Water Quality, Chlorophyll, and Periphyton Responses to Nutrient Addition in the Kootenai River, Idaho

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Water quality, chlorophyll, and periphyton responses to nutrient addition in the Kootenai River, Idaho

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Abstract: During the past century, the Kootenai River, Idaho (USA), has experienced cultural oligotrophication following extensive levee construction, channelization, wetland drainage, and impoundment. A multiyear, whole-river nutrient-addition experiment was undertaken to mitigate these effects. The river was dosed with liquid agricultural-grade ammonium polyphosphate fertilizer (10-34-0) from June through September 2006–2010 to achieve an in-river total dissolved P (TDP) concentration of 3.0 μg/L. A fine-scale monitoring program included 8 sites over a 20-km reach (2 upstream control sites, one injection site, and 5 downstream treatment sites). Nutrient addition did not significantly increase N and P concentrations in the water column, but it significantly increased chlorophyll accrual rates and densities of edible green algae and diatoms. Nutrient addition significantly reduced NO_3^-+NO_2^- concentrations, atomic TN : TP ratios, and densities of inedible cyanophytes. Mean NO_3^- +NO_2^- values decreased along a downstream gradient below the nutrient-addition site, whereas chlorophyll accrual rate typically peaked immediately downstream from the nutrient addition site then decreased progressively downstream. Our study showed that nutrient addition is a useful river restoration technique for the Kootenai River.
Key words: nutrient addition, phosphorus, nitrogen, TN : TP ratio, water quality, chlorophyll accrual, periphyton, river restoration

N and P additions in aquatic systems can increase periphyton biomass, chlorophyll accrual rate, and the abundance and biomass of plankton and invertebrate communities (Kohler et al. 2008, Kohler and Taki 2010). Investigators also have reported significant increases in salmon production following nutrient addition in nutrient-depleted lakes and streams in British Columbia, Idaho, and Alaska (Johnson et al. 1990, Stockner 2003). The effects of reduced nutrient availability and biological production on naturally reproducing anadromous Pacific salmon populations have been described extensively in the literature (Schindler et al. 2003, Wipfli et al. 2003, Janetski et al. 2009), but anthropogenic oligotrophication also has reduced nutrient availability and biological production in rivers and lakes beyond the extent of marine-derived nutrient contributions (Ashley and Stockner 2003). Dam construction, wetland drainage, native fish population reduction or elimination because of over-fishing, habitat loss, and climate change are human activities that contribute to N, P, and C removal from lakes, rivers, and streams (Stockner et al. 2000, Stockner and Ashley 2003). One example is the Kootenai River, a large altered montane river in British Columbia (Canada), Idaho, and Montana (USA). Extensive river diking, tributary channelization, impoundment, and the isolation and deforestation of >20,000 ha of floodplain habitat have contributed to decreased N, P, and C availability in the Kootenai River and the downstream Kootenay Lake (Canadian spelling) during the past century (Anders et al. 2002, Schindler et al. 2011). Impounded by Libby Dam, Koocanusa Reservoir is 32 km upstream from Libby, Montana, and acts as a large nutrient sink that retains an estimated 63% of total P and 24% of total N previously delivered downstream (Snyder and Minshall 2005). These effects have contributed to the decreased abundance of 6 native fish species in the river, with current estimates from 0 to 90% of historical numbers (KTOI and MFWP 2004). Snyder and Minshall (2005) conducted a study of autotrophic and detrital energy pathways in the Kootenai River

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and concluded that post-levee and post-dam P limitation probably was contributing to the reduced abundance of native fishes.

In response to this anthropogenic oligotrophy, a 5-y whole-river experimental nutrient addition study was implemented with the objectives of increasing nutrient availability and stimulating biological production in the Kootenai River. The process was assessed by: 1) monitoring nutrient concentrations (N and P) and TN : TP, 2) monitoring chlorophyll accrual and algal community composition; and 3) comparing results between upstream (control) and downstream (treatment) sites annually from June through September 2006–2010.

