variation, quantify index responses to restoration, and permit the completion of surveys within a single day. One treatment reach was in Broadstreet Hollow Brook, two treatment reaches were in Batavia Kill (upper and lower), and one treatment reach was in East Kill (Figure 1). The reference reaches were not altered during the study and thus provided information on natural year-to-year changes in fish density, biomass, and age-class distribution, which helped to differentiate the effects of restoration from changes due to variation in uncontrolled factors, such as water temperature, precipitation, and discharge.

Fish assemblages at treatment and reference reaches in each stream were surveyed within 1–3 d of each other to avoid interference from rain storms, high flows, or other factors that might displace fish. Surveys in Broadstreet Hollow Brook were completed in July 1999, 2000, and 2002–2004 (Figure 1). The treatment reach was about 3.2 km upstream from the confluence with Esopus Creek and had a drainage area of 11.9 km^2. Annual daily discharge at the reach averaged 0.37 m^3/s during the study years. The entire restoration project reach was about 0.34 km long. Annual daily discharge for the reference reach, located 0.7 km upstream from the treatment reach, was 0.32 m^3/s during the study years. The entire restoration project reach was restored in September and October of 2000. Surveys in the Batavia Kill reference reach and downstream (lower) treatment reach were completed during July or early August 2000–2004 (Figure 1). A second (upper) treatment reach in the Batavia Kill was also sampled

from 2002 to 2004. The lower treatment reach was 1.4 km upstream from a small flood control reservoir and 22 km upstream from the confluence with Schoharie Creek (Figure 1). The lower treatment reach had a drainage area of about 18.7 km^2; annual daily discharge at this reach averaged 0.58 m^3/s during 2000–2004. The upper treatment reach was 0.9 km upstream from the lower treatment reach and had an annual mean daily discharge of 0.48 m^3/s during the years surveyed (2002–2004). The reference reach, which was situated 1.0 km upstream from the upper treatment reach, had an annual mean daily discharge of 0.29 m^3/s during 2000–2004. The entire restoration project reach was about 1.6 km long. The lower two-thirds of the project reach were restored during fall 2001 and included the lower treatment reach; the upper third of the project reach was restored during fall 2002 and included the upper treatment reach. Surveys in the East Kill were completed in late July or August 2000, 2002, and 2003 (Figure 1). The treatment reach was 11 km upstream from the confluence with Schoharie Creek and had a drainage area of about 50.0 km^2. Annual average daily discharge was 1.33 m^3/s during the three study years. The reference reach, located 0.1 km upstream from the treatment reach, was contiguous with the upper end of the restoration project reach. It had an annual average daily discharge of about 1.20 m^3/s during the study period. The entire restoration project reach was 0.73 km long and was restored in July and August 2000. Additional information on the restoration projects, study watersheds, and stream management plans are available from GCSWCD (2005).

Restoration approach.—The NYCDEP and GCSWCD selected restoration reaches that had been judged in earlier basinwide assessments to have low geomorphic stability; they typically had high rates of bed and bank erosion, which produced overwidened, shallow channels; rapid channel migration; homogeneous riffle habitat; high bed sediment loads; and high concentrations of total suspended solids, especially where clay-rich deposits were exposed. The NCD restoration methods were designed to increase bed and bank stability, alleviate adverse effects of excessive erosion on water quality, minimize damage to public and private property (lands and infrastructure), and improve fish habitat and fish community health in the four project reaches. All restoration used the Rosgen (1994b, 1996) stream classification system, regional hydraulic geometry models, and NCDs based on bankfull channel characteristics measured in nearby stable reference reaches that were of the target stream type (class) and were located in a similar valley setting. Restoration generally followed NCD principles, although bank hardening was sometimes used at the request of landowners to ensure that some banks near homes and outbuildings were permanent. All reference reaches where fish were sampled appeared to be in a state of geomorphic equilibrium; however, their stability was not a critical requirement for the current analyses.

Habitat conditions.—Habitat surveys were completed in both treatment reaches in the Batavia Kill 1 year before restoration and several years after restoration to characterize changes induced by restoration. Habitat was not surveyed at treatment reaches in the East Kill and Broadstreet Hollow Brook before restoration; therefore, habitat data from nearby unstable, untreated control reaches (with habitat comparable to that of treatment reaches before restoration) were used as surrogates for prerestoration conditions.

Habitat conditions were characterized at each study reach shortly before or during corresponding fish community surveys using point-and-transect methods described by Mulvihill et al. (2003). Habitat survey reaches were 20 MSWs in length (Meador et al. 1993; Simonson et al. 1993, 1994). Instream channel features and bank conditions were measured or characterized at 11 equidistant transects. Bank height, bank angle, and riparian vegetation canopy closure were measured on both banks of each transect, and bank vegetation cover and bank stability were estimated. Measurements of water depth, substrate types, water temperature, and velocity were made at 9 equally spaced points across each transect for a total of 99 transect sample points/reach. Temperature, depth, velocity, and sizes of two particles were measured at each transect point, and embeddedness was estimated. Presence of fish cover, defined as sufficient cover for a 25.4-cm (10.0-in) trout (for example, undercut bank or boulder), was noted for each point. Wetted channel width and thalweg depth were measured at each transect, and the percent of stream area shaded between 1000 and 1400 hours was visually estimated. Pool : riffle ratio was calculated by measuring the total length of pools in a reach and dividing total pool length by the total reach length. Elevation and watershed drainage area for each reach were determined from digital or 1:24,000-scale USGS maps. Streamflow (discharge) during surveys at each site was calculated using standard USGS methods (Rantz 1982); mean daily flow at each study reach was estimated from flow records at nearby continuous USGS discharge gauges and from discharge–drainage area relations. For each reach survey, mean estimates for most channel and bank features were calculated from data collected at 99 transect points or 22 transect ends. These habitat data, along with infrequent pH samples and temperature data from continuous data loggers, were used to calculate a habitat suitability index (HSI) for each of the three local salmonid species

based on models created by the U.S. Fish and Wildlife Service (Raleigh 1982; Raleigh et al. 1984, 1986). Analysis of habitat responses to NCD restoration were limited to comparisons of absolute and relative (percent) changes in selected habitat features and HSI scores from a single survey (year) conducted before restoration and a single survey conducted after restoration. The habitat data presented herein describe the year before restoration and the first or second year after restoration (whichever year had the lower difference in discharge on the survey date relative to the prerestoration measurement).

