American Fisheries Society Symposium 34:149–162, 2003

Experimental Enrichment of Two Oligotrophic Rivers in South Coastal British Columbia

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Abstract.—Big Silver Creek and the Adam River are oligotrophic (conductivity < 45 μΩ/cm; TDP < 2–5 μg/L; NO_{2+3}-N < 45 μg/L), mid-sized coastal rivers in southwestern British Columbia. They were treated with inorganic P (phosphorus) and N (nitrogen) to examine the feasibility of low-level inorganic fertilization as a method of increasing resident fish populations in rivers subject to habitat loss by historical logging practices. Both rivers have low numbers and sizes of resident salmonids (<20/ha, >20 cm fork length), despite extensive suitable habitat. Water temperatures in summer average 12°C and 14°C with summer discharge averaging 12 and 4 m^3/s in Big Silver Creek and the Adam River, respectively. In 1992–1997, physical, chemical, and biological assessments took place from May to September in three reaches of each river. Liquid agricultural fertilizer was added to the lower reach(es) of each river from June to September of 1994–1997, while upstream reaches were monitored as controls. Fertilizer addition methods evolved from dripping through a hose and valve system, to a more dependable preprogrammable injection system, with the merits of each system discussed. In each river, chlorophyll-*a* accrual and benthic invertebrate biomass and density increased, on average, two to four-fold in the fertilized reaches. There was an average four-fold increase in rainbow trout abundance in each river following four summers of fertilization, with a large increase in mountain whitefish *Prosopium williamsoni* (Big Silver Creek) and a smaller increase in brown trout *Salmo trutta* (Adam River). The experimental treatments confirmed that low-level fertilization augmented productivity, resulting in a significant response of resident trout in two oligotrophic streams. The technique can be applied to aquatic systems with reduced fish populations resulting from habitat loss, overfishing, or to anadromous populations caught in the negative feedback loop of decreasing escapement and associated losses of marine-derived nutrients.

Introduction

Coastal drainages in the Pacific Northwest (PNW) are dominated by nutrient-poor, oligotrophic waters (Northcote and Larkin 1966) resulting from a combination of erosion-resistant granitic bedrock overlaid by shallow soils and high rainfall (Stockner 1981, 1987; Cannings and Cannings 1996). These streams have some of the lowest nutrient and net production values ever recorded (Stockner and Shortreed 1976). Gross et al. (1988) suggest that diadromous migrations of Pacific salmon evolved to take advantage of the productivity differential between the oligotrophic freshwater environment and the more productive marine environment.

A combination of environmental factors limit the growth and abundance of salmonids in streams, including physical habitat limitations (Ward and Slaney 1979, 1981), water temperature regimes (Holtby and Hartman 1982; Egglishaw and Shackley 1985), winter freshets, droughts, and poor egg survival resulting from sedimentation or bedload movement (Parkinson and Slaney 1975), or instream food supply (Egglishaw 1968). Food availability directly impacts territory size and, thus, abundance, growth, carrying capacity, and production of juvenile fish per unit of stream area (Slaney and Northcote 1974; Grant et al. 1998).

Primary production forms the basis of the food chain in large streams (Minshall 1978), and the addition of inorganic nutrients to oligotrophic streams has been shown to increase periphytic production (Stockner and Shortreed 1978; Peterson et al. 1985; Perrin et al. 1987) and thereby insect growth and abundance (Milbrink and Holmgren 1981; Peterson et al. 1985; John-ston et al. 1990; Mundie et al. 1991; Peterson et al. 1993) and the growth of steelhead trout *Oncorhynchus mykiss*, coho salmon *O. kisutch* (Slaney et al. 1986; Johnston et al. 1990), and Arctic grayling *Thymallus arcticus* (Deegan and Peterson 1992) in smaller streams. Additionally, small increases in juvenile and smolt size often result in significant increases in overwinter and ocean survival in anadromous species (Ward et al. 1989). Thus, controlled addition of limiting nutrients during the optimal growth period in oligotrophic rivers should result in increased growth, abundance, and production of fish per unit area. Fertilization could be a useful management tool to compensate for habitat loss from historical logging practices that significantly degraded instream fish habitat and to compensate for interruption in the nutrient cycle of PNW watersheds resulting from declines in anadromous fish returns (Stockner 1987; Kline et al. 1993).

Methods of nutrient addition to streams have evolved since Huntsman (1948) placed bags of fertilizer streamside or since Mason (1976) hand-fed coho in stream with marine euphausiids. Stockner and Shortreed (1978) demonstrated the significant nutrient limitation of autotrophy in a PNW ecosystem using concentrated solutions of $NaNO_3$ as a nitrogen (N) source and Na_2HPO_4 for phosphorus (P). Experimental instream fertilization experiments began in earnest in 1981 when organic (barley) and inorganic (dry agricultural) fertilizers were added to different reaches of the oligotrophic Keogh River (Vancouver Island); the latter increased autotrophic periphyton production an order of magnitude (Perrin et al. 1987). Other inorganic nutrient sources used include a slow-release fertilizer added to the Keogh River (Johnston et al. 1990) and liquid phosphoric acid added to the Kuparuk River, Alaska (Peterson et al. 1985). Liquid agricultural fertilizer, ammonium poly-phosphate (10–34–0; % by weight N-P_2O_5-K_2O), and ammonium nitrate (34–0–0), were tested in the early 1990s on the Salmon River, Vancouver Island (Slaney and Ward 1993), the benefits of which included low cost, availability, and safe handling (Ashley, this volume).

Nutrient stimulation of primary and secondary productivity has been demonstrated in smaller streams, but the effects of fertilization on productivity in larger rivers and associated resident salmonid populations remain uncertain. Dependable and cost-effective methods of nutrient addition are also required, if this restoration technique is to be extended to other/larger aquatic ecosystems. We examined the effects of low-level inorganic P and N additions, using liquid agricultural fertilizer in two medium-to-large coastal rivers (mean annual flow > 15 m^3/s) in southwest British Columbia, some of the largest streams yet fertilized. We assessed the effects on water chemistry, periphyton accrual, zoobenthos standing crop, and size and density of juvenile and adult fish, while developing and testing dependable liquid fertilizer application methods. A more detailed presentation of the following can be found in Wilson et al. (1999a, 1999b).

