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BRIDGES

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Restoration of an Indiana, USA, stream: bridging the gap between basic and applied lotic ecology

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Abstract. Stream restoration attempts to reverse the global degradation of rivers and streams, but rigorous evaluations are needed to advance the science. We evaluated a 3rd-order channelized Indiana (USA) stream that was restored in 1997 by constructing two meanders, each ~400 m long. Pool and riffle sequences were constructed, coarse substrate and wood were added to the channel, banks were stabilized and revegetated, and sedimentation was reduced by creating a sediment retention basin upstream. Habitat, periphyton, macroinvertebrates, and fishes were measured before restoration and for 5 y after restoration in the restored reaches and in an upstream, unrestored reach. Restoration improved habitat conditions (e.g., more pools, fewer fine sediments) in both restored reaches compared to the unrestored reach. Within 1 y after restoration, major trophic groups (i.e., periphyton, macroinvertebrates, and fishes) recovered to or exceeded levels in the degraded, unrestored reach. However, biotic responses varied with time, trophic level, and community parameter measured. Five years after the restoration, habitat quality, algal abundance, and macroinvertebrate density remained higher in the restored reaches, whereas macroinvertebrate diversity and fish abundance in the restored reaches were similar to or below levels in the unrestored, channelized reach. Although biotic recovery was relatively rapid, long-term persistence is uncertain because of continued sedimentation at a watershed scale. In many instances, reach-scale restorations may be ineffective in the face of basin-wide degradation. This study illustrates the importance of conducting long-term assessments of stream restorations, which can improve both knowledge and management of stream ecosystems.

Key words: stream habitat, sedimentation, biotic recovery, fish, macroinvertebrates, periphyton.

Aldo Leopold brought attention to the field of restoration ecology in the 1930s by promoting a land ethic of restoring farmland to tallgrass prairie. However, only in recent years has the field of restoration ecology developed into a formal discipline. Currently, centers (e.g., Center for Restoration Ecology at University of Wisconsin–Madison; Center for Urban Restoration Ecology at Rutgers University), societies (e.g., Society for Ecological Restoration), and journals (e.g., *Restoration Ecology*) have been dedicated to the field of restoration ecology.

Similar to Leopold's vision, much of the discipline remains focused on terrestrial ecosystems, although the need to restore degraded aquatic ecosystems also is urgent. Human activities have severely altered and impaired aquatic ecosystems for centuries, which has led to a decline in the ecosystem services provided by

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streams and rivers (NRC 1992, Wilcove and Bean 1994, Karr and Chu 1999). Several important scholarly works on restoration of aquatic ecosystems exist (e.g., Gore 1985, Brookes and Shields 1996, FISRWG 1998), but many basic questions remain unanswered.

Millions of dollars are being spent annually to restore and manage stream ecosystems to more naturally functioning and structured systems, but little is known about the effectiveness of these approaches. Project funding often supports the design and construction of the restoration, but no resources are allocated for monitoring before or after restoration (Kershner 1997). Many restoration efforts in Washington State are motivated by the decline in salmon populations, but only ~½ of the restoration and enhancement projects included monitoring of at least one biological, physical, chemical, or other water-quality measure (Bash and Ryan 2002). Moerke and Lamberti (2004) similarly determined that monitoring of stream restorations was uncommon in Indiana, where only 3 of 10 reach-scale restorations included some monitoring of biological parameters before and after restoration. Both studies observed that monitoring often was qualitative and short term (e.g., a one-time observation).

Quantitative evaluations of stream restorations have been rare overall (NRC 1992, Kershner 1997), and assessed restorations indicated mixed responses (e.g., Frissell and Nawa 1992). Stream restorations are intended to be beneficial to the ecosystem, but they may result in unintended outcomes, such as having no effect or causing further damage (NRC 1992, Iversen et al. 1993, Kondolf 1995, 1998, Frissell 1997). It is important to report failures so that project inadequacies can be identified and similar mistakes can be avoided in the future (Kondolf 1998). Increasing pressures from expanding populations and changing land use will cause stream restorations to be used increasingly as a tool to repair aquatic habitat and biota, but the success of restorations will depend on the practical and theoretical insights gained from past restoration attempts.

Stream restoration projects can provide insights into both practical and theoretical questions, yet few aquatic ecologists have taken full advantage of these opportunities to assess our current understanding of streams. Bradshaw (1987) suggested that restoration is the ultimate test of ecological understanding and, thus, can be a valuable technique in ecological research. Stream restorations can be viewed as large-scale experiments to test basic ecological concepts for lotic systems.

Streams often are restored in an attempt to enhance biotic recovery and, thus, they may provide an opportunity to assess patterns of colonization and succession of aquatic biota. Stream recovery usually is assessed after a natural (e.g., drought, spate) or anthropogenic (e.g., chemical spill, logging) disturbance, and studies have shown that rates of biotic recovery vary with trophic level, distance to source of colonists, and dispersal ability of colonists (e.g., Gore 1985, Yount and Niemi 1990, Lamberti et al. 1991). The type (e.g., pulse or press) of disturbance may also affect recovery rates (Niemi et al. 1990, Detenbeck et al. 1992). Recovery after a natural disturbance is relatively rapid in streams because communities generally are adapted to these disturbances (Yount and Niemi 1990). However, recovery by stream communities after severe anthropogenic alteration, such as channelization, varies and, in many instances, recovery is incomplete (Niemi et al. 1990, Detenbeck et al. 1992). Stream restoration attempts to shorten the recovery time after anthropogenic disturbance by creating suitable habitat for aquatic biota.