METHODS

Study area

The Kootenai River is a large, altered 7th-order river that drains a 42,000-km^2 watershed within mountainous boreal forestlands of British Columbia, Montana, and Idaho (Fig. 1). The basin is composed predominantly of folded, faulted metamorphosed sedimentary rock (Ferreira et al. 1992). The river is >700 km long and has a mean annual discharge of 390 m^3/s at the nutrient-addition site. The 20-km study area was in a lower canyon reach in a naturally constricted channel characterized by moderate bed gradient, gravel and cobble substrates, and intermittent bedrock outcrops (KTOI and MFWP 2004). This area was divided into 2 adjacent sections: an upstream 11-km control reach and a downstream 9-km treatment reach separated by the nutrient dosing site, which was in Idaho immediately downstream of the Idaho–Montana border (Fig. 1).

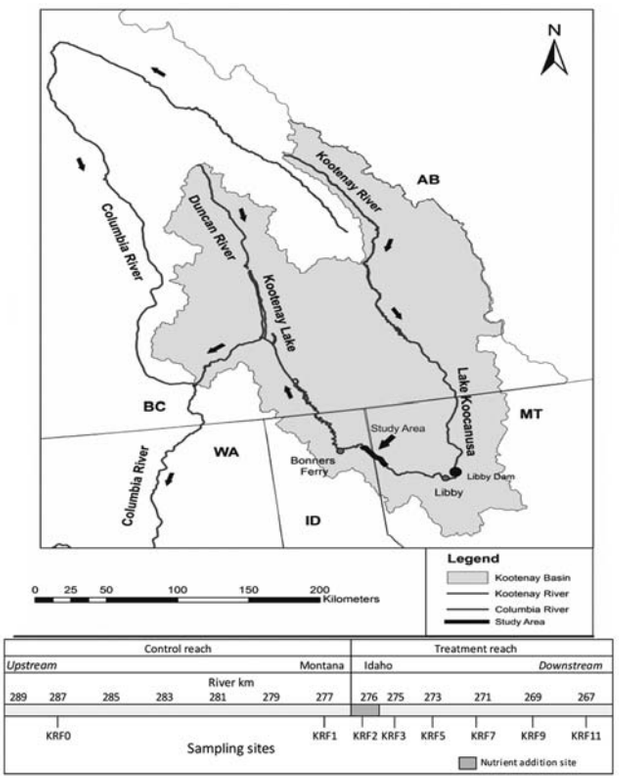

Figure 1. Study area and sampling sites used to evaluate nutrient addition in the Kootenai River, 2006–2010. AB = Alberta, BC = British Columbia, ID = Idaho, MT = Montana, WA = Washington.

Nutrient addition

An in-river concentration of 3.0 μg/L TDP (agricultural-grade liquid ammonium polyphosphate 10-40-0) was the annual target in the Kootenai River for 16 wk during the peak biological production season (1 June–1 October) from 2006 through 2010. Water-chemistry data showed the Kootenai River occasionally becomes N-limited in the late summer or early autumn (Hoyle 2003). Therefore, N fertilizer (liquid ammonium nitrate 32-0-0) was added as needed to maintain a minimum in-river TN : TP ratio of 20 : 1 if ambient NO_3^-+NO_2^- concentrations dropped <60 μg/L. Nutrients were added with a solar-powered gravity-flow dispensing system that included fertilizer storage tanks, a mixing head box, and dispensing pumps and flow monitoring meters as described by Holderman et al. (2009). Proper nutrient-dosing volumes and dilution rates were maintained to meet the 3.0 μg/L in-river TDP target by checking an on-site gage daily and adjusting dosing volumes accordingly.

Sampling sites

Nutrients were added to the Kootenai River 81 river km (rkm) downstream from Libby Dam (Fig. 1). Eight sites were sampled over the 20-rkm study reach. Two control sites, KRF0 and KRF1, were 11 and 1 rkm upstream, respectively, and a 3rd control site KRF2 was just upstream of the dosing site. Five treatment sites (KRF3–11) were situated every 2 rkm downstream, beginning 1 rkm downstream from the dosing site (Fig. 1).