Fish populations.—Fish in all study sites were collected from seine-blocked, 87–120-m-long reaches during three or more successive passes using a battery-powered backpack electrofisher and three fish netters. A fourth pass was added when the decrease in salmonid numbers between the second and third passes was insufficient to derive variances (95% confidence intervals [CIs]) that were smaller than 10% of the estimated salmonid population sizes. Fish from each pass were maintained in separate batches; individuals from each pass were identified to species. The lengths and weights of all salmonids were recorded; for nonsalmonid fish, length and weight data were collected only for individuals that were longer than 150 mm. Because condition and length frequency distributions of most nonsalmonids (<150 mm) were of less concern and because such fish were collected in the thousands at some study reaches, their total biomass was determined partly from pooled subsamples to curtail field processing time and effort. For subsamples, the lengths and weights from only 40–50 individuals/species were measured; thereafter, total weights and counts were recorded for batches of 10–50 individuals/species. All fish were returned to the stream after measurements from all fish collected in all passes had been obtained.

Data analyses.—At each reach, the number of fish captured during each pass was used to estimate population size (±95% CI) for each species and for the fish community; population estimation was based on the Moran–Zippin method of proportional reduction (Zippin 1958) as implemented in Microfish software (Van Deventer and Platts 1985). Common forage fish (slimy sculpin *Cottus cognatus*, eastern blacknose dace *Rhinichthys atratulus*, and longnose dace *R. cataractae*) were combined into a dace–sculpin group to assess the effects of NCD restoration on a prey guild; game fish (salmonids) were similarly combined for analysis of a top-predator guild. The total number of fish or total biomass of each species or group at each reach was divided by reach surface area to determine the density or biomass per square meter. The 95% CIs were asymmetrical, because the number of fish captured was used instead of the lower 95% confidence limit if the latter value was lower than the actual number captured. The overlap of 95% CIs was used to visually determine significant differences ($P < 0.05$) in estimates of species density and biomass between different sampling dates at the same reach (Warren and Kraft 2003). The assessments are analogous to one- or two-tailed Student's *t*-tests. These year-to-year differences in indices can be described as absolute changes or responses so as to distinguish them from before–after, control–impact (BACI; i.e., net) responses.

Population responses to restoration (and differences among streams) at the four treatment reaches were examined via BACI techniques (Stewart-Oaten et al. 1986; Underwood 1994) to test hypotheses that the density and biomass of an individual species or group were positively or adversely affected by NCD restoration. Estimates of density and biomass of each species or group were adjusted or standardized to the same index measured at the corresponding reference reach during each survey year to establish index differences (index differentials). An index differential is the difference between each index value (i.e., density or biomass) measured at a given reference reach and the index value measured at the treatment reach during the same sample period (year). Thus, an increase or decrease in an index differential at a given treatment reach after restoration quantifies the net response of the index (i.e., that due only to restoration) while accounting for normal year-to-year fluctuations in fish populations and communities. Overall effects of NCD restoration were evaluated using a two-factor analysis of variance (ANOVA; 2×4 design) to test for differences in differentials before and after restoration (2 periods) and among four treatment reaches; for each index, 6 samples were obtained before restoration and 10 samples were collected after restoration. The analysis was used to specifically assess (1) differences (net responses) in pre- and postrestoration index differentials, (2) differences in the magnitude of the differentials among sites, and (3) factor interaction, substantial differences in the direction or magnitude of responses to restoration among the four reaches. Unless otherwise noted, differences were considered significant when *P*-values were less than 0.05.

Results

Habitat Responses

With few exceptions, channel and bank features, which reflect the relative quality of fish habitat, responded to NCD restoration as predicted. The average depth, particle sizes, embeddedness, fish cover, thalweg depth, bank height, percentage of

TABLE 1.—Length and area of the fish survey reaches; annual mean daily discharge; selected habitat survey reach variables; and brook, brown, and rainbow trout habitat suitability indexes (HSIs) measured at four restored (treatment) reaches in three streams of the Catskill Mountains, New York, during one prerestoration survey year and one postrestoration survey year. Unstable control reaches were used as prerestoration surrogates where indicated. Two restored reaches (upper and lower) were present in the Batavia Kill.

	East Kill			Broadstreet Hollow Brook			Lower Batavia Kill			Upper Batavia Kill		
Variable	Before[a] (2003)	After (2003)	Percent change	Before[a] (2002)	After (2002)	Percent change	Before (2001)	After (2003)	Percent change	Before (2002)	After (2003)	Percent change
Mean daily flow(m^3/s)	1.48	1.41	−5	0.45	0.23	−49	0.45	0.75	67	0.25	0.61	144
Fish reach length (m)	110	124	13	103	108	5	100	102	2	109	102	−6
Fish reach area (m^2)	1,414	974	−31	524	398	−24	343	435	27	315	455	44
Mean depth (m)	0.16	0.35	123	0.12	0.09	−23	0.08	0.19	144	0.07	0.17	135
Mean velocity (cm/s)	15.5	19.4	25	15.9	14.5	−9	19.0	22.5	19	16.6	11.6	−30
Mean particle size (mm)	89.7	120.1	34	160.7	268.8	67	69.8	169.1	142	144.8	160.7	11
Mean embeddedness (%)	35.4	32.7	−7	43.0	30.3	−29	28.4	39.3	38	25.1	37.6	50
Mean fish cover (%)	0.0	6.0	999[b]	8.0[c]	18.0	125	4.0[c]	6.0	50	2.0	2.0	0
Mean channel width (m)	11.1	7.3	−34	7.2	3.9	−47	7.8	4.5	−42	3.6	4.5	24
Mean thalweg depth (m)	0.27	0.45	63	0.23	0.22	−4	0.18	0.31	74	0.13	0.30	137
Mean canopy closure (%)	27.2	4.5	−83	67.8	11.0	−84	11.2	5.1	−55	32.3	23.3	−28
Mean bank height (m)	1.52	1.80	18	1.68	1.43	−15	1.16	1.75	51	1.18	1.42	21
Mean bank angle (degree)	18.6	15.2	−18	25.0	22.9	−9	21.3	20.2	−5	22.4	15.9	−29
Mean bare bank (%)	40.7	22.0	−46	65.5	45.0	−31	86.3	59.8	−31	70.4	72.7	3
Mean grassy bank (%)	48.6	69.1	42	19.5	24.3	24	8.7	30.5	250	23.7	20.0	−16
Mean shrubbed bank (%)	9.8	8.9	−9	3.9	30.7	694	5.0	9.9	95	4.1	7.3	78
Mean treed bank (%)	0.9	0.00	−100	11.6	0.0	−100	0.0	0.0	0	1.8	0.0	−100
Mean bank stability (0–4)	2.6	3.6	38	2.4	3.2	32	0.2	2.5	1,173	1.8	2.9	60
Pool : riffle ratio	2.1	3.0	41	0.4	0.3	−21	0.5	1.5	188	0.5	3.0	457
Survey discharge (m^3/s)	0.156	0.161	3	0.049	0.049	0	0.068	0.084	24	0.030	0.052	75
Brook trout HSI	0.67	0.79	18	0.78	0.85	9	0.61	0.75	24	0.66	0.71	8
Brown trout HSI	0.57	0.66	16	0.65	0.70	6	0.50	0.62	24	0.57	0.59	3
Rainbow trout HSI	0.63	0.77	22	0.69	0.77	11	0.59	0.70	20	0.61	0.70	15