Stream restorations also may provide insight into the influence of habitat on biotic community structure. Ecological literature has suggested that habitat heterogeneity is an important factor regulating species diversity in various groups of organisms (Pianka 1967, Woodin 1981, Boomsma and Van Loon 1982, Schlosser 1982). Stream habitat heterogeneity can affect fish (Gorman and Karr 1978, Schlosser 1982, Meffe and Sheldon 1988) and macroinvertebrate diversity, biomass, and density (Allan 1975, Minshall 1984, Gore et al. 1998). Relationships between habitat heterogeneity and stream communities generally are accepted by ecologists, but few evaluations have been carried out in a restoration context (Palmer et al. 1997). Stream restoration goals often include enhancing habitat, so the influence of habitat heterogeneity on stream communities can be evaluated.

A stream restoration project on Juday Creek (St. Joseph Co., Indiana, USA) was completed in 1997 to satisfy state permitting requirements for the construction of a golf course. The restoration relocated a section of the stream channel to minimize impacts from golf course operations and to improve riparian and instream habitat. The restoration of Juday Creek provided a unique opportunity to assess the effectiveness of the restoration design and to evaluate a large-scale experiment in which a new stream environment was created. The objectives of our study were to 1) assess response of biological communities to restoration and persistence of habitat features over time, and 2) determine the effects of increased habitat heterogeneity, through stream restoration, on biological components of the stream ecosystem. Our study attempted to address some of the deficiencies in the field of stream restoration by assessing the effectiveness of specific restoration techniques, while providing information relevant to basic ecological concepts.

Restoration often is defined as returning an ecosystem to its predisturbance state (Bradshaw 1996), but this goal is usually nearly impossible (NRC 1992). Many streams were altered dramatically decades or even centuries ago. Little or no information exists on their original conditions, and historic conditions could not be recreated even if they were known. For our study, restoration is, therefore, defined as returning an ecosystem to a more natural condition by facilitating ecological recovery.

Study Site and Design

Juday Creek is a 3rd-order tributary of the St. Joseph River (Lake Michigan drainage) and is ~19 km long with a drainage area of 98 km^2. Juday Creek is one of a few groundwater-fed streams in northern Indiana with reproducing trout populations. However, most of the stream was channelized in the 1950s to accommodate agricultural and residential land use. Habitat loss and sedimentation have reduced macroinvertebrate densities (Kohlhepp 1991) and the amount of suitable spawning habitat for coolwater sport fishes (Lamberti and Berg 1995). The riparian vegetation surrounding Juday Creek consists of basswood (*Tilia americana*), silver maple (*Acer saccharinum*), eastern cottonwood (*Populus deltoides*), sandbar willow (*Salix exigua*), black cherry (*Prunus serotina*), highbush-cranberry (*Viburnum opulus*), common privet (*Ligustrum vulgare*), and staghorn sumac (*Rhus typhina*).

The Juday Creek restoration design incorporated hydrological, geomorphic, and biological principles to address high sediment loads and degraded fish habitat. The restoration consisted of new channel construction, revegetation of the banks, fine sediment trapping, and instream habitat improvement conducted during the summer of 1997 (Lee and Lovell 1998). Approximately 800 m of new channel was excavated into 2 meanders to relocate the existing channel through regrowth woodland. Channels were excavated to specific cross-sections to create a natural pool–riffle sequence, and gravel, boulders, and woody debris were added to the streambed. Stream banks were stabilized with biodegradable Bonterra® erosion control blankets that were seeded with a mixture of native grasses and forbs. Common buttonbush (*Cephalanthus occidentalis*) and dogwood (*Cornus* spp.) also were planted along the banks. A sediment retention basin (18 m L × 5 m W × 2 m D) was excavated upstream of the relocated channels and downstream of a designated reference reach. The sediment trap was dredged annually and expanded in 2001.

Three reaches (2 restored and 1 unrestored) were designated for study after construction was completed (Fig. 1). The restored reaches, R1 and R2, each were ~400 m long and characterized by meandering channels, gravel and cobble substrate, abundant large woody debris, and a moderate canopy. Habitat improvements were applied only to the restored reaches. Water flow into the restored reaches was initiated on 26 September 1997. The unrestored reach, U, was located upstream of the restored reaches and all improvements, including the sediment trap. The unrestored reach was ~100 m long and was characterized by straight runs, sand and silt substrate, dense overhanging canopy, and some undercut banks. A suitable reference stream within the same drainage did not exist for the Juday Creek restoration because similar groundwater-fed streams are rare and agricultural land use has degraded these streams for over a century. Thus, an upstream unrestored site in Juday Creek was selected for our reference site, and responses were evaluated before and after the restoration. However, the unrestored site represented the degraded condition from which the restored reaches were expected to deviate.

