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Protocol for Applying Limiting Nutrients to Inland Waters

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Abstract. The depressed status of many Pacific Northwest (PNW) salmonid stocks has focused considerable attention on the role of marine-derived nutrients (MDN) in maintaining the productivity of salmonid ecosystems and created a strong interest in stream and lake enrichment as an important salmon restoration technique. This paper reviews some of the technical and more applied aspects of stream, river, and lake enrichment as currently practiced in British Columbia and elsewhere in the world. The first step when considering potential stream and lake enrichment is to determine the ambient nutrient concentrations, stock of biogenic biomass, and trophic status of the candidate ecosystem by conducting nutrient bioassays, synoptic surveys, low-level nutrient analyses, and qualitative assessments of the ecosystems. Phosphorus is considered limiting when concentrations in composite stream or epilimnetic lake samples during the growing season are less than 1µg/L SRP and less than 2–3µg/L TDP. Nitrogen is considered limiting in streams when dissolved inorganic nitrogen (DIN) concentrations during the growing season are less than 20 µg/L and in lakes when spring epilimnetic concentrations are less than 30 µg/L. At minimum, a 1–2 year pre-treatment study is required to determine the nutrient status and requirements of the ecosystem. Water users and regulatory agencies must be notified in advance of plans to add nutrients to rivers, lakes, or streams, and provincial, state, and/or federal permitting processes and guidelines should be followed. All nutrient enrichment programs must consider seven key variables: (1) desired concentration of nutrients, (2) type of nutrients, (3) seasonal timing of application, (4) frequency of nutrient addition, (5) location of application sites, (6) DIN:TDP (total dissolved phosphorus) ratio of nutrients to be added, and (7) application technique. Enrichment programs should attempt to mimic the anadromous salmon 'nutrient pump' where applicable and implement a nutrient prescription that assures the production of edible phytoplankton/periphyton and avoids the occurrence of nuisance algae. In addition, sufficient funds should be secured to monitor the ecosystem responses.

Introduction

The depressed status of many Pacific Northwest (PNW) salmonid stocks (Nehlsen et al. 1991) has recently focused a considerable amount of attention on the role of marine-derived nutrients (MDN) in maintaining the productivity of salmonid ecosystems. The Returning Nutrients to Salmonid Ecosystems conference held in Eugene, Oregon, on 24–26 April 2001 attracted nearly 400 delegates from Japan to Scandinavia, clearly demonstrating the growing interest in this topic. The emerging recognition that salmonid carcasses are ecologically important sources of marine-derived organic carbon (C), nitrogen (N), and phosphorus (P) for aquatic and terrestrial ecosystems provides a compelling argument for abandoning single-species stock–recruitment-based fisheries and adopting holistic ecosystem-based resource management models (Schuldt and Hershey 1995; Willson and Halupka 1995; Bilby et al. 1996; Michael, this volume).

Recent quantitative estimates of the 'nutrient deficit' in the PNW have created a strong interest in the efficacy of stream and lake enrichment (fertilization) as a salmon restoration technique (Larkin and Slaney 1997; Gresh et al. 2000; Stockner et al. 2000). The goal of stream and lake enrichment is to rebuild salmonid escapement to historical levels via temporary supplementations of limiting nutrients using organic and/or inorganic formulations. Stream and lake enrichment should not be used as a 'techno-fix' to perpetuate the existing mismanagement of salmonids when there is any possibility of re-establishing self-sustaining wild populations through harvest reductions and restoration of salmonid habitat. Therefore, fertilization should be viewed as an interim restorative measure that is most effective if all components of ecosystem recovery and key external factors (e.g., overfishing) are cooperatively achieved and coordinated. This paper reviews some of the technical and more applied aspects of stream, river, and lake enrichment as currently practiced in British Columbia and elsewhere. As a caveat, the discussion assumes that salmonid stock status of candidate lakes and streams has been quantified and classified as significantly depressed and that additional limiting factors (e.g., habitat/water quality and quantity) have been addressed and/or incorporated into an integrated basin or lake 'restoration' plan. It also assumes that salmonid harvest/exploitation rates have been previously reduced to near zero and that the stock is not recovering naturally due to severe nutrient loss (oligotrophication), reduced habitat, or nonaddressable external factors (e.g., reduced ocean survivals).