[a] Prerestoration conditions were determined from nearby unstable control reaches.
[b] A value of 999 is used to denote an infinite percentage change.
[c] Cover data was not recorded but was estimated from other sampling periods.

grasses and shrubs on banks, pool : riffle ratios, and visual bank stability generally increased, whereas the average channel width, riparian canopy closure, bank angle, percentage of bare banks, and percentage of banks with trees decreased at the four treatment reaches after restoration (or as compared to surrogate control reaches; Table 1). The most noteworthy exceptions occurred at Broadstreet Hollow Brook, where the control reach used as the prerestoration surrogate was so much larger than the treatment reach that changes or differences in mean depth, embeddedness, bank height, and pool : riffle ratio were not readily comparable. The mean channel width increased at the upper Batavia Kill treatment reach after restoration; the increase was probably attributable to postrestoration streamflow being almost twice as high as prerestoration streamflow (Table 1). The HSIs for all three salmonid species increased by 15% (3–24%) on average at the four treatment reaches after restoration (Table 1).

Fish Communities

Net changes in the three community indices were relatively consistent among the four treatment reaches. The net increase in the number of species was significant ($P = 0.041$) and positive (mean = 1.58 species; a 34% increase) after restoration, the net responses (differentials) did not differ among sites ($P = 0.470$), and factor interaction was not significant (Table 2). The net decrease in richness was −0.5 species at the lower Batavia Kill treatment reach, but an increase as high as 3.8 species was observed at the other three restored reaches (Figure 2). The net decrease in total fish density (density of all fish species combined) after restoration averaged −0.34 fish/m^2 and was not significant (Table 2). The net increase in fish community density was about 1.0 fish/m^2 at Broadstreet Hollow Brook; community density exhibited a net decrease (range = −0.4 to −1.1) at the other three restored reaches (Figure 3). Though total fish community density declined at both Batavia Kill treatment reaches during the first year after restoration (relative to density at the reference reach), it increased during the subsequent 1–2 years (Figure 3A). The net increase in total biomass averaged 3.10 g/m^2 (a 40% increase) and was marginally significant ($P = 0.064$) at the four treatment reaches after restoration; however, biomass differentials among sites were marginally significant ($P = 0.088$) and factor interaction was significant ($P =$

TABLE 2.—Description of community, species, and group indices (richness, biomass, or density) at four restored (treatment) reaches in three study streams of the Catskill Mountains, New York, 1999–2004, including prerestoration mean index values, mean net change (response to restoration), and percent change ($n = 16$). Also shown are P-values for two-factor analyses of variance used to assess differences in differentials (1) before versus after restoration, (2) among treatment reaches, and (3) due to factor interaction (bold type indicates $P < 0.05$).

Index or group	Prerestoration mean	Mean response	Percent change	P-values for differences: Before–after	Among streams	Factor interaction
Community indices						
Total richness (number of species)	**4.7**	**1.58**	**34**	**0.041**	0.470	0.093
Total density (fish/m^2)	2.24	−0.34	−15	0.516	0.314	0.468
Total biomass (g/m^2)	**7.71**	**3.10**	**40**	0.064	0.088	**0.005**
Species or group density (fish/m^2)						
Salmonid group	**0.06**	**0.16**	**253**	**0.029**	**0.019**	0.286
Brown trout	**0.05**	**0.10**	**206**	**0.020**	0.076	0.136
Brook trout	0.002	0.02	1,068	0.443	**0.011**	0.620
Rainbow trout	0.015	0.03	194	0.435	0.408	0.515
Sculpin–dace group	2.15	−0.29	−14	0.538	0.397	0.169
Slimy sculpin	0.94	−0.02	−2	0.961	0.143	0.372
Eastern blacknose dace	1.08	−0.35	−32	0.453	0.076	0.914
Longnose dace	0.12	−0.22	−187	0.107	0.997	0.099
Other fish species	**0.03**	**0.15**	**448**	**0.037**	**0.047**	0.078
Species or group biomass (g/m^2)						
Salmonid group	**1.53**	**3.65**	**239**	**0.002**	**0.001**	**0.010**
Brown trout	**1.06**	**2.69**	**253**	**0.022**	0.126	0.126
Brook trout	0.01	0.19	1,529	0.657	**0.005**	0.881
Rainbow trout	0.54	0.78	144	0.209	0.180	0.191
Sculpin–dace group	6.10	−0.38	−6	0.392	0.277	0.101
Slimy sculpin	3.68	−0.03	−1	0.983	0.105	0.089
Eastern blacknose dace	2.08	−0.65	−31	0.469	0.089	0.922
Longnose dace	0.35	−0.71	−204	0.176	0.356	0.094
Other fish species	**0.12**	**0.94**	**805**	**0.030**	0.375	0.121

0.005; Table 2, Figure 4). The different directions of the biomass responses among treatment reaches accounted for the significant factor interaction; biomass exhibited a net increase at Broadstreet Hollow Brook (15.0 g/m^2) and East Kill (1.5 g/m^2), but net decreases (range = −1.0 to −3.1) were observed at the two restored Batavia Kill reaches (Figure 4B, C).

Salmonid Group

The net increase in density of pooled salmonid species (brook trout *Salvelinus fontinalis*, brown trout *Salmo trutta*, and rainbow trout *Oncorhynchus mykiss*) at the four treatment reaches was significant ($P = 0.029$) and averaged 0.16 fish/m^2 (a 253% increase) after restoration (Table 2). Salmonid density differentials, however, differed among sites ($P = 0.019$), but factor interaction was not significant (Table 2). The net increase in salmonid biomass at the four treatment reaches was significant ($P = 0.002$) and averaged 3.65 g/m^2 (a 239% increase) after restoration (Table 2). Like density, the differentials for salmonid biomass differed among sites ($P = 0.001$); however, unlike density, there was a significant factor interaction ($P = 0.010$; Table 2, Figure 6). Net increases were found for salmonid density and biomass at each of the four treatment reaches on average; density increases ranged from 0.05 to 0.35 fish/m^2 and biomass increases ranged from 1.11 to 9.30 g/m^2 after restoration (Figures 5, 6).