Methods

Study Area

The Adam River (50°40'W by 126°20'N) is located 12 km northwest of Sayward on Vancouver Island and originates from the Vancouver Island Mountain Range, flowing northwest for 50 km into Johnstone Straight (Figure 1). Waterfalls located at River km 4 (upstream from river mouth) are a barrier to fish migration. Watershed area and mean annual flow are 320 km^2 and 14–15 m^3/s, respectively, with summer water temperatures averaging 14°C. Wild rainbow *Oncorhynchus mykiss* and introduced brown trout *Salmo trutta* inhabit the river above the falls, with low densities of cutthroat trout *O. clarki*, and Dolly Varden *Salvelinus malma*. Most rainbow trout are small (<20 cm), with densities 10–20/ha (30–45/km) before fertilization. Densities of brown trout in the main stem ranged from less than 0.5 to 5/ha (1–14/km) prior to fertilization, with most of catchable size, but only a few (<1/ha, 1–2/km) more than 40 cm in length.

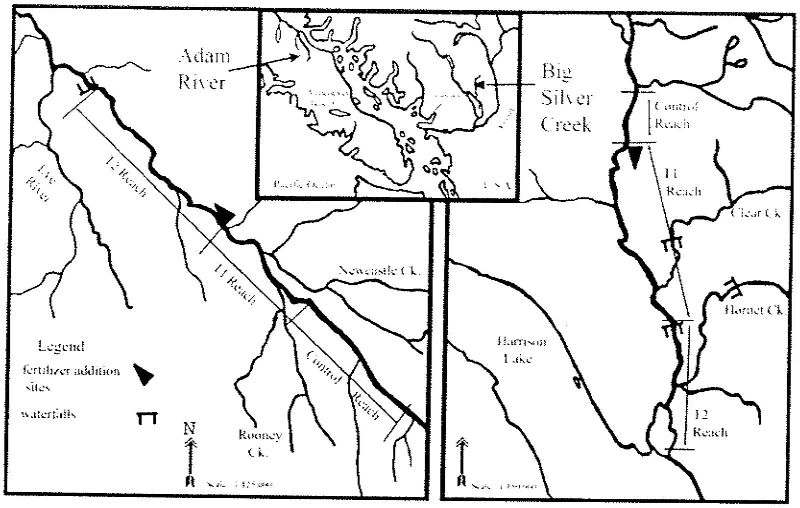

FIGURE 1. Study area showing the three experimental reaches in the Adam River and Big Silver Creek and points of fertilizer addition.

Big Silver Creek (49°40'W by 121°51'N), located 35 km north of Harrison Hot Springs, originates in the Lillooet Range of the Coast Mountains and flows west for 40 km into Harrison Lake (Figure 1). Waterfalls at River km 6 limit migrant fish, with the possible exception of a few summer run steelhead trout *O. mykiss*, to the lower river. Below the falls several anadromous species are found, in addition to fluvial or lacustrine-adfluvial populations of rainbow trout, cutthroat trout *O. clarki*, Dolly Varden *Salvelinus malma*, and mountain whitefish *Prosopium williamsoni*. Upstream of the km-6 barrier, rainbow trout are relatively abundant but depressed in size with a density of 10/ha (43/km) for fish less than 20 cm in length. No fish have been found upstream of River km 15, where steep canyons appear to limit fish distribution. Steelhead parr (<5 g mean size) have been stocked annually (4–12,000 per year) above the barrier at River km 6, since 1993 (except 1995), and all were clipped for differentiation from wild fish. Historical flow records are not available for Big Silver Creek, but spring flows during 1992–1993 averaged 50–60 m^3/s from May to June, then declined to summer lows of about 10 m^3/s in August and September, with water temperatures averaging 12°C during summer.

The predominant human activity in the watershed of both rivers, for the past 40 years, has been intensive logging. Little old growth remains on the lower slopes, but secondary growth is well established with riparian vegetation of western red cedar *Thuja plicata*, western hemlock *Tsuga heterophylla*, alder *Alnus rubra*, and Douglas fir *Pseudotsuga menziesii* along the Adam River and Douglas fir, western hemlock, maple, alder, and some cottonwood along Big Silver Creek.

Both rivers are extremely oligotrophic, with alkalinity less than 20 mg/L, conductivity less than 45 μΩ/cm (<20 μΩ/cm in Big Silver Creek), total reactive phosphorus (TRP) concentrations less than 1 mg/L, and total phosphorus (TP) less than 3–5 mg/L. Nitrogen concentrations are also low, with dissolved nitrate + nitrite-nitrogen (NO_{2+3}-N) levels typically dropping to 35–45 mg/L in Big Silver, and less than 15 mg/L in the Adam River during summer. The rivers contain good fish habitat with a positive riffle-to-pool ratio ranging from 3:1 to 1:1 in assessed sections, many large bedrock-controlled pools and runs, and substrate of gravel and cobble. The abundance of favorable fish habitat suggests that mean size and abundance of trout are limited by very low biological productivity rather than physical habitat.

Experimental Design and Data Analysis

The lower portion of each river was divided into three contiguous reaches, 3–8 km in length. Proceeding downstream, the reaches were designated as control reach, treatment 1 (T1) reach, and treatment 2 (T2) reach (Figure 1). In each reach, chemical and biological sampling took place during the growing seasons (May to September) of 1992–1993 for the prefertilization assessment, and in 1994–1997 during fertilization of the downstream reach(es). To test for significant effects, we used a BACI experimental design (Stewart-Oaten et al. 1986), which relies on a temporal series of data taken before and after (or during) a perturbation, simultaneously at both a control and impact site. Inferential statistics (*t*-tests) were applied to the difference in values from the control and impact sites, during the prefertilization and fertilization periods. Data were log-transformed to improve normality and homogeneity of variances. The additivity and independence assumptions were tested using the Tukey test for nonadditivity (Tukey 1949) and the von Neumann ratio test (Stewart-Oaten et al. 1986), respectively. Assumptions were met and variation given as ± SE of untransformed data, unless otherwise noted.