Water chemistry

Total P (TP), total dissolved P (TDP), total N (TN), and NO_3^-+NO_2^- were sampled weekly at all sites at right-bank, mid-channel, and left-bank positions. Water samples were taken with a 2-L Van Dorn bottle within 4 m of the water surface and transferred to 250-mL bottles prerinsed with deionized water. Samples were stored on ice and shipped within 24 h to Aquatic Research Incorporated Laboratory (Seattle, Washington) for analyses. TP, TDP, TN, and NO_3^-+NO_2^- were analyzed with standard methods (APHA 2012). Samples were not filtered in the field or preserved because of the short holding times. Detection limits were

2.0 μg/L for TP and TDP, 10.0 μg/L for NO_3^-+NO_2^-, and 50.0 μg/L for TN. Atomic TN : TP (mass : mass) ratios were calculated from mean TN and TP values (Ashley and Stockner 2003). Resulting empirical TN : TP < 10 : 1 indicated N limitation, values between 10 : 1 and 20 : 1 indicated colimitation, and values > 20 : 1 indicated P limitation (Redfield 1958, Ashley and Stockner 2003).

Chlorophyll accrual

Two 30 × 30-cm cement tiles with 4 sections of 2.5-cm-thick Styrofoam® glued to their upper surfaces were placed on the substrate at each site to estimate chlorophyll biomass (μg/cm^2) and accrual rate (μg cm^{-2} d^{-1}) using methods published by Perrin et al. (1987) and Bothwell (1989). Total chlorophyll (chlorophyll *a* + chlorophyll *b*) was sampled every 2 wk by collecting 2 Styrofoam punch cores per tile per sampling date with a circular metal corer (3.8 cm^2; Bothwell 1989). Styrofoam substrate was replaced every sampling period to calculate accrual rates. Samples were removed from the corer and placed in labeled Whirl-Pak® bags, stored in brown plastic bottles, frozen at –20°C, and shipped to the University of Idaho Analytical Services Lab (Moscow, Idaho) for chlorophyll analysis (Wintermans and de Mots 1965).

Algal community composition

Algal taxonomic composition was estimated from randomly selected, fixed-area (645.2 mm^2) periphyton scrapes from rocks. One sample was collected per site per sampling date. Rocks were sampled randomly from near-shore areas at depths and velocities suitable for wading. Samples were preserved in 1% Lugol's solution by volume and sent to Aquatic Taxonomy Specialists (Malinta, Ohio) for taxonomic identification and enumeration. Soft-bodied periphyton cells were identified by viewing 300 cell-count wet mounts at 400× magnification. Bacillariophytes were identified in subsample burn mounts magnified up to 1000×. All enumerated algal specimens were identified at least to genus and were grouped as Chlorophyta (green algae), Bacillariophyta (diatoms), Cyanophyta (blue–green algae), or Other for analysis.

Statistical analyses

A repeated measures analysis of variance (rmANOVA) was carried out on the nutrient and chlorophyll accrual responses. Response values for chlorophyll accrual were log(x)-transformed to meet distributional assumptions of the analyses. Analyses were used to evaluate the effects of sample site, time of sample, and the site × time interaction. Single degree-of-freedom contrasts were used to assess overall treatment effects between treatment and control sites. Values of ½ the laboratory detection limit were used for analysis when nutrient values were at or below detection limits. All nutrient and chlorophyll analyses were done separately with data from each year (2006–2010).

A contingency table with associated χ^2 tests of homogeneity was used to compare the overall consistency of algal community composition between treatment and control sites based on the 4 taxonomic groups listed above. Before χ^2 analysis, annual data from all sites were pooled within the control and treatment sites to assess treatment effects (nutrient addition) while retaining sufficient sample sizes for statistical analyses. All analyses were carried out using SAS OnlineDoc (version 9.2; SAS Institute, Cary, North Carolina) and statistical significance was assessed at the α = 0.05 level.