Brown Trout

The net increase in brown trout density was significant ($P = 0.020$) and averaged 0.10 fish/m^2 (a 206% increase) after restoration (Table 2). Density differentials for brown trout differed moderately among sites ($P = 0.076$), and factor interaction was not significant (Table 2). Net increases in brown trout density at the four treatment reaches were relatively small (0.03 fish/m^2) to large (0.25 fish/m^2) (Figure 7). The net increase in brown trout biomass at the four treatment reaches after restoration was significant ($P = 0.022$) and averaged 2.69 g/m^2 (a 253% increase); differentials among sites and factor interaction were not significant (Table 2). The net increase in brown trout biomass generally ranged from 1.22 to 6.17 g/m^2 after restoration (Figure 8).

Brook Trout

Changes in brook trout density and biomass were sometimes similar to, and sometimes an order of magnitude lower than, brown trout density and biomass changes in the same stream reaches; however, net responses to restoration were seldom similar between

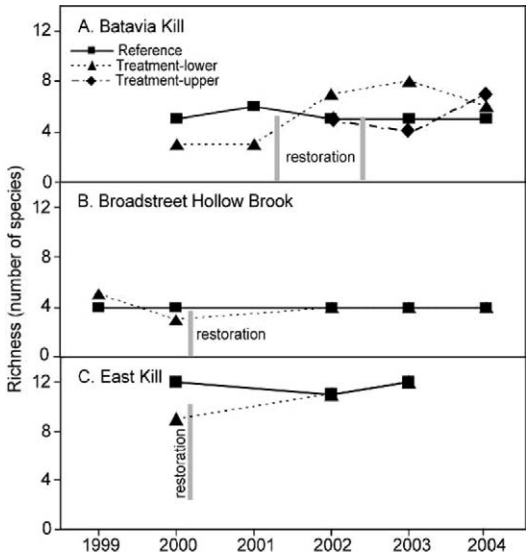

FIGURE 2.—Total fish community richness (number of species) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (data modified from Baldigo et al. [2008]; shaded vertical bars = approximate period in which restoration activities occurred).

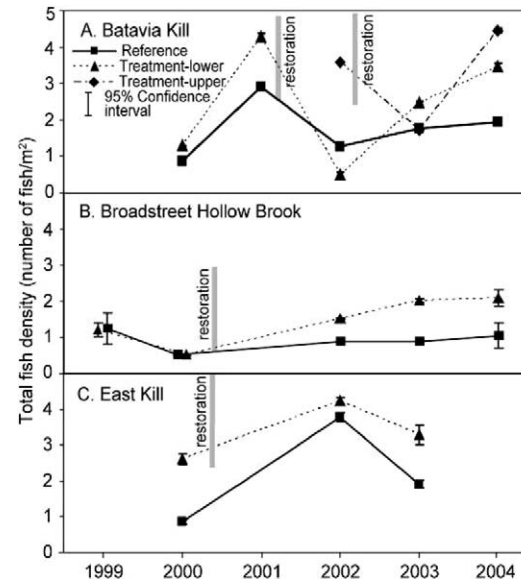

FIGURE 3.—Total fish community density (fish/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (data modified from Baldigo et al. [2008]; shaded vertical bars = approximate period in which restoration activities occurred).

the two species. Brook trout were not collected at East Kill reaches. Net increases in brook trout density at the other three treatment reaches averaged 0.02 fish/m^2 after restoration and were not significant (Table 2). Density differentials for brook trout differed among sites ($P = 0.011$), and factor interaction was not significant (Table 2); net density either increased or decreased slightly (range = −0.02 to 0.07 fish/m^2) depending on the stream examined (Figure 9). Net brook trout biomass in the three treatment reaches increased by an average of 0.19 g/m^2 after restoration; the increase was not significant at any of the sites. Biomass differentials differed significantly among sites ($P = 0.005$), and factor interaction was not significant (Table 2, Figure 9). Like density, the net biomass of brook trout at treatment reaches did not respond consistently after restoration; net biomass either increased or decreased slightly (range = −0.11 to 0.71 g/m^2).

Rainbow Trout

Analyses of the effects of NCD restoration on rainbow trout populations were limited to treatment reaches at Broadstreet Hollow Brook and lower Batavia Kill, because this species was not observed at the other two treatment reaches. Net increases in rainbow trout density averaged 0.03 fish/m^2 after restoration, but this average was not significant; net responses among sites and factor interaction were also nonsignificant (Table 2). Net increases in rainbow trout biomass at the treatment reaches averaged 0.78 g/m^2 after restoration, but the average increase, differentials among sites, and factor interaction were not significant (Table 2). Net rainbow trout density increased by 0.001–0.124 fish/m^2 and net biomass increased by about 0.2–2.9 g/m^2 at the two treatment reaches after restoration.

Dace–Sculpin Group

Although net changes in density and biomass of pooled daces and sculpins in response to NCD restoration often were nonsignificant or nontestable, both indices tended to decrease as hypothesized. The net decrease in dace and sculpin density at the four treatment reaches averaged −0.29 fish/m^2 after restoration but was not significant; differentials among sites and factor interaction also were not significant (Table 2). The net change in dace and sculpin density at both Batavia Kill treatment reaches was negative during the first year after restoration and then was positive during the next 2 years (Figure 10A); net changes averaged

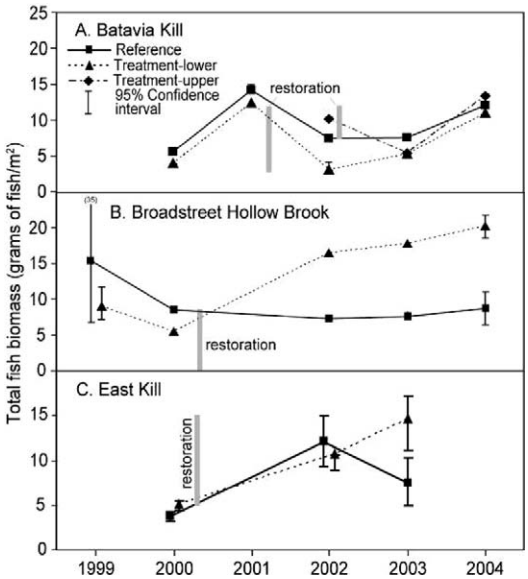

FIGURE 4.—Total fish community biomass (g/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (data modified from Baldigo et al. [2008]; shaded vertical bars = approximate period in which restoration activities occurred).