Nutrient additions were conducted during 1994–1997, when liquid agricultural grade ammonium polyphosphate (10–34–0; % by weight $N\text{-}P_2O_5\text{-}K_2O$) was added to each river between June and September. In Big Silver Creek, fertilizer was added at the junction of the control and T1 reaches (Figure 1). This allowed examination of the nutrient addition on both the isolated resident (T1 reach) and the lacustrine-adfluvial (T2 reach) salmonid populations, while ensuring a long fertilized section to determine effective distance. In the Adam River, fertilizer was added at the junction of the T1 and T2 reaches. In both rivers, addition rates were adjusted to increase concentrations of instream dissolved inorganic phosphorus by 5 μg/L P, at the point of addition. The nitrogen component of the ammonium polyphosphate added 3.5 μg/L N to the rivers at target phosphorus loadings. In the Adam River, additional nitrogen was added using liquid agricultural grade urea-ammonium nitrate (28–0–0; % by weight $N\text{-}P_2O_5\text{-}K_2O$) added at target concentrations of 5 μg/L N. In 1994, fertilizer was gravity fed into the river through a hose and valve systems with rates adjusted manually on each site visit, usually 10–14 d apart, to flow conditions in the stream at that time determined using stage-discharge relationships. Drip rates usually declined between site visits as changes in ambient temperatures caused viscosity changes in the fertilizer, sedimentation (crystallized fertilizer) tended to clog the valves, and tank head pressure declined. As a result, nutrient loading rates were usually below target concentrations. A similar system was in use on the Mesilinka River Fertilization Experiment, where nutrient loading rates were usually 40% below target concentrations (Larkin et al. 1999).

A battery-driven flow-proportional injection system was developed and installed during the 1995 field season, which automatically changed addition rates to match changes in river level (Ashley, this volume). The system generally functioned well, but the four 12-V deep-cycle batteries had to be changed every two weeks, and loading rates between site visits were not recorded. Nutrient loading rates recorded during site visits ranged between 4.8 and 8.5 μg/L P and 3.4–6.0 μg/L N to Big Silver Creek and averaged 4.6 μg/L P and 7.6 μg/L N to the Adam River. A preprogrammable injection system was developed for the 1997 field season, which was gravity fed, eliminating the need for the large batteries and contained other improvements to prevent clogging in the hoses (Larkin et al. 1997). It decreased fertilizer addition rates once per day to match the flow in the descending limb of a spring-summer hydrograph, which were found to follow exponential decay curves in snow and glacier-headed systems (Larkin et al. 1997). Loading rates measured on site visits averaged 5.1 μg/L P and 7.6 μg/L N to the Adam and 5.2 μg/L P and 3.6 μg/L N to the Big Silver. While loading rates were often below target concentrations, rates were almost always above the levels demonstrated, to saturate lotic diatoms at the cellular level and produce exponential growth at the community level (2 μg/L P; Bothwell 1988, 1989). Therefore, the four annual treatments are referred to as the 'fertilization period' with no distinction made between years.

Concurrent field testing of solid 'slow-release' fertilizer briquettes ($MgNH_4\text{-}PO_4\text{-}H_2O$; 7–40–0; % by weight $N\text{-}P_2O_5\text{-}K_2O$) for small stream restoration was conducted on the Adam River tributaries of the Rooney and Newcastle creeks and on the Big Silver tributary of Clear Creek (Figure 1), starting in 1994 (Ashley and Slaney 1997; Sterling et al. 2000).

Sampling Procedures

Water temperatures were recorded hourly in summer with Ryan RTM 200 temperature loggers installed in the T1 reach of the Adam River and the control reach of Big Silver Creek. Daily maximum, minimum, and average temperature readings were calculated based on hourly measurements. A stage–discharge relationship was developed for each river. Discharge was determined by dividing the streams into 1-m cross-sectional areas; the flow within each was determined, then summed for total flow. Water velocity was determined using a Marsh-McBirney (Frederick, Maryland) Model 201 electromagnetic velocity meter and stage by measuring the distance from a permanent mark on a logging bridge to the water surface. Mainline logging bridges at River km 14 and km 4 on the Adam River and Big Silver Creek, respectively, were used.

Water samples were collected at two week to monthly intervals and transported on ice within 24 h to Zenon Environmental Laboratories, Vancouver (1993–1995) or to the Pacific Environmental Science Center, North Vancouver, British Columbia (1996–1997). Samples were analyzed for TRP, TP, total dissolved phosphorus (TDP), NO_{2+3}-N, ammonia (NH_4^+ + NH_3-N), and total nitrogen (TN) using standard methods of analysis as described in APHA et al. (1992).

Periphyton biomass was estimated at 2–3 sites within each reach by extracting chlorophyll *a* on open-cell Styrofoam substrata. At each site, a pair of Styrofoam blocks (19 cm × 39 cm × 1.25 or 0.075 cm) were attached to concrete blocks and placed in the river, as described in Perrin et al. (1987). At approximately two-week intervals, duplicate core samples of Styrofoam substrata (5.7 cm^2) were extracted from each block. Cores were placed in an opaque desiccator until delivery to the laboratory, followed by extraction in 90% acetone and spectrophotometric determination of chlorophyll *a*. Styrofoam substrata were replaced after six weeks or three sampling periods. Thus, each replicated set of chlorophyll *a* determinations indicated periphyton biomass accumulation over fixed incubation periods referred to as early (late May to June) or middle (July to early August), with a late (August to September) incubation period in some years. The values from all sites within a reach were averaged to indicate periphyton biomass.

Benthic invertebrate populations were assessed using artificial substrate, by placing two groups of five gravel baskets in each reach. Each of the cylindrical baskets (22 cm in diameter, 13 cm in depth; 0.04 m^2 in area, and 0.005 m^3 in volume) was filled with 1–3 cm diameter clean gravel, placed in approximately 0.4 m of water with a velocity of 0.3–0.4 m/s, surrounded by cobbles, and left to colonize with invertebrates for six weeks. In the Adam River, baskets were placed for two six-week periods each summer, June–July and July–August, while in the Big Silver, they were placed for July–August. Baskets were removed using a Surber sampler (0.15-mm mesh net) with samples preserved in 80% alcohol. Invertebrates collected from each basket were stained with Rose Bengall, separated from detritus, and allowed to air dry for 2–3 min before the total wet-weight of invertebrates in each basket was determined. Four samples from each reach, in each year, were randomly chosen for taxonomic identification to at least the family level using McCafferty (1981), Stehr (1987), Pennak (1989), and Merritt and Cummins (1996). Periphyton plates and invertebrate baskets were moved as river levels changed, to maintain constant physical conditions, but invertebrate baskets remained undisturbed for a minimum of two weeks prior to removal.

Underwater fish counts were conducted annually in both rivers to estimate the abundance and size distribution of fish. Groups of 3–4 snorkelers swam the rivers when temperatures were 12–14°C (typically 1100–1600 hours) and visibility was 3–6 m (determined with Secchi disk between swimmers). Fish were counted using standardized methods described in Gardiner (1984) and Slaney and Martin (1987). Counts in each lane were expanded to cover the wetted width determined for each reach. The methodologies for swims remained standard, but swim dates and portions of each reach enumerated varied slightly, and only swims conducted under moderate summer flows (4–8 and 7–17 m^3/s in Adam River and Big Silver Creek, respectively) were included in the analysis. Counts were conducted in early September of 1993–1997 on Big Silver Creek and in June of 1993 and 1994, July of 1995, and September of 1996 and 1997 on the Adam River. In Big Silver Creek, fish less than 20 cm in length were excluded to avoid confusion with the stocked steelhead.