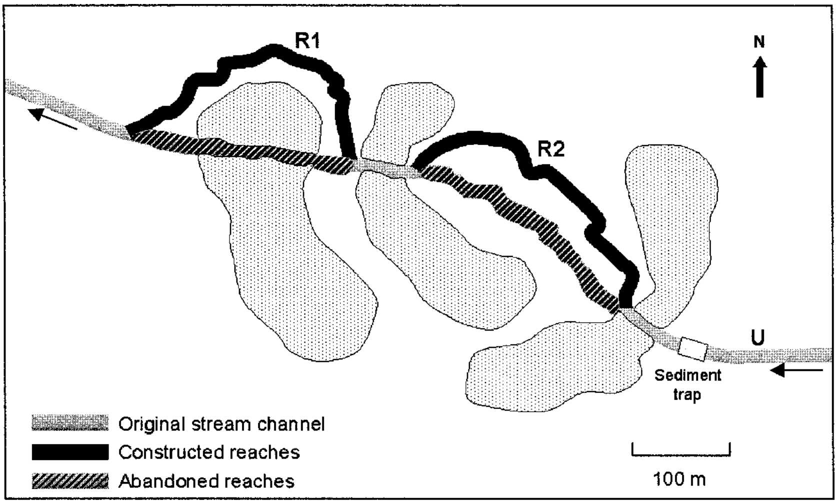

FIG. 1. Juday Creek, Indiana, USA. R1 = downstream restored reach, R2 = upstream restored reach, U = unrestored reach. Stippling represents golf course fairways. Arrows indicate direction of stream flow.

Methods

The effects of stream restoration on the habitat and biota of Juday Creek were evaluated by measuring selected physical and biological parameters of the restored stream reaches and comparing them to reach U over time. Responses were measured in stream habitat and 3 basic biological units: periphyton (abundance), macroinvertebrates (density and diversity), and fishes (catch per unit effort [CPUE] and biomass). Variables were measured both before and after restoration in reach U, but only after in the restored reaches because they did not exist prior to restoration.

Habitat characterization

Habitat surveys of Juday Creek were conducted 1 mo before restoration (1997) and each year after restoration for 5 y (1998–2002). All surveys were conducted at base flow by teams of 2 to 3 researchers. Study reaches were divided into stream units (riffle, run, or pool) based on standard criteria (Bisson and Montgomery 1996). The length, width, and depth of each unit were measured. Each reach was scored for habitat quality using the Qualitative Habitat Evaluation Index (QHEI, Rankin 1989) from 1998 to 2002. The overall QHEI is calculated from 6 component scores that assess the quality of substrate, instream cover, channel morphology, banks and riparian zone, pools and glides, and riffles and runs. Overall QHEI scores >60 suggest high habitat quality, whereas scores <45 suggest poor habitat quality. Percent canopy was measured at 3 to 6 sites per reach using a concave spherical densiometer (Murphy et al. 1981). The volume of large woody debris (LWD) was determined by measuring the length and diameter of wood pieces >1 m in length and 10 cm in diameter over the entire study reach. The volume of logs and rootwads was quantified using calculations for a cylinder and cone, respectively. Substrate composition was measured by taking 3 cores (10 cm deep, 5 cm diameter) per reach. Substrate cores were wet- and dry-sieved into 12 size fractions, dried at 60°C, weighed, ashed at 550°C, and weighed to calculate dry mass and ash-free dry mass. Percent fine sediments was calculated as: (mass of sediment <2 mm in diameter)/(total mass of the sample) × 100.

Periphyton

Periphyton was sampled 2 wk after restoration (1997) and on at least 2 dates annually from 1998 to 2001. From each reach, 3 samples consisting of 3 gravel pieces each were placed in Whirl-pak® bags, placed on ice in a cooler, and transported to the laboratory. In the laboratory, periphyton was removed from gravel by brush-

TABLE 1. Habitat characteristics of restored reaches in Juday Creek. Pool–riffle length ratios were calculated for the entire study reach. 1997 = before restoration, 1998–2002 = after restoration. LWD = large woody debris, QHEI = Qualitative Habitat Evaluation Index, R1 = downstream restored reach, R2 = upstream restored reach, U = unrestored reach, — = not measured.

	QHEI			Volume of LWD (m^3/m stream length)			% canopy			Combined pool–riffle ratio (m : m)
	R1	R2	U	R1	R2	U	R1	R2	U	
1997	—	—	—	—	—	0.002	—	—	—	1:13
1998	67.5	71.0	—	0.036	0.053	0.006	23	27	57	1:2.5
1999	71.5	59.5	46.0	0.067	0.054	0.007	34	25	63	1:2.8
2000	69.0	64.0	44.0	0.026	0.030	0.016	58	54	77	1:1.5
2001	66.5	63.0	46.0	0.026	0.027	0.014	62	63	86	1:1.3
2002	69.5	62.5	44.5	0.021	0.027	0.017	67	53	75	1:1.6

ing each piece vigorously, and the algal slurry was filtered onto 47-mm Gelman glass fiber filters. Chlorophyll *a* (chl *a*) was extracted from the filters at 4°C in 90% buffered acetone for 24 h and then measured using the spectrophotometric method (Steinman and Lamberti 1996).

Macroinvertebrates

Benthic macroinvertebrates were sampled using a modified Hess sampler (area = 0.09 m^2) with a 300-μm mesh (Waters and Knapp 1961). Three replicate samples were taken seasonally from each reach. The contents of each Hess sample either were live-picked in the laboratory or were preserved in the field and later sorted using sugar flotation (Anderson 1959). All samples were preserved in 70% ethanol. Invertebrates were counted and identified to genus when possible, with the exception of Diptera, which were identified to family. Macroinvertebrate diversity was calculated using the Shannon–Weiner index (Molles 1999).