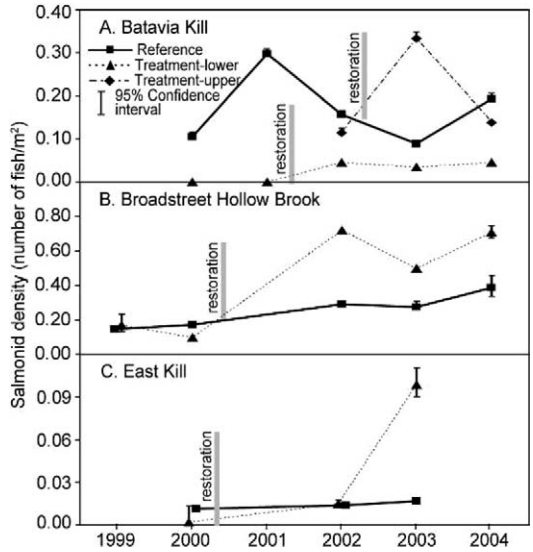

FIGURE 5.—Total salmonid density (fish/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

−0.700 to 0.002 fish/m^2 at these reaches. Dace and sculpin density exhibited an average net increase of 1.3 fish/m^2 at the Broadstreet Hollow Brook treatment reach and a net decrease of −1.75 fish/m^2 at the East Kill treatment reach after restoration (Figure 10B, C). The lack of data from Broadstreet Hollow Brook and East Kill during 2001 (the first year after restoration) hinders a definitive assessment of the potential reversal in response direction over time at the four treated reaches. The net decrease in dace and sculpin biomass averaged −0.38 g/m^2 at the four treatment reaches after restoration but was not significant ($P = 0.392$), and differentials among sites and factor interaction were also nonsignificant (Table 2). The net decrease in biomass averaged −2.7 g/m^2 at the lower Batavia Kill reach, −4.2 g/m^2 at the upper Batavia Kill reach, and −4.25 g/m^2 at the East Kill; biomass demonstrated a net increase (5.7 g/m^2) at Broadstreet Hollow Brook after restoration (Figure 11).

Slimy Sculpin

The net decrease in slimy sculpin density at the four treatment reaches averaged −0.02 fish/m^2 after restoration, but this decrease, the differentials among sites, and the factor interaction were not significant (Table 2). The net decrease in slimy sculpin density averaged about −0.5 fish/m^2 at the lower Batavia Kill treatment reach and −0.9 fish/m^2 at the upper Batavia Kill reach; the net change in density was positive at Broadstreet Hollow Brook (1.3 fish/m^2) and East Kill (0.01 fish/m^2) after restoration. The net decrease in slimy sculpin biomass at the four treatment reaches averaged −0.03 g/m^2 after restoration but was nonsignificant, and differentials among sites and factor interaction were also nonsignificant (Table 2). Biomass exhibited net decreases at the lower (−1.9 g/m^2) and upper (−3.9 g/m^2) Batavia Kill reaches but net increases at Broadstreet Hollow Brook (5.7 g/m^2) and East Kill (0.01 g/m^2) after restoration.

Eastern Blacknose Dace

The net decrease in eastern blacknose dace density at the four treatment reaches averaged −0.35 fish/m^2 after restoration but was not significant; differentials among sites and factor interaction also were not significant (Table 2). The net change in eastern blacknose dace density was consistently negative, averaging from −0.002 to −0.900 fish/m^2 at the four treatment reaches after restoration. The net decrease in eastern blacknose dace biomass at the four treatment reaches averaged −0.65 g/m^2 after restoration, but this decrease, the

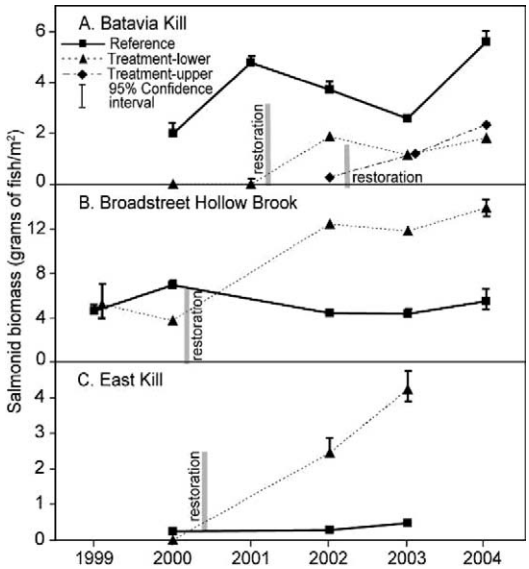

FIGURE 6.—Total salmonid biomass (g/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

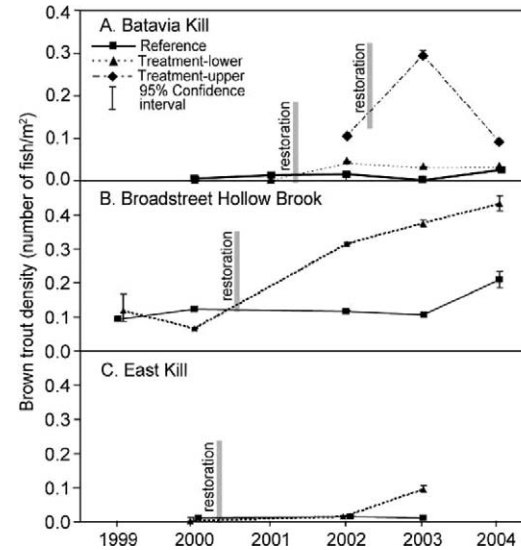

FIGURE 7.—Total brown trout density (fish/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

differentials among sites, and the factor interaction were all nonsignificant (Table 2). Like density, the net changes in biomass were negative, averaging from −0.003 to −1.300 g/m^2 at the four treatment reaches after restoration.

Longnose Dace

Longnose dace were absent from the treatment and reference reaches in Broadstreet Hollow Brook. The net decrease in longnose dace density at the other three treatment reaches was nonsignificant and averaged −0.22 fish/m^2 after restoration; likewise, the differentials among sites and factor interaction were nonsignificant (Table 2). The net change in longnose dace density was near zero (−0.002 to 0.02 fish/m^2) at both Batavia Kill treatment reaches and was negative (−0.9 fish/m^2) at the East Kill treatment reach after restoration. Longnose dace biomass at the three treatment reaches exhibited a nonsignificant net decrease of −0.71 g/m^2 (P = 0.176); differentials among sites and factor interaction were also nonsignificant (Table 2). The net change in longnose dace biomass was positive (0.5 g/m^2) at the lower Batavia Kill treatment reach and negative (−0.01 to −3.30 g/m^2) at the East Kill and upper Batavia Kill treatment reaches after restoration.