Sampling of juvenile fish for size-at-age data were conducted between 17 September and 5 October in 1992–1996 from each reach of the Adam River and on 26 August, 10 September, 23 September, 2 November, and 2 October of 1993–1997, respectively, from Big Silver Creek (except no T2 reach sampling). Samples were captured with a Smith Root Type VII backpack electrofisher from established sites along the shorelines and out to a depth of approximately 1 m. In the Adam River, rainbow and cutthroat trout were grouped (most were rainbow) to avoid confusion due to their similar appearance and possible hybridization. In Big Silver Creek, only wild (unclipped) rainbow were included. All fish captured were anesthetized, measured to the nearest millimeter, and weighed to the nearest 0.1 g on an electronic balance, with scale samples taken, processed, and read, as described in Ward and Slaney (1988). Captured fish were then revived with song and released.

Results

Physicochemical

Adam River flows typically declined from a May/June average of 12 m^3/s, to summer lows averaging 4 m^3/s in July to September (Figure 2). Lowest flows were recorded in 1996, and highest in 1997, with July to September averages of 1.5 and 6 m^3/s, respectively. Spring flows in Big Silver Creek were relatively high, averaging 55 m^3/s in May/June, declining to summer lows averaging 12 m^3/s from August to September (Figure 2). At Big Silver Creek, lowest flows were recorded in 1994 and highest in 1996, with August to September averages of 10 and 16 m^3/s, respectively. Wetted widths in the study reaches measured during the September snorkel surveys averaged 22 m and 33 m in the Adam River and Big Silver Creek, respectively.

Adam River water temperatures ranged from 7°C to 23°C during summer (June to September), averaged 14°C, and were usually more than 10°C from July to mid-September (Figure 2). Average summer temperatures ranged from 16°C in 1993 to 13°C in 1995. Big Silver Creek temperatures were slightly lower, ranging from 7°C to 17°C during summer, averaged 12°C, and were usually more than 8°C from July to September. Summer averages ranged from 13°C in 1994 to 11°C in 1996.

Both rivers showed no elevated nutrient concentrations downstream of the fertilizer inputs, indicating complete uptake by primary producers. Nitrogen and phosphorus co-limitation of attached algae was suggested in the fertilized reaches of both rivers during 1995–1997, when NO_{2+3}-N concentrations in Big Silver Creek decreased to 15 µg/L in July, and in the Adam River, concentrations usually decreased to detection limit levels of 5 µg/L during June, despite the addition of 3–8 µg/L N with the fertilizer (Figure 3).

Periphyton

Periphyton biomass in the Adam River was similar in all unfertilized sections, with maximum chlorophyll *a* concentrations averaging 12 mg/m^2 and ranging from 3 to 22 mg/m^2 (Figure 4A). Values peaked in July or early August, just before maximum temperatures and a month before low flows. Unfertilized chlorophyll *a* biomass was slightly lower in Big Silver Creek, averaging 8 mg/m^2 with a peak of 15 mg/m^2 in the T1 reach in 1993 (Figure 4B). Concentrations peaked between August and September, during low flows but after peak temperatures. There was no significant difference (t-test, $p > 0.1$) in maximum values between incubation periods in either river prior to fertilization. Values were within the range reported for streams at this latitude in the PNW (Stockner and Shortreed 1976, 1978; Perrin et al. 1987; Slaney and Ward 1993).

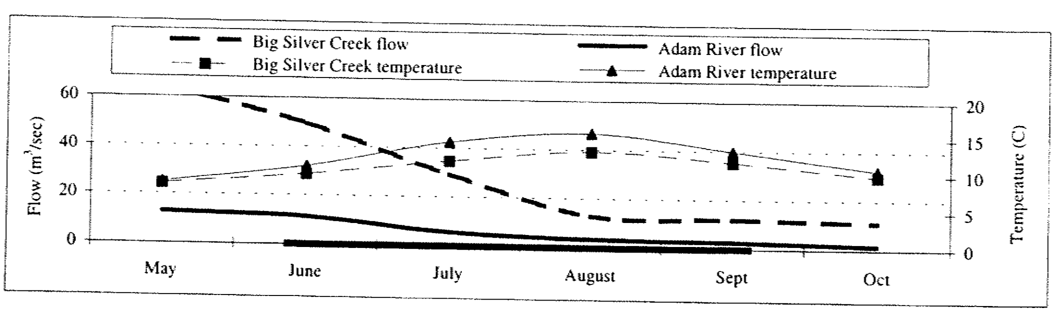

FIGURE 2. Average monthly flows and water temperatures of the Adam River and Big Silver Creek, 1993–1997. Dark bar on x-axis indicates approximate time of liquid fertilizer additions to the Adam River T2 reach and Big Silver Creek T1 and T2 reaches.

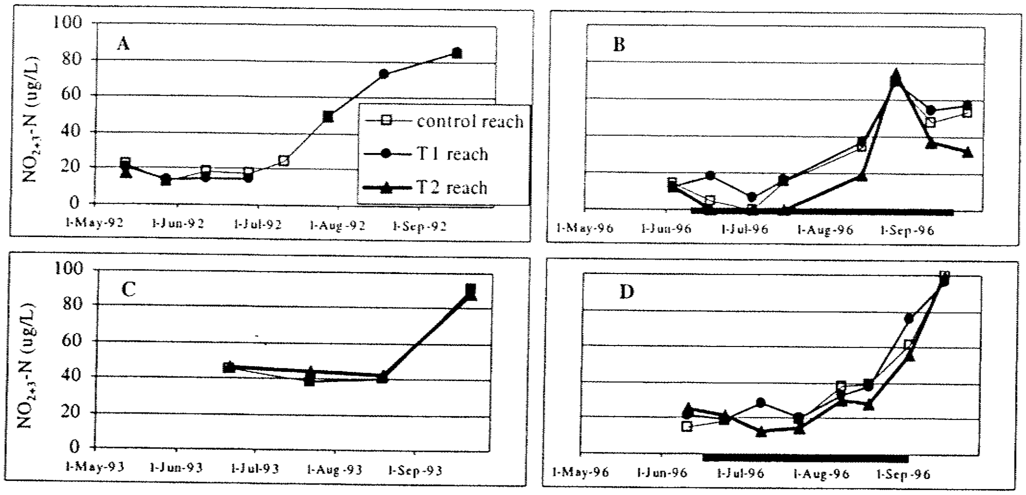

FIGURE 3. Nitrate + nitrite nitrogen concentrations in the three experimental reaches of the Adam River and Big Silver Creek during prefertilization and representative fertilization years. Adam River prefertilization in 1992 (A) and during fertilization in 1996 (B); Big Silver Creek prefertilization in 1993 (C) and during fertilization in 1996 (D). Dark bars on *x*-axes indicate fertilization periods.