RESULTS

Nutrients and chlorophyll

Mean TDP concentrations did not differ between treatment and control sites except during 2009, when TDP was significantly higher at treatment than at control sites (Table 1). Mean TDP concentrations ranged from 2.2 to 3.4 μg/L at treatment sites vs 2.0 to 4.8 μg/L at control sites (Table 2). Mean NO_3^-+NO_2^- concentrations were significantly lower at treatment than control sites (df = 1,16, p < 0.0001) during all years except 2007 (df = 1,16, p = 0.5563) (Table 1). Mean NO_3^-+NO_2^- values ranged from 97.4 to 140.7 μg/L at treatment sites vs 102.5 to 144.0 μg/L at control sites (Table 2). Mean TN : TP was significantly lower at treatment than at control sites during all years (Table 1), but the overall range of ratio values was nearly identical for the treatment and control sites and ranged from 20.4 to 44.1 over the duration of the study (Table 2). Chlorophyll accrual rates were significantly higher at treatment than at control sites during all years (Table 1) and ranged from 0.02 to 0.54 μg cm^{-2} d^{-1} at treatment sites and 0.007 to 0.061 μg cm^{-2} d^{-1} at control sites (Table 2). Up to 6-fold increases in chlorophyll accrual rates were observed at treatment vs control sites (Fig. 2). Immediately downstream from the nutrient dosing site, NO_3^-+NO_2^- values decreased significantly and chlorophyll

Table 1. *p*-values for contrasts between control sites (KRF0, KRF1, KRF2) and treatment sites (KRF3, KRF5, KRF7, KRF9, and KRF11) in the Kootenai River, 2006–2010. TDP = total dissolved P, TP = total P.

Year	Chlorophyll accrual	TDP	NO_3^-+NO_2^-	TN : TP
2006	0.0001	0.9343	0.0001	0.0001
2007	0.0001	0.8962	0.5563	0.0003
2008	0.0001	0.8106	0.0001	0.0001
2009	0.0001	0.0001	0.0001	0.0001
2010	0.0001	0.6326	0.0001	0.0001

Table 2. Mean (±1 SE) response values for control (KRF0, KRF1, KRF2) and treatment (KRF3, KRF5, KRF7, KRF9, and KRF11) sites in the Kootenai River, 2006–2010.