Other Fish Species

At three of the four treatment reaches, the density and biomass of fish species other than salmonids, daces, or sculpins generally increased after restoration, but changes within each species or within individual streams were nonsignificant or were nontestable because of low fish numbers and limited distributions (Table 2). Other fish species were not present at study reaches in Broadstreet Hollow Brook. Before restoration, the lower Batavia Kill treatment reach contained a few rock bass *Ambloplites rupestris* and creek chub *Semotilus atromaculatus* but no salmonids. After restoration, the reach contained brook, brown, and rainbow trouts and white suckers *Catostomus commersonii*. The upper Batavia Kill treatment reach showed a similar response: creek chub density decreased and white sucker density increased. Before restoration, the East Kill treatment reach contained largemouth bass *Micropterus salmoides*, margined madtoms *Noturus insignis*, common shiners *Luxilus cornutus*, cutlip minnow *Exoglossum maxillingua*, white suckers, and creek chub; no longnose dace and only two brown trout were found at that reach. After restoration, several of

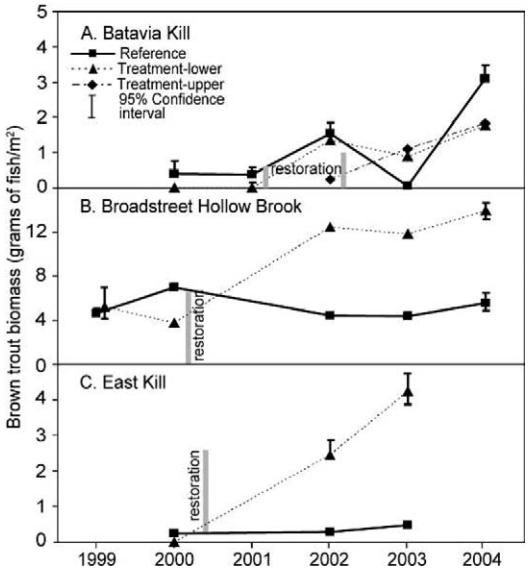

FIGURE 8.—Total brown trout biomass (g/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

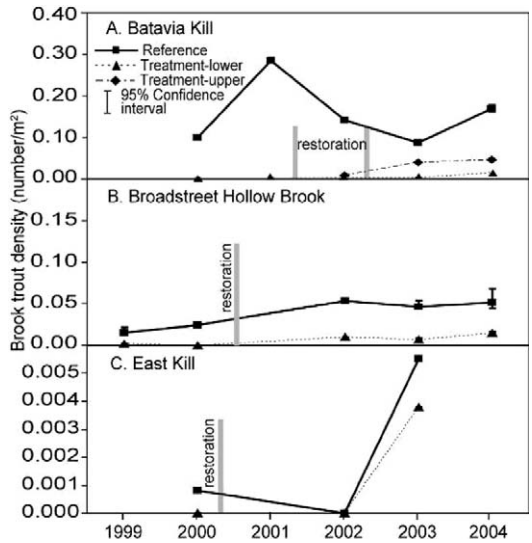

FIGURE 9.—Total brook trout density (fish/m^2; ±95% confidence interval) at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

the aforementioned species were absent or decreased in number, but three new species (tessellated darter *Etheostoma olmstedi*, pumpkinseed *Lepomis gibbosus*, and brook trout) were collected. The treatment and reference reaches at Broadstreet Hollow Brook only contained coldwater species (all three salmonids and slimy sculpin) before and after restoration; although warmwater species, such as cutlip minnow, longnose suckers *Catostomus catostomus*, white suckers, and creek chub were collected from an unstable control reach located much further downstream.

The density and biomass of combined fish species (other than salmonids, daces, and sculpins) generally increased at treatment reaches after restoration (Table 2). The net increase in combined density of other fish species at the three treatment sites (i.e., excluding Broadstreet Hollow Brook) after restoration was significant ($P = 0.037$) and averaged 0.15 fish/m^2 (a 448% increase); differentials among sites were also significant ($P = 0.047$) after restoration, but the factor interaction was only marginally significant ($P = 0.078$; Table 2). The net increase in combined density of other fish species ranged from 0.001 to 0.510 fish/m^2 at the individual treatment reaches after restoration. The net change in combined biomass of other fish species at the three treatment reaches was significant ($P = 0.030$) and averaged 0.94 g/m^2 (an 805% increase) after restoration; differentials among sites and factor interaction were not significant (Table 2). The net change in combined biomass at individual treatment reaches was 1.25 g/m^2 at the lower Batavia Kill reach, 2.53 g/m^2 at the East Kill reach, and −0.03 g/m^2 at the upper Batavia Kill reach.

Discussion

The significant increases in the number of fish species (average richness increase = 1.58 species), total fish community biomass (principally salmonids), and density and biomass of other fish species suggest that many species were strongly affected by NCD restoration. In general, many of the fish species collected at unstable treatment reaches before restoration were characteristic of large, warm streams; after reach restoration, such species either disappeared or exhibited decreases in population density and biomass. The fish species found at restored treatment reaches and at stable reference reaches after restoration were generally intolerant fauna that were characteristic of small, cold headwater streams in the Catskill Mountains region. These changes indicate that the structure, function, and integrity (relative health) of local fish communities

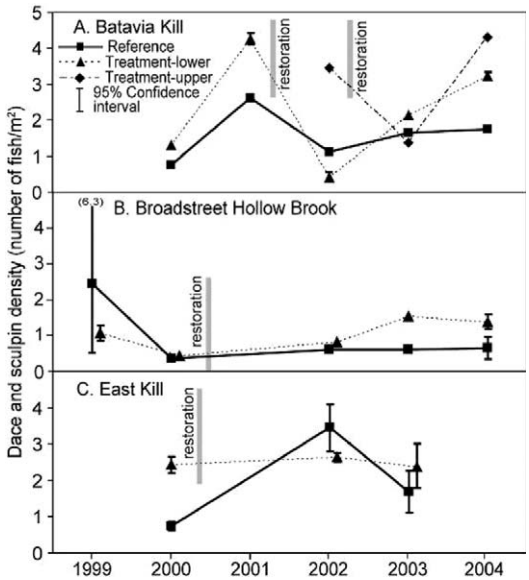

FIGURE 10.—Total density (fish/m^2; ±95% confidence interval) of daces and sculpins at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