Chlorophyll *a* concentrations increased 5-fold and 3-fold in the fertilized Adam River T2 reach during the early and late incubations periods, respectively, to an average of 32 mg/m^2 (Figure 4A). Values increased through the second year of fertilization (1995), then declined, with an intriguing increase, but of lower magnitude, in the unfertilized T1 reach. During September 1996, fertilizer addition rates to the Adam River were intentionally increased 3.5-fold, which resulted in a 10-fold increase in chlorophyll *a* concentrations to 70–100 mg/m^2 in the T2 reach (data not shown). In the fertilized reaches of Big Silver Creek, peak concentrations increased an average 2-fold, with significant increases in the T1 ($p = 0.009$) and T2 ($p = 0.036$) reaches during the August–September

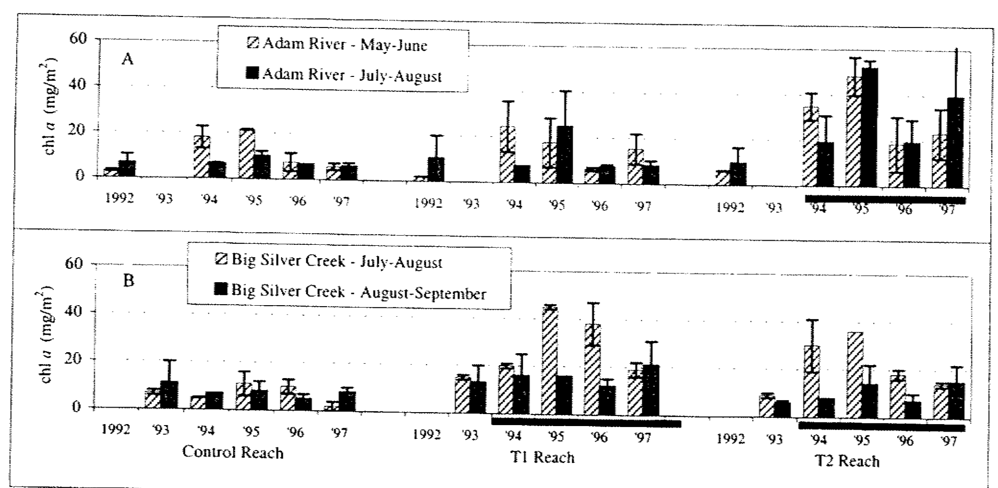

FIGURE 4. Peak chlorophyll *a* concentrations (±SD) in the three experimental reaches of the Adam River (A) and Big Silver Creek (B) during 2 incubation periods 1992–1997. Dark bars on *x*-axes indicate fertilization periods.

incubation periods (Figure 4B). Chlorophyll *a* values also increased through the second year of fertilization, then declined, and were significantly (*t*-test, $p < 0.05$) higher in the July–August incubation period compared with the August–September period, in Big Silver Creek.

Benthic Invertebrates

Benthos populations in unfertilized sections of each river were similar and dominated by chironomid and tipulid dipterans, hepatgeniid and baetid ephemeropterans, chloroperlid plecopterans, and hydropsychid tricopterans. Overall, dipterans were the most numerous in Big Silver Creek and ephemeropterans in the Adam River. Control reach populations were relatively consistent in each river during the study, with total average biomass values of 155 (±27), 228 (±26), and 151 (±17) mg/basket in Big Silver Creek (August), Adam River (July), and Adam River (August) incubation periods, respectively (Figure 5), and density values averaging 180 (±14), 150 (±31), and 151 (±33) individuals/basket during the same time periods (Figure 6). Prefertilization (1993) populations in the lower reaches of the Adam River were similar, but density increased downstream in Big Silver Creek to 429/basket in the T2 reach, resulting from the presence of more dipterans (Figure 6A).

After nutrient additions began, a few large changes were evident in each river, with maximum yearly increases in density and biomass of 5 to 10-fold, but average increases closer to 2-fold. In Big Silver Creek, the mean biomass of benthic invertebrates increased 2-fold and 5.7-fold in the fertilized T1 and T2 reaches, respectively. There was no change in density in the T1 reach (Figure 6A), but on average, there was a 1.8-fold increase in density in the T2 reach associated with significant increases in family Chironomidae abundance ($p = 0.005$). There were also smaller increases in the Baetidae, Simuliidae, and Capniidae families. The largest responses were recorded during the first year of fertilization (Figure 6A).

In the Adam River, mean benthos density in the fertilized T2 reach increased 2.4-fold compared with prefertilization values during the July colonization period, with a significant increase in family Chironomidae density ($p = 0.047$) resulting in significant increases in both dipteran ($p = 0.045$) and total ($p = 0.005$) densities. There was also a smaller but significant increase in the family Baetidiae ($p = 0.006$). The largest responses were recorded in the second or third years of fertilization (Figure 6B). In the August colonization period, density and biomass increased, on average, 1.4-fold and 2.5-fold, respectively, in the fertilized reach resulting from an increase in chironomids (Figure 6C), but the results were not statistically significant ($p = 0.092$).