Fishes

Fishes were sampled by backpack electrofishing 2 mo before restoration (1997) and every June after restoration from 1998 to 2002. A Smith–Root Model 12 POW backpack electrofishing unit was used to sample a stream length of 60 m chosen to be representative of each study reach. Block nets (mesh size 5 mm) were set at the upstream and downstream ends of the sampling reach. Three sequential passes were made through each reach to deplete the reach of fish. Fishes were identified, weighed, and measured, and then returned to the sampled reach. CPUE was calculated as the sum of all fish captured in 3 passes of equal duration.

Statistical analyses

A repeated measures ANOVA was run on fine sediment, periphyton, and macroinvertebrate data using the PROC MIXED statement with reach and time as the fixed effects (SAS 8.02, SAS Institute, Inc., Cary, North Carolina). The LS MEANS statement was used to obtain the simple effects of reach at each time if a significant reach × time interaction was found. PROC MULTTEST was used to run a Bonferroni test to obtain adjusted α-values to control cumulative Type I error. Non-normally distributed data were log-transformed to meet the assumptions of parametric statistics.

Results

Habitat characterization

Habitat quality in reach U was consistently low, with QHEI scores ranging from 44.0 to 46.0 over the study period (Table 1). Habitat quality scores in reaches R1 and R2 ranged from 59.5 to 71.5 and exceeded those for U throughout the 5-y study. However, QHEI scores for both R1 and R2 appeared to decline over the study. The volume of LWD was consistently lower in U than in R1 and R2. LWD volume increased over time in U, suggesting that wood was recruited to that reach, but not to R1 or R2 (Table 1). Percent canopy cover in U was variable, ranging from 57 to 86% over time (Table 1). Percent can-

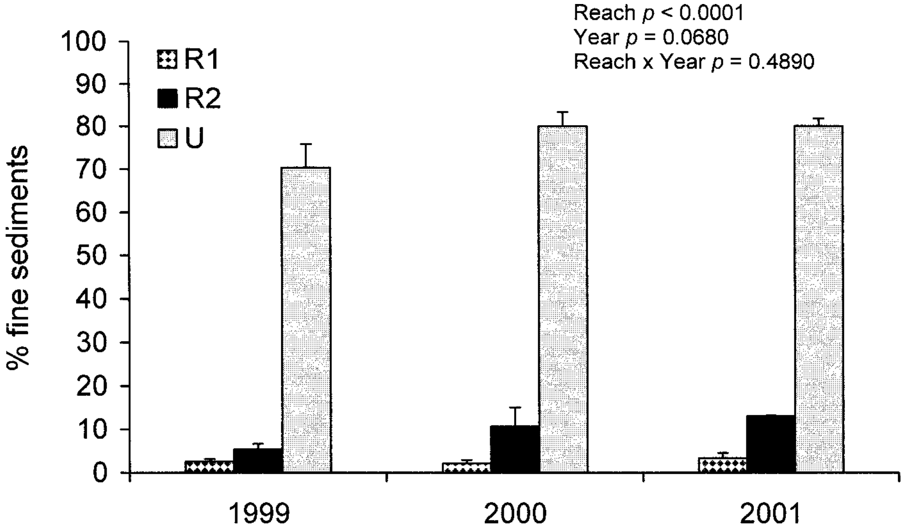

FIG. 2. Mean (+ SE) % fine sediments (<2 mm diameter) in cores from restored (R1, R2) and unrestored (U) reaches of Juday Creek. Data shown are from October sediment cores in each year. ANOVA results appear at the top of the figure.

opy cover in R1 and R2 was <30% immediately after restoration, but canopy values increased to ~60% over time. However, canopy cover remained higher in U than in R1 or R2. Pool–riffle length ratios for the entire study reach (R1, R2, and U combined) increased from 1:13 prior to restoration to 1:2.5 at 1 y after restoration (Table 1). Pool–riffle ratios remained high (1:1.6) 5 y after restoration.

Substrate composition in U was dominated by fine sediments, with >70% of the sediments comprised of fines each year (Fig. 2). In contrast, substrate composition in R1 and R2 was dominated by gravel, and fines remained below 15%. Over time, fines in R1 remained at 2 to 3%, whereas fines in R2 increased to 15%, but the restored reaches did not differ significantly on any sampling date (1999: $p = 0.48$; 2000: $p = 0.14$; 2001: $p = 0.08$).

Periphyton

Two weeks after restoration, chl *a* levels in R1 and R2 were similar to U, with mean concentrations of ~1.5 μg/cm^2 (Fig. 3). One year after restoration, chlorophyll *a* remained similar among reaches but, by 2 y after restoration, R1 and R2 levels were higher than in U. Three years after restoration, mean chl *a* concentrations in R1 and R2 exceeded 5 μg/cm^2. Chlorophyll *a* levels tended to be lowest in mid-summer of each year.