Year	Site	TDP (µg/L)	NO_3^-+NO_2^- (µg/L)	TN : TP	Chlorophyll *a* + *b* (µg cm^{-2} d^{-1})
2006	KRF0	2.177 ± 0.207	102.457 ± 2.316	44.140 ± 1.44	0.008 ± 0.001
	KRF1	2.041 ± 0.192	107.641 ± 2.097	39.927 ± 1.307	0.012 ± 0.003
	KRF2	2.451 ± 0.237	105.619 ± 2.387	24.835 ± 2.708	0.009 ± 0.003
	KRF3	2.153 ± 0.178	104.783 ± 2.483	25.961 ± 1.042	0.165 ± 0.026
	KRF5	2.448 ± 0.201	103.763 ± 2.426	26.043 ± 1.445	0.113 ± 0.019
	KRF7	2.328 ± 0.252	99.074 ± 2.269	25.336 ± 1.169	0.290 ± 0.080
	KRF9	2.222 ± 0.179	97.367 ± 2.553	44.140 ± 1.112	0.136 ± 0.030
	KRF11	2.191 ± 0.162	98.122 ± 2.386	26.466 ± 1.163	0.168 ± 0.030
2007	KRF0	2.587 ± 0.189	143.973 ± 2.645	33.011 ± 1.516	0.061 ± 0.012
	KRF1	2.652 ± 0.210	140.668 ± 2.210	31.401 ± 1.473	0.059 ± 0.016
	KRF2	3.321 ± 0.179	141.466 ± 2.123	20.438 ± 1.969	0.052 ± 0.009
	KRF3	3.335 ± 0.165	140.672 ± 2.133	22.140 ± 0.703	0.435 ± 0.094
	KRF5	3.286 ± 0.209	139.396 ± 2.047	21.741 ± 0.786	0.536 ± 0.111
	KRF7	3.282 ± 0.196	138.844 ± 2.117	23.733 ± 0.937	0.362 ± 0.068
	KRF9	3.223 ± 0.179	136.944 ± 2.067	21.577 ± 0.829	0.322 ± 0.062
	KRF11	2.957 ± 0.167	136.404 ± 2.226	22.615 ± 0.868	0.388 ± 0.070
2008	KRF0	2.053 ± 0.118	134.054 ± 3.835	37.392 ± 2.388	0.025 ± 0.003
	KRF1	2.130 ± 0.161	130.268 ± 4.031	36.313 ± 2.508	0.012 ± 0.002
	KRF2	2.484 ± 0.199	132.127 ± 4.053	21.605 ± 2.617	0.010 ± 0.002
	KRF3	3.082 ± 0.256	129.697 ± 4.065	21.791 ± 0.854	0.064 ± 0.010
	KRF5	2.592 ± 0.202	123.539 ± 3.702	22.585 ± 0.995	0.063 ± 0.006
	KRF7	2.906 ± 0.217	124.391 ± 3.418	20.809 ± 1.078	0.110 ± 0.020
	KRF9	2.864 ± 0.186	121.851 ± 3.479	22.696 ± 1.104	0.045 ± 0.006
	KRF11	2.647 ± 0.137	119.265 ± 3.599	21.447 ± 1.433	0.074 ± 0.017
2009	KRF0	2.002 ± 0.130	120.274 ± 3.676	31.683 ± 1.352	0.026 ± 0.004
	KRF1	2.138 ± 0.12	117.726 ± 3.647	29.584 ± 1.462	0.008 ± 0.001
	KRF2	2.410 ± 0.150	118.076 ± 3.389	27.266 ± 1.416	0.011 ± 0.002
	KRF3	2.764 ± 0.199	119.174 ± 3.412	20.618 ± 0.848	0.081 ± 0.007
	KRF5	2.738 ± 0.143	115.083 ± 3.624	20.498 ± 0.954	0.139 ± 0.033
	KRF7	2.783 ± 0.170	112.929 ± 4.022	20.625 ± 0.818	0.097 ± 0.013
	KRF9	2.812 ± 0.189	110.731 ± 3.857	21.640 ± 0.825	0.035 ± 0.004
	KRF11	2.843 ± 0.157	109.176 ± 3.869	21.786 ± 0.831	0.063 ± 0.007
2010	KRF0	2.278 ± 0.194	127.791 ± 2.504	43.280 ± 1.783	0.008 ± 0.001
	KRF1	2.300 ± 0.210	123.318 ± 2.405	41.539 ± 1.976	0.007 ± 0.001
	KRF2	4.771 ± 1.088	123.631 ± 2.416	31.562 ± 2.245	0.007 ± 0.001
	KRF3	3.436 ± 0.423	120.278 ± 2.238	24.334 ± 0.940	0.141 ± 0.023
	KRF5	2.762 ± 0.340	116.509 ± 2.468	25.183 ± 0.969	0.139 ± 0.051
	KRF7	2.707 ± 0.263	117.116 ± 2.503	24.700 ± 0.974	0.054 ± 0.006
	KRF9	2.724 ± 0.203	115.404 ± 2.624	24.709 ± 0.870	0.022 ± 0.002
	KRF11	2.282 ± 0.201	113.233 ± 2.837	24.941 ± 0.847	0.079 ± 0.017

accrual rates peaked, followed by progressively decreasing downstream values for both metrics.