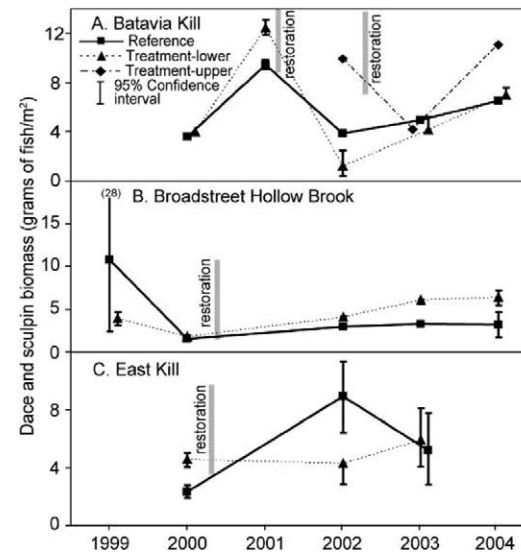

FIGURE 11.—Total biomass (g/m^2; ±95% confidence interval) of daces and sculpins at four restored (treatment) reaches and three reference reaches in three study streams of the Catskill Mountains, New York, before and after restoration, 1999–2004: **(A)** Batavia Kill (two restored reaches: upper and lower), **(B)** Broadstreet Hollow Brook, and **(C)** East Kill (shaded vertical bars = approximate period in which restoration activities occurred).

generally improved due to restoration, at least during the period of this study. However, contrary to expectations, total fish community abundance (density) did not decrease in response to NCD restoration. Although it is possible that NCD restoration has no real effect on community abundance or that natural variability is too large to permit characterization of a significant response, two reasonable explanations for the lack of significant decreases in total density are that (1) prerestoration communities were far below their normal carrying capacities (in terms of biomass) and (2) postrestoration communities exceeded reach carrying capacities. Instead of a smaller number of larger individuals (unchanged community biomass), restoration produced no significant change in the total number of individuals but increased the total community biomass through the addition of more species and increases in average individual weight (mean individual fish weight increased from 4.2 to 5.6 g; net increase = 1.4 g/fish) and species-specific combined weight. The fish assemblages and stream conditions characterized during the first 3 years after restoration probably had not reached equilibrium, but population responses during that time suggest that NCD restoration notably increased the quality, quantity, and heterogeneity of stream habitat while improving geomorphic stability at the four treated reaches. These changes appear to benefit salmonids (game fish) more so than forage species (daces and sculpins), yet there were no obvious negative effects on most other species.

Changes in the structure and function of fish communities were caused mainly by shifts in the dominant species. For example, the biomass of fish communities at the East Kill and the Batavia Kill treatment reaches before restoration consisted almost entirely of one or two small prey species (as much as 99% of the biomass was made up of slimy sculpin, eastern blacknose dace, or longnose dace), whereas few individuals of top-predator species were present. After restoration, the biomass and proportion of brown, brook, and rainbow trouts increased, whereas the biomass and proportion of small forage species decreased. The fish communities that were reestablished in restored reaches generally resembled the diverse and evenly balanced fish communities found in relatively undisturbed reference reaches nearby. Thus, NCD restoration helped to reconstitute more-natural (if not entirely native) fish communities, thereby enhancing the biological integrity of local stream ecosystems.

A major finding of this study involved the consistent increases in salmonid density and biomass in treated

reaches after NCD restoration. This appears to be a direct response to the increased quality or quantity of habitat available to the three salmonid species, as reflected by the moderate increases in salmonid HSI scores after restoration of the four treatment reaches. The increase in brown trout accounted for most of the net increases in salmonid density and biomass and for the related shifts in community structure after restoration. Net fish community biomass increased considerably by 4.23 g/m^2, and the salmonid group accounted for 95% (4.00 g/m^2) of that increase. The increased brown trout biomass accounted for 69% (2.77 g/m^2) of the total increase in salmonid biomass. Net biomass of brown trout at the four treatment reaches increased by an average of 260% after restoration, and net density of brown trout increased significantly by 0.12 fish/m^2 (246% increase) and contributed to a significant (285%) increase in salmonid density (0.18 fish/m^2). Net density and biomass of brook and rainbow trouts at restored sites often increased slightly after restoration, but numbers of these species were always low and the increases were seldom significant. The increases in salmonid number and biomass in restored reaches are noteworthy considering that improved game fish populations and habitat are often stated as primary or secondary goals for stream restoration projects.

The response of salmonids at treatment reaches was sequential and tended to track changes in stream habitat that occurred over the first 1–3 years after restoration. The number of salmonids and the number of adults (age $>$ 1) generally increased during the first year postrestoration (and usually stayed near these higher densities) when water depth and lateral banks or rock veins and boulders were the primary source of new cover. Numbers of age-0 salmonids generally increased more (in proportion to the total number of salmonids at each reach) during the second or third year (relative to the first year) after restoration as banks became densely vegetated with low shrubs and grasses, one or more high flow events transported new sediments into and out of the reach, and stream habitat became more heterogeneous. At 12–24 months postrestoration, some boulders were relocated by high flows, low vegetation increased shade and cover along channel margins, small amounts of woody debris sometimes settled into the reaches, riffles became more confined (channelized), and materials in riffles became larger and less embedded. Although the source of additional age-0 salmonids could have been either increased immigration or improved spawning and reproduction success within the restored reach, the outcome was increased density and biomass of age-0 (and adult) salmonids in most restored reaches.

The absolute response and the importance of changes in brook trout density and biomass are not always adequately quantified by the BACI analysis of net changes, thus illustrating one limitation of this method and emphasizing the need for graphical inspection of data to ensure reasonable interpretations. The apparent lack of significant increases in both indices stems from the absence of brook trout or the very low brook trout density and biomass at all four treatment reaches and the relatively high brook trout density, biomass, and variability at the corresponding reference reaches. No brook trout were collected at the lower Batavia Kill or East Kill treatment reaches, and only one was collected (during prerestoration surveys) at the Broadstreet Hollow Brook treatment reach. Even though net increases were not significant, average brook trout density increases from 0.002 to 0.014 fish/m^2 at the four treatment reaches after restoration (Figure 9) show that the restoration efforts essentially helped return this native species to three of the four communities. Any increase in biodiversity should help headwater ecosystems maintain their fundamental structure and function under periods of environmental duress. Thus, the addition of a fish species (and absolute numbers of that species), even one as highly variable as brook trout, can sometimes illustrate the tangible effects of NCD restoration more reliably than net responses defined by BACI analyses.

The net density and biomass of eastern blacknose dace, longnose dace, and slimy sculpin did not decrease significantly after NCD restoration, indicating that these populations were relatively resilient to effects of restoration, habitat change, and changes in predator density and biomass. The absence of significant postrestoration decreases in density and biomass of the most common small forage species (daces and sculpins) and the presence of significant increases in salmonid density, biomass, and richness have several important implications.