Macroinvertebrates

Before restoration of Juday Creek, mean macroinvertebrate density in U was 907/m^2 (Fig. 4A). Two weeks after water first entered, macroinvertebrate density in R2 ($\bar{x}$ = 2726/m^2) was significantly higher than in U ($\bar{x}$ = 500/m^2) ($p = 0.01$), but densities in R1 ($\bar{x}$ = 1151/m^2) did not differ significantly from U ($p = 0.34$). Four months after restoration, mean densities in R1 and R2 exceeded 10,000/m^2 compared with ~4000/m^2 in U. In 1999 to 2000, macroinvertebrate densities converged in the 3 reaches, but R1 and R2 again diverged from U in 2001 to 2002. Over the entire study, densities varied widely in R1 (range: 582–15,322/m^2) and R2 (1483–10,759/m^2), but generally were lower and less variable in U (430–4044/m^2).

Two weeks after restoration, macroinvertebrate diversity was significantly lower in R1 and R2 than in U (Fig. 4B). However, 4 mo after restoration, macroinvertebrate diversity in R1 and R2 did not differ significantly from diversity in U. Over the entire study, few differences in macroinvertebrate diversity between reaches were found. However, a general trend towards in-

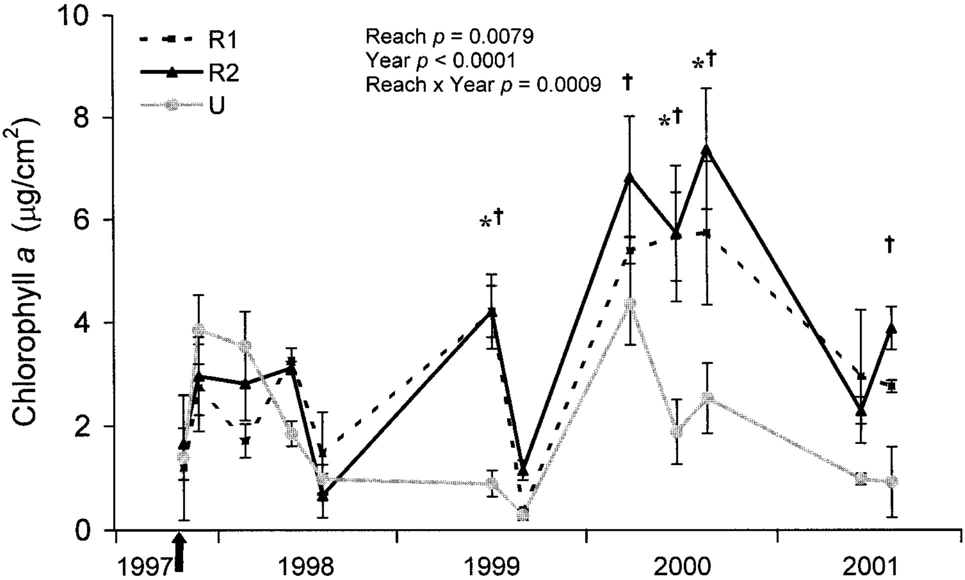

FIG. 3. Mean (± SE) algal abundance, measured as chlorophyll *a*, on gravel substrates in restored (R1, R2) and unrestored (U) reaches of Juday Creek. Arrow represents the date the restoration was completed. * = significant difference between R1 and U, † = significant difference between R2 and U ($p < 0.05$). ANOVA results appear at the top of the figure.

creasing diversity was noted in all reaches over the 5-y study period.

Fishes

Nine months after restoration (June 1998), fish CPUE in R1 and R2 had already reached levels similar to U (Fig. 5A). However, 3 to 5 y after restoration, CPUE in U was higher than in R1 and R2. Five years after restoration (2002), fish CPUE for all reaches was higher than in previous years. Also, a general pattern of increasing CPUE was found across all reaches over time.

Before restoration, fish biomass in the unrestored reach was 689 g/100 m^2 and remained fairly stable over time (range: 384–1052 g/100 m^2) (Fig. 5B). Nine months after restoration, fish biomass in R1 already surpassed levels in R2 and U, and peaked 2 y after restoration with a subsequent decline. Fish biomass in R2 remained low throughout the study. Five years after restoration, fish biomass in all 3 reaches converged to similar levels (543–763 g/100 m^2).

Recovery

Recovery of periphyton abundance, macroinvertebrate diversity, and fish biomass were assessed by comparing biological metrics in the restored reaches to those in the degraded, unrestored reach (Fig. 6). Fourteen days after restoration (1997), periphyton in R2 had recovered to 98% of the level in reach U and R1 had recovered to 78% of U. One year after restoration, both R1 and R2 had recovered to >100% of levels in U and continued to increase over the study period. At 14 d, macroinvertebrate diversity in R1 and R2 recovered to 38% and 29%, respectively, of the diversity in U. About 1 y after restoration, diversity in R2 had recovered to 100%, whereas R1 remained below 75%. From 2 to 5 y after restoration, macroinvertebrate diversity in R1 and R2 remained around 100% of levels in U. One year after restoration, fish biomass in R1 had reached 191% recovery, whereas biomass in R2 was 39%. Recovery of fish biomass in R1 peaked 2 y after restoration and then declined to 80% by 5 y after restoration. In contrast, fish biomass in R2 remained low throughout the study period, and only peaked to 71% of reach U 5 y after restoration.