Bacillariophyte abundance was higher at treatment than control sites (df = 3, p = 0.0382) and accounted for 86 to 96% of the taxa. Edible algal forms (e.g., chlorophytes and bacillariophytes) were enhanced by up to 30 percentage points by nutrient addition, whereas the prevalence of inedible cyanobacteria decreased from 26 to as low as 6%,

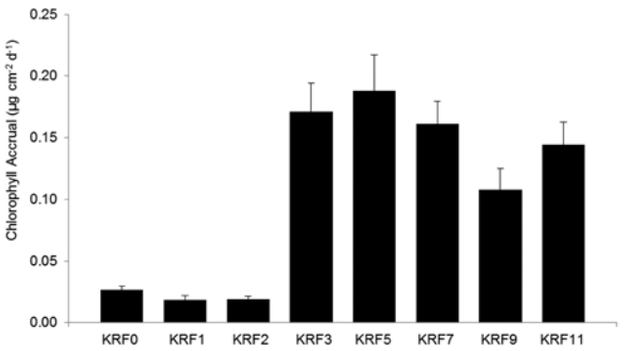

Figure 2. Mean (+1 SE) chlorophyll accrual, measured as chlorophyll *a* + chlorophyll *b*, at the control sites (KRF0, KRF1, KRF2) and treatment sites (KRF3, KRF5, KRF7, KRF9, and KRF11) in the Kootenai River, 2006–2010.

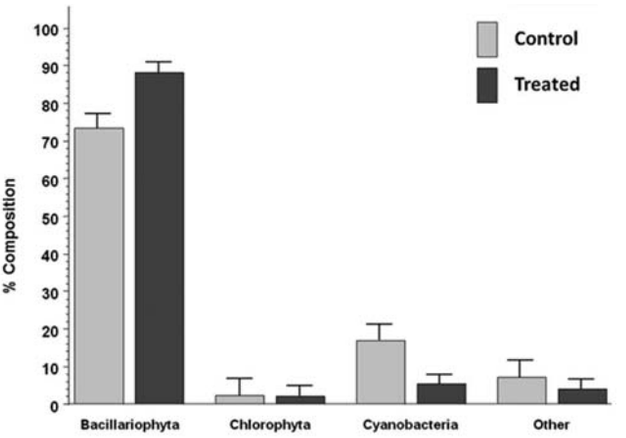

Figure 3. Mean (+2 SE) % composition of algal orders sampled in the Kootenai River at the control and treatment sites, 2006–2010.

with a mean reduction in relative abundance from 17 to 5.5% following treatment (Fig. 3).

DISCUSSION

Nutrient addition in the Kootenai River did not significantly increase TDP concentrations downstream of the injection location, except during 2009, when ambient N was low. Reductions and progressively decreasing downstream NO_3^-+NO_2^- values in the treatment reach probably resulted from rapid biological uptake, as seen in other nutrient-addition programs in ultraoligotrophic waters (e.g., Schindler et al. 2011). Slavik et al. (2004) attributed lower NO_3^- concentrations in the P-enriched reach of the Kuparuk River, Alaska, to increased biological uptake. Nutrient uptake was supported by observed increases in chlorophyll accrual rates, which were significantly higher in the treatment reach than in the control reach during all years of this study. The largest increase in chlorophyll accruals occurred in the 2nd season of the 3.0 µg/L P additions, whereas chlorophyll accrual decreased in subsequent seasons. This decrease in chlorophyll standing crop indicates a possible increase in benthic macroinvertebrate grazing pressure, as seen by Mundie et al. (1991) and Peterson et al. (1993). In the Kuparuk River, epilithic algae initially was limited by P availability, then by grazing benthic macroinvertebrates, followed by a shift to a moss-dominated periphyton community (Slavik et al. 2004). Increases in chlorophyll production following additions of limiting nutrients also were seen in southeastern Idaho rivers where biofilm responses varied spatially and seasonally and occurred in 59% of all instances (Marcarelli et al. 2009).

Nutrient addition produced favorable shifts in algal taxonomic composition, including increased densities of edible green algae and diatoms and reduced densities of inedible cyanophytes, that can contribute to foodweb enrichment (Naiman et al. 2012). Nutrient addition also reduced TN : TP from as high as 45 : 1 in the control reach to 20–30 : 1 in the treatment reach. This change constituted a substantial reduction in the degree of P limitation and partially counteracted the negative biological effects of anthropogenic oligotrophication.