Fish Populations

Young-of-the-year (age-0) rainbow trout in the control reaches of both rivers were similar in size and did not change during the study. Adam River annual size averages ranged from 1.7 g to 2.5 g and 55–60 mm in 1992–1997, while in Big Silver Creek, they ranged from 2.0 g to 2.7 g and 53–61 mm (Table 1). Prefertilization sizes of age-0 fish in the lower reaches were similar. In the Adam River fertilized T2 reach, the age-0 fish increased to an average 4.1 g and 69 mm during

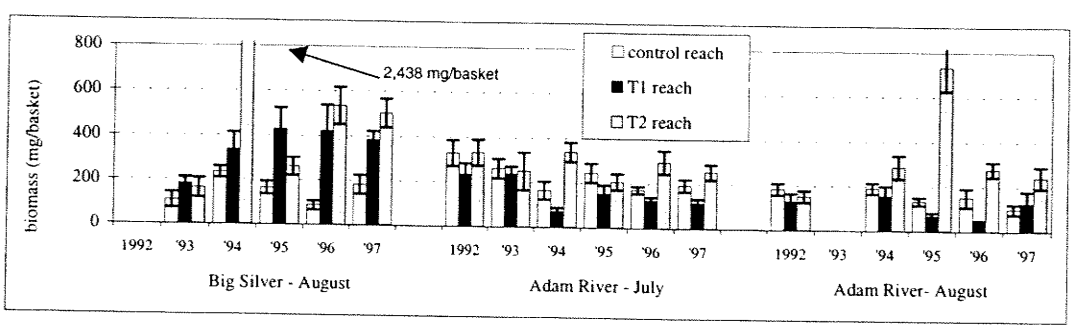

FIGURE 5. Biomass (wet-weight) of benthic invertebrates (±SE) in the three experimental reaches of the Adam River and Big Silver Creek, collected during August in Big Silver Creek and July and August from the Adam River, 1992–1997. Note: Adam T2 reach and Big Silver T1 and T2 reaches fertilized summers of 1994–1997.

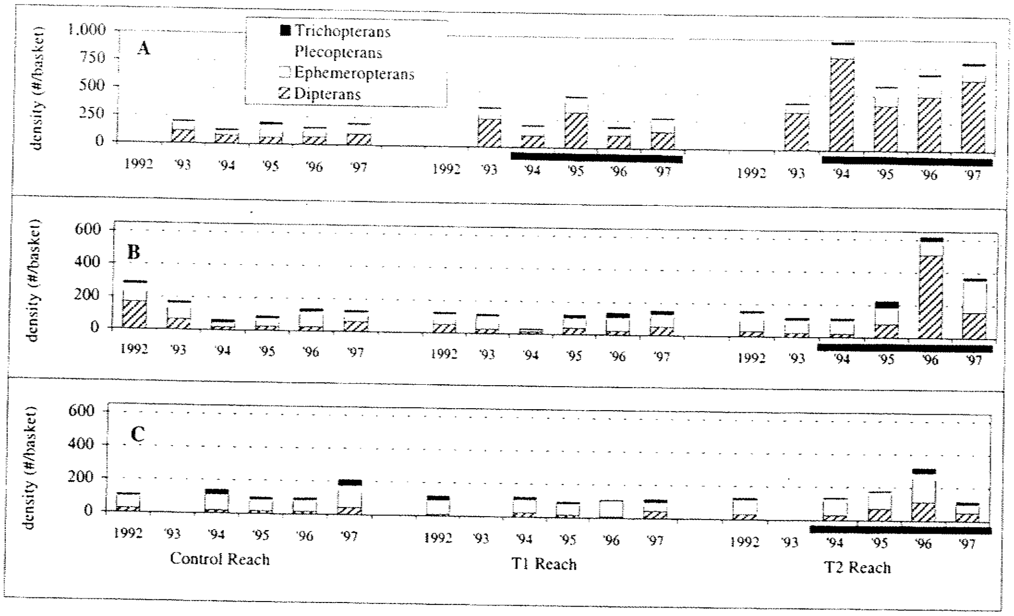

FIGURE 6. Benthic invertebrate density in the three experimental reaches of Big Silver Creek in August (A), Adam River in July (B) and August (C), 1992–1997 colonization periods. Dark bars on x-axes indicate fertilization periods.

TABLE 1. The average weight (g) and length (mm) of age-0 rainbow trout (± SD) in the Adam River and Big Silver Creek, 1992–1997. Values averaged from all sites within a reach. Adam River T2 reach and Big Silver T1 and T2 reaches fertilized summers 1994–1997. * denotes significant difference from prefertilization values by BACI analysis, $p < 0.05$.

		Adam River				Big Silver Creek		
reach	year	weight	length	ratio	year	weight	length	ratio
control	1992 prefert	1.7 ±0.5	55 ±1	0.031	1992 prefert	–	–	
	1993 prefert	2.0 ±1.0	57 ±8	0.035	1993 prefert	2.0 ±0.9	58 ±8	0.034
	1994 unfert	2.5 ±0.6	60 ±5	0.042	1994 unfert	2.4 ±1.3	59 ±9	0.041
	1995 unfert	2.1 ±0.5	57 ±5	0.037	1995 unfert	2.7 ±1.0	61 ±8	0.044
	1996 unfert	2.3 ±0.8	57 ±7	0.040	1996 unfert	2.4 ±0.6	56 ±6	0.043
	1997 unfert	–	–		1997 unfert	2.0 ±0.0	53 ±0	0.038
	mean unfert	**2**	**58**	**0.034**	**mean unfert**	**2.4**	**57**	**0.042**
T1	1992 prefert	1.7 ±0.5	55 ±5	0.031	1992 prefert	–	–	
	1993 prefert	2.4 ±0.8	59 ±5	0.041	1993 prefert	1.8 ±0.3	52 ±4	0.035
	1994 unfert	2.8 ±0.9	61 ±6	0.046	1994 fert	3.3 ±1.4	64 ±12	0.052
	1995 unfert	2.9 ±0.9	63 ±7	0.046	1995 fert	3.9 ±1.4	68 ±8	0.057
	1996 unfert	3.3 ±1.7	64 ±5	0.051	1996 fert	2.5 ±1.0	56 ±8	0.045
	1997 unfert	–	–		1999 fert	2.7 ±0.0	58 ±0	0.047
	mean unfert	**3.0**	**63**	**0.048**	**mean fert**	**3.1**	**62***	**0.050**
T2	1992 prefert	–	–		1992 prefert	–	–	
	1993 prefert	3.0 ±0.9	65 ±6	0.046	1993 prefert	–	–	
	1994 fert	4.7 ±1.5	73 ±7	0.064	1994 fert	–	–	
	1995 fert	3.3 ±1.3	66 ±7	0.050	1995 fert	–	–	
	1996 fert	4.2 ±1.4	69 ±7	0.061	1996 fert	2.3 ±0.7	57 ±5	0.040
	1997 fert	–	–		1997 fert	–	–	
	mean fert	**4.1**	**69**	**0.059**	**mean fert**	–	–	

fertilization, a 1.4 fold increase in weight. Big Silver Creek T1 reach age-0 fish increased to an average 3.1 g and 62 mm, a 1.7-fold increase in weight. The largest size increases were within the first two years of fertilization (Table 1), with maximum average sizes of 4.7 g and 73 mm in the Adam T2 reach in 1994 and 3.9 g and 68 mm in the Big Silver T1 reach in 1995. However, the only significant increase was length in the Big Silver T1 reach ($p = 0.045$). There was also an increase in weight per unit length in the fertilized reaches, particularly in the first year of fertilization, indicating an increase in condition factor (Table 1).