Discussion

Stream recovery following restoration

Many studies have been done to evaluate stream recovery from various anthropogenic

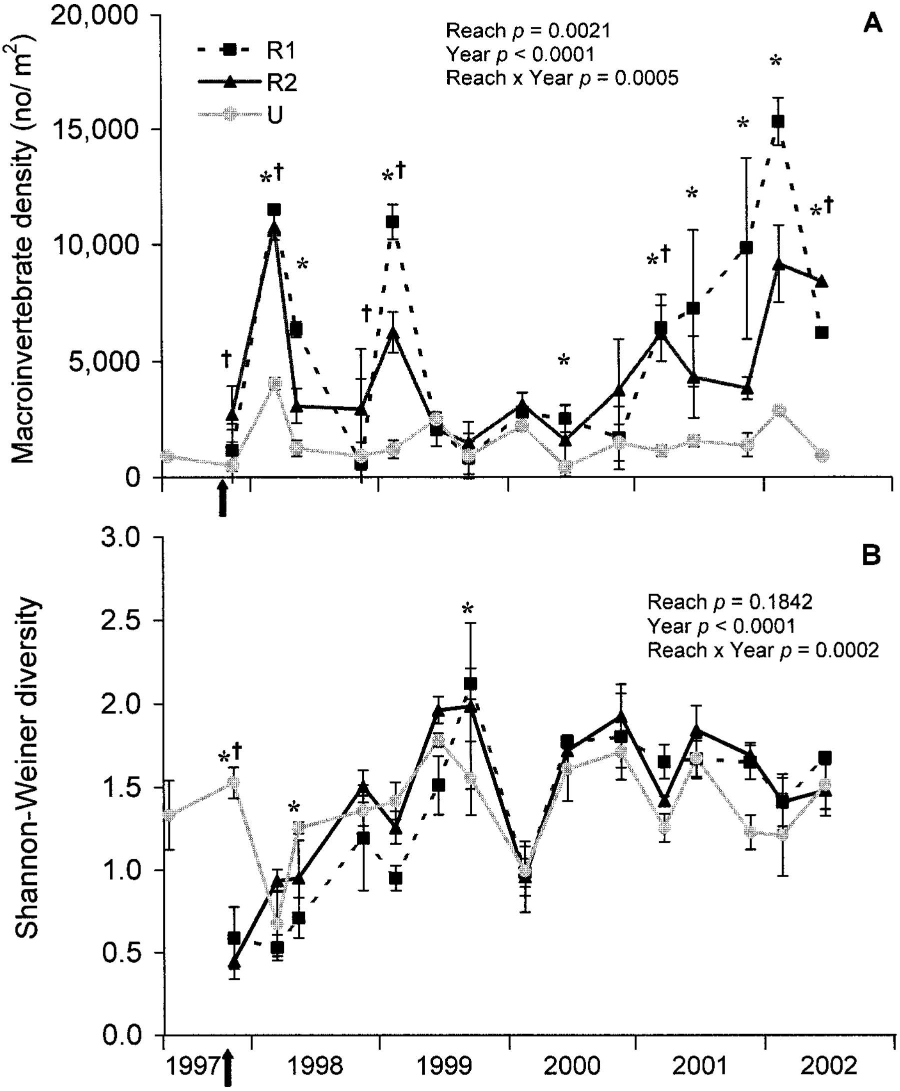

FIG. 4. Mean (± SE) macroinvertebrate density (A) and diversity (B) in restored (R1, R2) and unrestored (U) reaches of Juday Creek. Arrow represents the date the restoration was completed. * = significant difference between R1 and U, † = significant difference between R2 and U ($p < 0.05$). ANOVA results appear at the top of panels A and B.

disturbances (see review by Niemi et al. 1990), but studies of stream recovery after large-scale restoration attempts are rare or unreported (but see Gore 1979, 1982). In our study of Juday Creek, recovery was defined as the convergence with or exceedence of the reference condition, which was an unrestored, degraded portion of the same stream. Several biological parameters were predicted to improve relative to reference levels in response to improved habitat, ongoing succession, and a presumed increase in resources in the restored reaches. Chlorophyll *a,* macroinvertebrate density, and fish biomass (in R1) recovered to over 200% of the unrestored reach, but macroinvertebrate diversity, fish CPUE, and fish biomass (in R2) did not recover to levels greater than in U. Fish species diversity also recovered to unrestored levels rapidly, but did not exceed richness in U (Moerke and Lamberti 2003). In addition, rates of recovery varied