The consistent, positive responses and the absence of undesirable outcomes lead us to recommend nutrient addition as a valuable restoration technique to enhance primary production in the Kootenai River and potentially in other anthropogenically oligotrophic rivers and streams, with the caveat that ecosystems respond to nutrient additions in highly specific ways (Artigas et al. 2013). Nutrient addition, coupled with other management tools, such as habitat restoration and foodweb analysis (Naiman et al. 2012), collectively can help restore threatened fish populations.

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LITERATURE CITED

Anders, P. J., D. L. Richards, M. S. Powell. 2002. The first endangered white sturgeon population (*Acipenser transmontanus*): repercussions in an altered large river-floodplain ecosystem. Pages 67–82 *in* W. Van Winkle, P. Anders, D. Dixon, and D. Secor (editors). Biology, management, and protection of North American sturgeons. Symposium 28. American Fisheries Society, Bethesda, Maryland.

APHA (American Public Health Association). 2012. Standard methods for the examination of water and wastewater. 22nd edition. American Public Health Association, American Wa-

ter Works Association, and Water Environment Federation, Washington, DC.

Artigas, J. E., E. García-Berthou, D. E. Bauer, M. I. Castro, J. Cochero, D. C. Colautti, A. Cortelezzi, J. D. Donato, A. Elosegi, C. Feijoó, A. Giorgi, N. Gómez, L. Leggieri, I. Muñoz, A. Rodrigues-Capítulo, A. M. Romaní, and S. Sabater. 2013. Erratum: Global pressures, specific responses: effects of nutrient enrichment in streams from different biomes. Environmental Research Letters 8:014002.

Ashley, K. I., and J. G. Stockner. 2003. Protocol for applying limiting nutrients to inland waters. American Fisheries Society Symposium 34:245–258.

Bothwell, M. L. 1989. Phosphorus-limited growth dynamics of lotic periphyton diatom communities: area biomass and cellular growth rate responses. Canadian Journal of Fisheries and Aquatic Sciences 46:1293–1301.

Ferreira, R. F., D. B. Adams, and R. E. Davis. 1992. Development of thermal models for Hungry Horse Reservoir and Lake Koocanusa, Northwestern Montana and British Columbia. Water-Resources Investigations Report 91-4134. US Geological Survey, Reston, Virginia.

Holderman, C., G. Hoyle, R. Hardy, P. Anders, P. Ward, and H. Yassien. 2009. Libby Dam Hydro-electric Project mitigation: efforts for downstream ecosystem restoration. Pages 6214–6222 *in* Section C-4 of 33rd International Association of Hydraulic Engineering and Research Congress, Vancouver B.C., August 9–14, 2009. 33rd IAHR Congress: Water Engineering for a Sustainable Environment. (Available from: http://www.fishsciences.net/reports/view_report.php?rid=3715)

Hoyle, G. M. 2003. Responses of periphyton, benthic macroinvertebrates, and juvenile white sturgeon to experimental additions of nitrogen and phosphorous in the Kootenai River, Idaho. MS Thesis, University of Idaho, Moscow, Idaho.

Janetski, D. J., D. T. Chaloner, S. D. Tiegs, and G. A. Lamberti. 2009. Pacific salmon effects on stream ecosystems: a quantitative synthesis. Oecologia (Berlin) 159:583–595.

Johnson, N. T., C. J. Perrin, P. A. Slaney, and B. R. Ward. 1990. Increased juvenile growth by whole-river fertilization. Canadian Journal of Fisheries and Aquatic Sciences 47:136–144.

Kohler, A. E., A. Rugenski, and D. Taki. 2008. Stream food web response to a salmon carcass analogue addition in two central Idaho, USA streams. Freshwater Biology 53:446–460.

Kohler, A. E., and D. Taki. 2010. Macroinvertebrate response to salmon carcass analogue treatments: exploring the relative influence of nutrient enrichment, stream foodweb, and environmental variables. Journal of the North American Benthological Society 29:690–710.