In the unfertilized Adam River T1 reach, the size of the age-0 fish increased consistently from an average 1.7 g and 55 mm in 1992 to 3.3 g and 64 mm in 1996 (Table 1). Rooney Creek, which joins the Adam River in the vicinity of the site where the samples were collected, was fertilized annually since 1993 as part of the experimental testing of slow release fertilizer previously mentioned, as was Newcastle Creek just downstream (Figure 1). Direct nutrient loading to the Adam River would have been very low, as flow contributions from these tributaries were small, approximately 3% and 10% of Adam River flow, respectively, and slow release fertilizer loading rates were below 3 μg/L P (Mouldey Ewing and Ashley 1998). However, there were increases in periphyton and benthos biomass in the tributaries, and movement of fish between systems was possible.

Density of adult rainbow trout (>20 cm length) in Big Silver Creek was initially similar throughout the river, averaging 10/ha (±3) in the control reach, with prefertilization densities of 12 and 10/ha in the T1 and T2 reaches, respectively (Figure 7A). Following the first summer of fertilization, density in the T1 reach increased to 37/ha and averaged 38/ha (±11) for a 3-fold increase during fertilization. Rainbow from 20 cm to 30 cm in length increased 2.8-fold from 12 to 33/ha (±10), and those 30–40 cm increased 20-fold from 0.2 to 4/ha (±1.5). The density of both size-classes reached a maximum in 1997, the fourth year of fertilization and the final year of evaluation. Below the waterfalls barrier, rainbow trout density in the T2 reach showed no perceptible change, although these fish are migratory and larger fish may have migrated to the lake or ocean, but mountain whitefish increased from 53/ha in 1993 to an average of 129/ha (±29) during fertilization, including a high of 204/ha in 1995 (Figure 7B). Whitefish 10–20 cm in length showed the largest increase, from 8/ha in 1993 to an average 48/ha (±13) during fertilization.

Fish populations in the Adam River exhibited a slower response compared with Big Silver Creek, but initial densities were much lower. Numbers of fish in the control reach were consistent through the study period (Figure 8): rainbow trout (>10 cm in length) averaged 10/ha (±1.5); brown trout 0.5/ha (±0.2); and rainbow, more than 20 cm in length, just 1.5/ha (±0.4). The density of both species increased in the unfertilized T1: the rain-

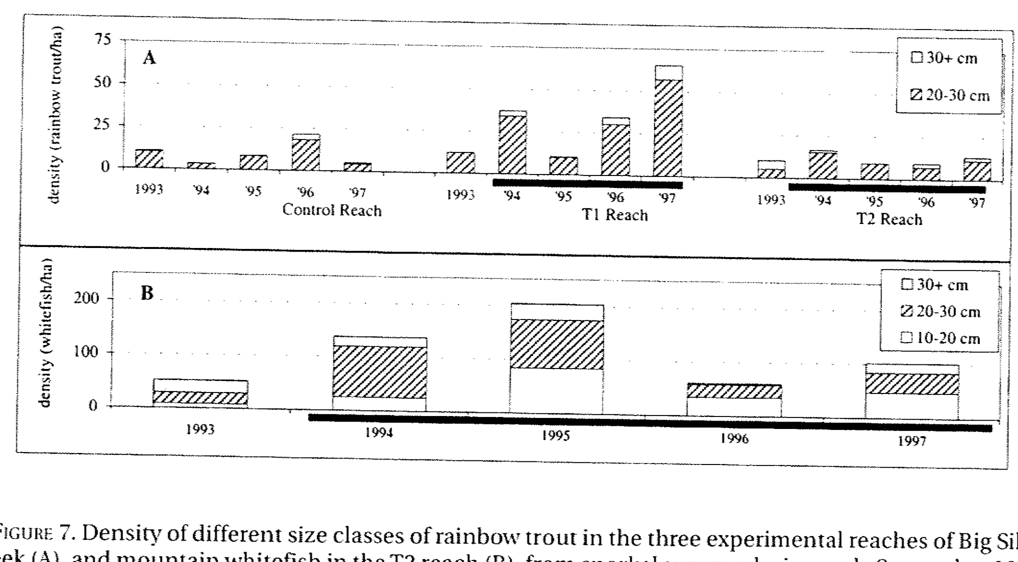

FIGURE 7. Density of different size classes of rainbow trout in the three experimental reaches of Big Silver Creek (A), and mountain whitefish in the T2 reach (B), from snorkel surveys during early September 1993–1997. Dark bars on x-axes indicate fertilization periods.

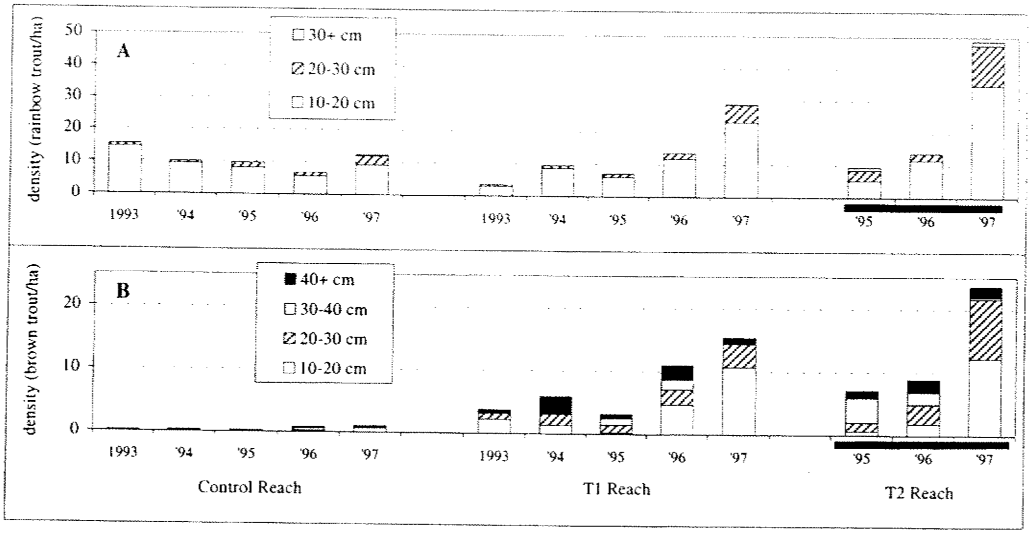

FIGURE 8. Density of different size classes of rainbow trout (A), and brown trout (B) in the three experimental reaches of the Adam River, from snorkel surveys during June 1993 and 1994, July 1995, and September 1996 and 1997. Dark bars on x-axes indicate fertilization periods.

bow from 3.5/ha in 1993 to a high of 29/ha in 1997 and brown trout from 3.8 to 15/ha, at the same time (Figure 8). In the fertilized T2 reach, no data were available for 1993–1995, but there were 3-fold and 5-fold increases in rainbow and brown trout density, respectively, between 1995 and 1997, when their densities peaked at 49/ha and 24/ha, respectively (Figure 8).