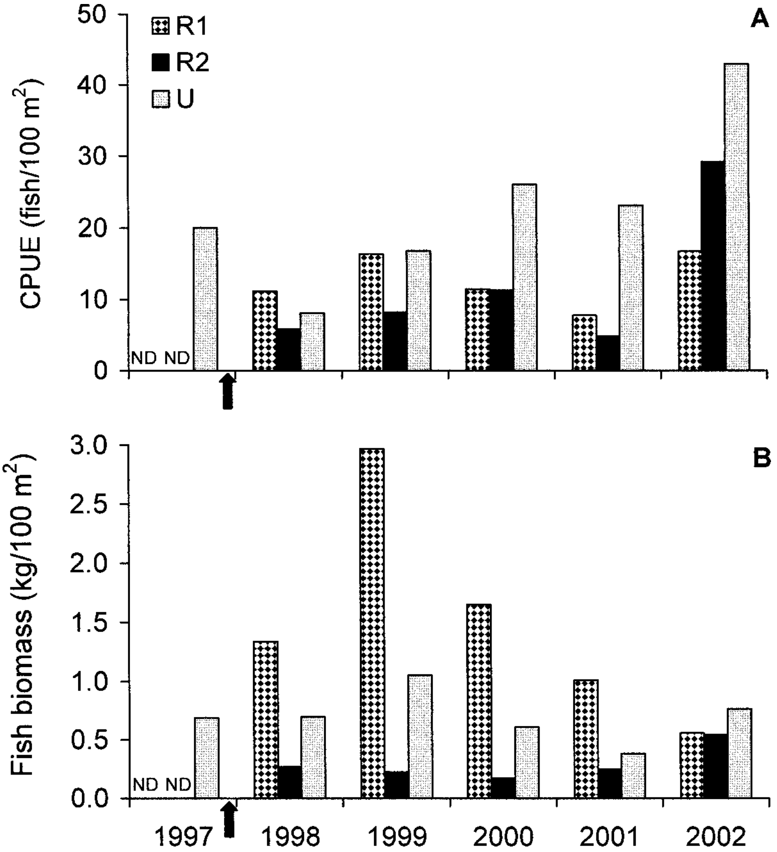

FIG. 5. Fish catch per unit effort (CPUE) (A) and biomass (B) of restored (R1, R2) and unrestored (U) reaches of Juday Creek. Arrow represents the date that the restoration was completed. ND = no data.

across taxa (i.e., periphyton, macroinvertebrates, and fishes) and recovery endpoints (i.e., density, diversity, and biomass).

Periphyton abundance recovered to unrestored levels within 14 d after restoration. Few studies have examined algal recovery rates, but an overview by Niemi et al. (1990) found that recovery of periphyton biomass after natural disturbances ranged from 7 to 153 d, with a median recovery time of 36 d. The restored reaches were newly constructed channels, so remnant algal cells or microbial colonies were absent. However, intact degraded stream reaches immediately upstream of the restored reaches likely served as a source of algal colonizers and enabled rapid recovery.

Macroinvertebrates in Juday Creek recovered rapidly compared to other studies. Macroinvertebrate densities in R1 and R2 recovered to densities in U within 14 d, whereas macroinvertebrate diversity recovered by ~120 d after restoration. Other recolonization studies of denuded or enhanced stream reaches have found that macroinvertebrates required 70 to 150 d to reach maximum densities (Cairns et al. 1971, Williams and Hynes 1977, Gore 1979), and >250 d for the development of stable communities (Gore 1982). Macroinvertebrate abundance and diversity in a 1.3-km re-engineered reach in a Danish stream required 2 y to recover to unrestored levels (Friberg et al. 1994). These authors suggested that recovery was not limited by colonization, but that erosion of the new channels degraded the new habitat and slowed recovery. The time at which a disturbance or restoration takes place also may affect the rate of biotic recovery (Gore 1985, Niemi et al. 1990). For example, macroinvertebrates may colonize reaches at different rates, depending on season. Macroinvertebrate colonization of new reaches occurs by drift, ae-

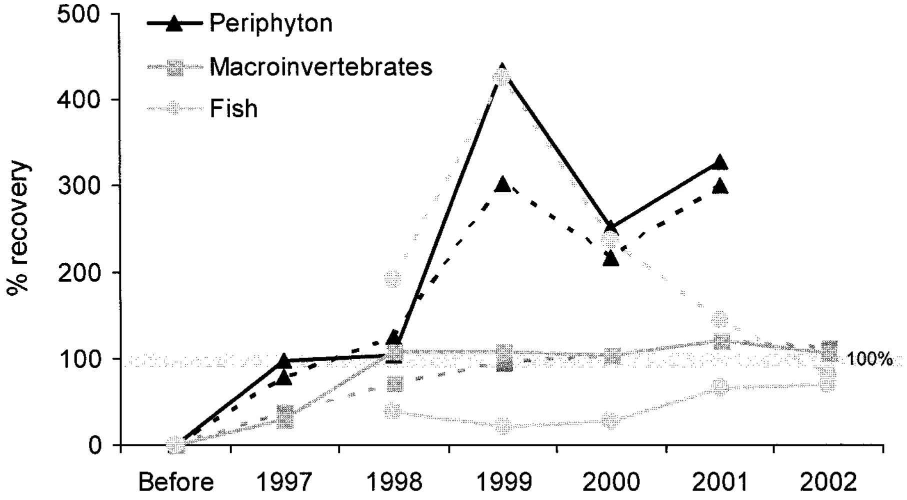

FIG. 6. Percent recovery (restored/unrestored x 100) of periphyton abundance (chlorophyll *a*), macroinvertebrate diversity, and fish biomass in restored reaches (R1 and R2) compared to the unrestored reach. Data shown are mean values for each year, except for 1997 when values are for 14 d after restoration. Before = 0 for all taxa because the restored reaches were newly constructed. R1 = dashed lines, R2 = solid lines.

rial sources, hyporheic sources, and upstream migration (Williams and Hynes 1977, Mackay 1992). Aerial colonization and drift from upstream in Juday Creek likely were the most important modes of colonization by macroinvertebrates because the restoration was completed in early autumn, a time of active drift and oviposition by aerial adults (Gore 1985).