KTOI and MFWP (Kootenai Tribe of Idaho and Montana Fish, Wildlife and Parks). 2004. Kootenai Subbasin Plan. A report prepared for the Northwest Power and Conservation Council, Portland, Oregon. (Available from: http://www.nwcouncil.org/fw/subbasinplanning/kootenai/plan/)

Marcarelli, A. M., H. A. Bechtold, A. T. Rugenski, and R. S. Inouye. 2009. Nutrient limitation of biofilm biomass and metabolism in the Upper Snake River basin, southeast Idaho, USA. Hydrobiologia 620:63–76.

Mundie, J. H., K. S. Simpson, and C. J. Perrin. 1991. Responses of stream periphyton and benthic insects to increases in dissolved organic phosphorus in a mesocosm. Canadian Journal of Fisheries and Aquatic Sciences 48:2061–2072.

Naiman, R. J., J. R. Alldredge, D. A. Beauchamp, P. A. Bisson, J. Congleton, C. J. Henny, N. Huntly, R. Lamberson, C. Levings, E. N. Merrill, W. G. Pearcy, B. E. Rieman, G. T. Ruggerone, D. Scarnecchia, P. E. Smouse, and C. C. Wood. 2012. Developing a broader scientific foundation for river restoration: Columbia River food webs. Proceedings of the National Academy of Sciences of the United States of America 109:21201–21207.

Perrin, C. J., M. W. Bothwell, and P. A. Slaney. 1987. Experimental enrichment of a coastal stream in British Columbia: effects of organic and inorganic additions on autotrophic periphyton production. Canadian Journal of Fisheries and Aquatic Sciences 44:1247–1256.

Peterson, B., B. Fry, and L. Deegan. 1993. The trophic significance of epilithic algal production in a fertilized tundra river ecosystem. Limnology and Oceanography 38:872–878.

Redfield, A. C. 1958. The biological control of chemical factors in the environment. American Scientist 46:205–221.

Schindler, D. E., M. D. Scheuerell, J. W. Moore, S. M. Gende, T. B. Francis, and W. J. Palen. 2003. Pacific salmon and the ecology of coastal ecosystems. Frontiers in Ecology and the Environment 1:31–37.

Schindler, E. U., D. Sebastian, H. Andrusak, L. Vidmanic, G. F. Andrusak, M. Bassett, T. Weir, and K. I. Ashley. 2011. Kootenay Lake Nutrient Restoration Program, year 17 (North Arm) and year 5 (South Arm) (2008) report. Fisheries Project Report No. RD 131 2011. Resource Management Ministry of Forests, Lands and Natural Resource Operations, Province of British Columbia, Vancouver, British Columbia, Canada.

Slavik, K., B. J. Peterson, L. A. Deegan, W. B. Bowden, A. E. Hershey, and J. E. Hobbie. 2004. Long-term responses of the Kuparuk River ecosystem to phosphorus fertilization. Ecology 85:939–954.

Snyder, E. B., and G. W. Minshall. 2005. An energy budget for the Kootenai River, Idaho (USA), with application for management of the Kootenai white sturgeon, *Acipenser transmontanus*. Aquatic Sciences 67:472–485.

Stockner, J. G. 2003. Nutrients in salmonid ecosystems: sustaining production and biodiversity, Symposium 34. American Fisheries Society, Bethesda, Maryland.

Stockner, J. G., and K. I. Ashley. 2003. Salmon nutrients: closing the circle. American Fisheries Society Symposium 34:3–15.

Stockner, J. G., G. E. Rydin, and P. Hyenstrand. 2000. Cultural oligotrophication: causes and consequences for fisheries resources. Fisheries 25(5):7–14.

Wintermans, J. F., and A. de Mots. 1965. Spectrophotometric characteristics of chlorophylls *a* and *b* and their pheophytins in ethanol. Biochimica et Biophysica Acta 109:448–453.

Wipfli, M. S., J. P. Hudson, J. P. Caouette, and D. T. Chaloner. 2003. Marine subsidies in freshwater ecosystems: salmon carcasses increase the growth rates of stream-resident salmonids. Transactions of the American Fisheries Society 132: 371–381.