Discussion

The addition of phosphorus and nitrogen-based fertilizer stimulated growth (increased biomass) at all trophic levels analyzed, indicating that this restoration method is applicable to larger nutrient-deficient streams. We could not investigate specific rates or food chain links, but increases in autotrophic periphyton growth following nutrient addition and subsequent translocation of carbon and nutrients through the food chain to fish has been demonstrated on smaller systems (Peterson et al. 1985; Perrin et al. 1987; Peterson et al. 1993) that produced standing crop/biomass/size responses similar to our study.

Peak periphyton values attained in the Adam River and Big Silver Creek were 50% those reported for the Kuparuk, Nechako, Keogh, and Salmon rivers (Perrin et al. 1987; Slaney and Ward 1993; Peterson et al. 1993; Slaney et al. 1994). However, phosphorus-loading rates in the previous studies were at least double our target concentration of 5 μg P/L, which often was not attained. Additionally, when fertilizer addition rates to the Adam River were intentionally increased 3.5-fold (in September 1996), periphyton values increased almost 10-fold to values that were comparable with the other rivers.

The average 2-fold increase in benthos population over four years in both the Adam River and Big Silver Creek, including peak annual increases of 4-fold, are similar to the 3 to 5-fold increases on the Salmon and Keogh rivers (Slaney and Ward 1993). Increases on all rivers were limited to large increases in the same few families: collectors/gatherer dipterans (family Chironomidae) and ephemeropterans (Family Baetidae) and some predatory stoneflies (family Perlodidae). Additionally, the 1.5-fold increase in weight of age-0 rainbow was similar to results found in the Keogh (Johnston et al. 1990) and Salmon rivers (Slaney and Ward 1993), as well as to increases in age-0 Arctic grayling in the Kuparuk River (Peterson et al. 1993).

The delayed response of benthos and fish populations in the Adam River was likely related to their initial depressed populations. The prefertilized benthic density of 100 individuals per basket was low compared with values of 200 per basket in Big Silver Creek and 250 per basket in the Salmon River (Slaney and Ward 1993). Adult rainbow (>20 cm length) initially averaged 10/ha in Big Silver Creek, but only 1.5/ha on the Adam River. Additionally, low initial (1994) fertilizer loading rates and nitrogen limitation of the periphyton likely influenced response patterns. The increase in fish density and the size of age-0 fish in the unfertilized Adam River T1 reach is attributable to several factors. Rooney and New-castle creeks, which flow into the lower half of the T1 reach (Figure 1), were fertilized annually in 1993–1997. Therefore, the lower part of this reach was essentially fertilized at a very low level. The fertilized tributaries would provide good rearing habitat for the juveniles, some of which probably move into the main stem. The lower portion of this reach also contains good fish habitat, so there could easily be movement of adult fish between the fertilized and unfertilized reaches of the main stem as well.

The differential response in the two fertilized Big Silver reaches are likely a result of life history differences in fish stocks or strains because fish of the lower reach are largely migratory, making use of the large Harrison Lake or ocean (salmon and steelhead) for rearing from juveniles or smolt stages to adult.

The effective distance of the nutrient enrichment was estimated at 8–11 km in our study, based on a doubling of periphyton biomass, which was limited by the downstream extent of assessment. In comparison, the effective enrichment distance in the Salmon River and larger Mesilinka River was 15 km and at least 20 km, respectively, and the Mesilinka River was also N and P co-limited (Slaney and Ward 1993; Larkin et al. 1999). An earlier study at the larger Nechako River suggested 50 km, but nutrients were delivered in 5-min pulses, and the river was also N and P co-limited (Slaney et al. 1994).

Many of the periphyton and insect responses were not statistically significant using the BACI method because of only one or two years of prefertilization data and fertilization responses which were cumulative, delayed, and often highly variable. However, the increasing trend over time, particularly of fish abundance when supported by responses in both periphyton and insect communities in both rivers, strongly suggests that nutrient additions stimulated overall productivity of the rivers. The maximum fish densities in each river were attained in the final year of assessments, suggesting populations had not reached equilibrium. Longer-term investigations are needed, especially in rivers with low populations and/or water temperatures. Ideally, several years of prefertilization assessments would be followed by a multiyear transition period after fertilization begins, followed by several years of fertilization assessment. Additional nitrogen should also be added to ensure that nitrogen does not become limiting.

Nutrient enrichment of oligotrophic rivers would be a cost-effective and ecologically sound method of increasing fish populations, provided habitat is intact, compared with the current practice of stocking hatchery-reared fish. Annual fertilizer costs for the larger of the two rivers, Big Silver Creek, were modest, less than $4,000CDN (9.5 metric tons of fertilizer at $400/ton) for 10 km of river. More importantly, the genetic or behavioral viability of the wild fish are not compromised, as there are no interactions between wild and stocked fish, thus preserving biodiversity.

Acknowledgments

This project was funded by the Provincial Fisheries Branch (1992) and by the Habitat Conservation Trust Fund (HCTF). Encouragement and good advice was offered by A. Martin, S. Rimmer, C. Wightman, and Trout Unlimited Canada. Field work was conducted by S. Biancolin, S. Carswell, P. Davidson, T. Godin, Loreta Hansen, S. Jennings, W. Koning, S. Moldey, M. Neilsen, E. Standen, M. Stanford, B. Toth, K. Tsumura, C. Warren, and D. Zaldokas. A noble spirit embiggins the smallest man. Staff and volunteers of the Fraser Valley Trout sorted the benthos samples. Thanks to Jordan Rosenfeld, Megan McCusker, and two anonymous reviewers who graciously provided very helpful comments on drafts of this paper.

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