Fish CPUE and biomass in R1 recovered by 9 mo after restoration. Surprisingly, CPUE and biomass in R2 did not recover to unrestored levels during our 5 y of study. Jungwirth et al. (1995) found that total fish density and biomass exceeded unrestored levels 1 y after restoration of a channelized stream in Austria. Studies of recovery of fish communities after natural disturbances (e.g., floods or droughts) suggest that fish recovery is relatively rapid (e.g., <2 wk) (e.g., Bayley and Osborne 1993), although these communities most likely are adapted to temporary disturbances associated with hydrologically variable systems. Juday Creek is a hydrologically stable (i.e., groundwater-fed) stream, so fishes in Juday Creek are likely less exposed to frequent disturbance. However, fish catch may have recovered sooner than 9 mo, but our sampling intervals did not detect it. Fish in Juday Creek were counted by snorkeling 18 d after restoration and fish had colonized R1 and R2, but abundance in U was 5× greater than in R1 and R2 (AHM, unpublished data). R1 and R2 had upstream and downstream sources of colonists and no barriers to colonization existed, so habitat quality may have played a major role in the different recovery trajectories of fish metrics.

Biological responses to new habitat

People restoring streams often assume that biota are habitat-limited and that "if you build it, they will come" (i.e., Field of Dreams Hypothesis, Palmer et al. 1997). Habitat quality and heterogeneity (e.g., QHEI scores, substrate composition) in Juday Creek exceeded unrestored levels immediately after restoration and, although habitat quality appeared to decline over the study period, it remained above degraded (unrestored) levels. However, responses to the new habitat varied among taxa and endpoints measured. Substrate in R1 and R2 was composed of diverse size classes (sand, gravel, cobble, and boulders), but macroinvertebrate diversity in R1 and R2 did not differ from the sand-dominated U reach. However, macroinvertebrate densities in R1 and R2 appeared to respond positively to the increased habitat heterogeneity. In contrast, Brooks et al. (2002) manipulated substrate composition and found no difference in macroinvertebrate abundances on highly heterogeneous substrates compared to homogenous substrates. Past studies suggest that the highest diversity and density of macroinvertebrates are found in habitats with cobble and gravel substrates (e.g., Hynes 1970, Hart 1978). Findings from the Juday Creek restoration suggest that increases in habitat heterogeneity and large, stable substrates may lead to increased macroinvertebrate densities, but not to increased diversity when compared to more homogeneous, sand-bed reaches. However, previous studies on Juday Creek suggest that diversity is a poor indicator of recovery when compared to density and secondary production (Kohlhepp 1991). Thus, genus-based diversity should be used with caution because it may be unable to detect species losses and important changes in species composition.

Fishes in R1 and R2 appeared to track changes in habitat quality and availability. Higher total fish biomass in R1 than in R2 indicated that R1 supported larger, adult fishes. In contrast, R2 showed no positive responses to the increased habitat quality, and fish biomass levels were lower than in degraded reach U. However, fish habitat is composed of feeding, resting, and spawning areas, which are determined by the combined effects of depth, current velocity, substrate particle size, cover, and temperature (Rabeni and Jacobson 1993). Habitat quality was similar in R1 and R2, based on qualitative indices, but pool habitat was less available in R2 than R1, which suggests that differences in total fish biomass in the restored reaches of Juday Creek are related to differences in adequate pool habitat (Moerke and Lamberti 2003). Other studies have found that fish density and biomass increased with habitat complexity and heterogeneity (e.g., Angermeier and Karr 1984, Jungwirth et al. 1995). However, findings from our study suggest that increased habitat quality may not always lead to increases in fish biomass and density if life-stage habitat needs (e.g., deep-water habitat for large fishes) are not met by the restoration.

Increased sedimentation, particularly in R2, likely led to changes in habitat, including a decrease in pool habitat. Although a sediment trap was constructed upstream of R1 and R2, it initially was constructed too small to retain fine sediments effectively. The sediment trap was enlarged 3 y after restoration and is now functioning properly (KJG, unpublished data). Reduced sediment loads, either by maintenance of the sediment trap or through watershed restoration efforts, may be critical for the long-term success of the Juday Creek restoration.

Restoration assessments

Most assessments of stream restoration or enhancement projects are short-term (<1 y), focus on a single taxon (e.g., salmon in the Pacific Northwest), and go unreported in the peer-reviewed literature. The Juday Creek restoration is an exception. Our study demonstrates the need to assess a suite of parameters, in the context of habitat changes, for a thorough understanding of stream responses to restoration. Minns et al. (1996) recommended that functional (i.e., process) measures be incorporated into restoration assessments. Although we did not measure ecosystem function directly, the many structural measures we provided likely serve as surrogate measures of function. However, future scientific evaluations that incorporate both structural and functional metrics may help to identify the least spatially and temporally variable metrics for future assessments of stream restorations.

Stream restorations are becoming more common, yet scientists have neither recognized nor taken advantage of these opportunities to strengthen both ecological theory and the foundation of stream restoration and management. Understanding of ecological concepts, such as succession, disturbance, resistance, and resilience (Connell and Sousa 1983), may improve after being tested in a large-scale restoration context. In addition, the science of restoration ecology and ecosystem management (e.g., identifying effective restoration techniques) will be advanced by improving our understanding of the structure and function of natural communities. Ultimately, the exchange of information between these two research areas, and the use of restorations as scientific opportunities, will benefit both ecologists and resource managers.

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