First, NCD restoration appears to increase the quantity, quality, or diversity of habitat, which mainly benefits the larger fish species (higher trophic levels) within the food web. The NCD restoration consistently increased pool percentage and size, and the large rock structures associated with restoration provided more-heterogeneous habitat for a wider variety of fish than was present before restoration. The increase in habitat for large fish species did not appear to decrease the amount of habitat available to common small forage species; also, there was no evidence that increased density and biomass of piscivorous salmonids adversely affected density or biomass of the various prey species. Alternatively, improved quality or quantity of habitat for small species may have offset any negative effects due to increased predator abundance and

permitted the prey species to maintain the same relative density and biomass even after restoration. The results suggest that restoration helped segregate the two groups of fish; in other words, the diverse habitat created by restoration may have decreased predation and competition for food and habitat relative to pressures occurring in the more-homogeneous habitats that existed before restoration. However, most of the recreated pools lacked complexity except in areas immediately adjacent to rock veins. Accordingly, future restoration techniques that add structure or woody debris to pools could further improve habitat complexity and visual isolation for large fish and refuge areas for small fish.

Second, the significant increase in total fish community biomass after NCD restoration indicates that (1) at most unstable treatment reaches before restoration, biomass was below the reach carrying capacity; or (2) more probably, reach carrying capacity was smaller before restoration than after restoration. Examination of community responses in the three streams (Figure 4) shows, however, that total biomass ranged naturally from 5 to 15 g/m^2 and that a significant net increase only occurred at Broadstreet Hollow Brook. The differences in biomass between reference and treatment reaches before and after restoration were relatively small and comparable to the normal year-to-year fluctuations within each reach. Except at Broadstreet Hollow Brook, total fish community biomass appeared to respond conservatively to NCD restoration (i.e., did not change sharply). The large increase in fish community biomass at Broadstreet Hollow Brook may reflect an exaggerated community (primarily salmonid) response that exceeded the reach's carrying capacity for the duration of this study, particularly because no corresponding increase in total biomass was seen at the Broadstreet Hollow Brook reference reach during 2002–2004. This indicates that the response at the restored reach was primarily due to NCD restoration. Fish communities at reference reaches were not intended to act as literal or exact targets; therefore, the potential for exceeding the restored reach's carrying capacity could not be thoroughly evaluated. Nevertheless, a small change or a lack of change in community biomass was a credible response to restoration, given that biomass stability is a conservative property of aquatic ecosystems and is generally independent of the number of resident species (Tremblay and Richard 1993).

Third, the changes in fish community composition after NCD restoration of the four treatment reaches generally reflected a shift from species that were more tolerant of nonspecific stressors to species that were less tolerant. Barbour et al. (1999) compiled data from numerous publications into a set of tolerance classifications for selected fish species; the three salmonid species in our study were designated as moderately tolerant, eastern blacknose dace and slimy sculpin were classified as tolerant, and longnose dace were designated as intolerant. A newer general tolerance classification, based on fish and physiochemical data from 773 streams across the United States, used weighted averages of 10 physiochemical variables to derive optima for 105 fish species (Meador and Carlisle 2007). Slimy sculpin optima were not evaluated, but the three salmonid species were classified as intolerant and eastern blacknose and longnose daces were classified as moderately tolerant. The data analyzed by Meador and Carlisle (2007) indicated optimal temperatures of 14.2–15.5°C for the salmonids and approximately 18.5°C for both dace species and suspended sediment concentrations of 11–18 mg/L for the salmonids and 36–44 mg/L for the daces. Natural channel design restoration typically increases local channel stability and thereby decreases local bed and bank erosion (aggradation and degradation), narrows and deepens wetted stream channels, and increases the interaction between stream surface and hyporheic zone waters. These changes can effectively decrease suspended sediment concentrations and water temperatures and potentially increase the ability of intolerant species to successfully compete for available habitat in restored reaches. Significant net biomass increases for intolerant salmonid populations and slight, nonsignificant net biomass decreases for tolerant daces and sculpins (or relative decreases in the proportion of community totals contributed by these species) after restoration generally substantiated species tolerance classes and the positive effects of NCD restoration.

With the exception of Baldigo and Warren (2008, this issue), studies that describe the responses of fish populations and communities to NCD restoration are rare. However, related and unrelated investigations of other restoration and habitat enhancement methods that produce features similar to those created by NCD restoration (Shields et al. 1997, 1998, 2000; Roni and Quinn 2001) indicate that fish populations and communities are affected in a manner similar to that observed in the four restored reaches within streams of the Catskill Mountains, at least for the duration of monitoring. With only 2 years of postrestoration data in three of the same study reaches described herein, Baldigo et al. (2008) showed that total (net) community biomass, species richness, and biomass equitability increased due to NCD restoration. In other studies, placement of drop-log structures in six small Colorado streams decreased water velocity; increased pool volume, depth, and cover; and generally increased the

abundance and biomass of age-2 brook, brown, and rainbow trouts (Riley and Fausch 1995). Increases in pool abundance (with or without the addition of logs) increased the probability that cutthroat trout *O. clarkii* and rainbow trout would be present in streams of the Cascade Mountains (Latterell et al. 2003). Habitat manipulations (mainly bank stabilizations and addition of timber, log, or rock check dams) that decreased bank erosion and increased instream cover and residual pool depth generally increased the abundance and biomass of brown, brook, rainbow, and cutthroat trouts in 25 of 30 Wyoming streams (Binns 2004). In Maryland's coastal plain, Scott and Hall (1997) found that fish communities in geomorphically degraded streams (i.e., in a state of disequilibrium) had low species diversity and were dominated by a few tolerant taxa, whereas streams that were less severely affected had more-balanced species assemblages and higher richness and abundance of indigenous species. Although most prior studies do not assess specific effects from NCD restoration, their observations support the present results, which show that a variety of restoration techniques can greatly benefit fish communities and stream ecosystems.

Improved health of fish communities was not a primary motivation for restoring the four stream reaches in this study, yet community richness and biomass increased significantly, which demonstrates that NCD restoration can vastly improve the structure, function, and biological integrity of resident fish communities in streams of the Catskill Mountains. The evaluation of fish species indicated that postrestoration changes in community structure were caused mainly by shifts in populations of the dominant species. Fish community biomass and density were usually dominated by either daces or daces and sculpins before restoration and by one or more salmonid species after restoration. Fish community composition generally shifted from species that were tolerant of nonspecific stressors to less-tolerant species after restoration. Changes in fish species and communities were related to habitat quality, quantity (area), and heterogeneity increases that were generated by the increase in geomorphic stability. Many sampling and analysis strategies are available to document effectiveness of restoration depending on project goals, the level of interest, and availability of funding. An equally wide range of findings is possible from such efforts and can dramatically alter final interpretations and conclusions about restoration effects on targeted resources. In the companion paper, Baldigo and Warren (2008, this issue) shows how changes in biomass of brown trout, all salmonids, or the entire fish community can be detected and interpreted using various a posteriori sampling and analysis strategies.

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