Nutrient Limitation

Phosphorus and nitrogen are the primary limiting macronutrients in most freshwater ecosystems in the PNW and elsewhere (Wetzel 1975). The first step when considering potential candidates for enrichment is to determine the trophic status of each stream and/or lake by examining seasonal concentrations of P and N and standing stock and abundance of phytoplankton, zooplankton, and fish. There are essentially four nutrient assessment techniques available:

(1) Run bioassays to determine nutrient limitation (i.e., floating or streamside mesocosms in which limiting nutrients are applied over several weeks or months at known rates);
(2) Conduct synoptic surveys so that comparisons of community composition and biomass of periphyton/phytoplankton and benthic invertebrate/zooplankton can be made and nutrient/trophic standards established (e.g. ultra-oligo, oligo-, meso-, and eutrophic);
(3) Obtain samples for low-level (detection level required: <1 μg/L SRP; 1–3 μg/L TDP; 4–5 μg/L DIN) water chemistry analyses for soluble reactive and total dissolved phosphorus (SRP and TDP) and dissolved inorganic nitrogen (DIN = NO_3-N + NO_2-N + NH_3-N) during the summer growing season to determine ambient nutrient status;
(4) A strictly qualitative assessment of the general 'slippery feel' and relative abundance of periphyton on natural substrates and density of aquatic insects beneath stones in streams during the growing season (lotic ecosystems only).

The last technique is quite basic, but when conducted by an experienced stream ecologist, it can be surprisingly informative and reliable. Techniques 2 and 3 will likely form the basis of most nutrient assessments, owing to their relatively low cost and quantitative nature, while qualified individuals typically will use technique 4 during preliminary stream reconnaissance surveys.

Phosphorus is considered the limiting nutrient when concentrations in composite stream or epilimnetic lake samples during the growing season are routinely at limits of detection (less than 1 μg/L SRP; less than 2–3 μg/L TDP). Lotic ecosystems are remarkably efficient at removing phosphorus at low concentrations, and experimental studies have demonstrated that SRP concentrations as low as 0.3–0.6 μg/L are sufficient to saturate specific growth rates of unicellular periphytic diatoms (Bothwell 1988). However, biomass accrual continues to increase with increasing SRP as the relationship shifts from cellular- to community-controlled growth rates (Bothwell 1989; Quamme and Slaney, this volume). In streams, DIN concentrations less than 20 μg/L may become limiting (Bothwell 1988), and in lakes, spring epilimnetic concentrations less than 30 μg/L usually signal N-limitation of phytoplankton by mid-summer (Stockner and Shortreed 1985). Most of the background DIN will be in the form of NO_3-N, as NO_2-N is ephemeral and, like ammonium, is usually found under anoxic conditions. Ammonia (NH_3-N) is not as mobile as NO_3-N in groundwater and is generally undetectable in well-oxygenated lake and stream water. As in lakes, additional nitrogen is generally not required in streams if the background concentration of DIN is between 30–50 μg/L. However, in some situations, DIN concentrations near the low range (<30 μg/L) can become co-limiting during enrichment experiments due to the increased biological uptake of DIN caused by addition of P. The form of DIN most rapidly assimilated by both attached algae and phytoplankters is NH_3-N rather than NO_3-N. Organic forms of N are ubiquitous in freshwaters, but most compounds are refractory (e.g., tannins, lignin, humates) and require a slow microbial reduction before their N components can be utilized. However, urea is the exception to the above and is an excellent nutrient source readily assimilated after reduction by phytoplankters and bacteria.

Legal Application and Notification Requirements

The addition of limiting nutrients, either in the form of salmon carcasses, organic nutrient analogues, or inorganic nutrients, to lakes, rivers, and streams initially appears at odds with more than four decades of efforts to reduce nutrient discharges and can be interpreted by provincial, state, and federal authorities as being in violation of water pollution control laws (e.g., Clean Water Act). Hence, water users and regulatory agencies must be notified in advance, and provincial, state, and/or federal permitting processes and guidelines should be followed. Since nutrient enrichment is a relatively new procedure, existing guidelines are now being modified, or new guidelines developed, to address the issue. In Washington State, a National Pollutant Discharge Elimination System (NPDES) Waste Discharge Permit is being modified to allow temporary water quality modification for nutrient restoration (H. Michael, Washington Department of Fish and Wildlife, Olympia, Washington, personal communication). In British Columbia, draft guidelines for instream placement of hatchery salmon carcasses have been developed and are currently being reviewed by field staff and hatchery managers (A Fedorenko, Canada Department Fisheries and Oceans, Vancouver, British Columbia, personal communication). Similar guidelines are being developed in Oregon to facilitate application of surplus hatchery carcasses in culturally oligotrophic streams (D. Shively, U.S. Forest Service, Mt. Hood National Forest, personal communication).

In addition to the formal water quality regulatory agencies, it is important to determine which additional agencies and individuals should to be notified. In British Columbia, under the Water Act, downstream water users must be notified of any activities that may impact the water quality of their licensed withdrawals. Accordingly, water licensees on treatment streams must be notified in advance in order to avoid complaints of water quality degradation and health issues (C. Cross, Fisheries and Oceans Canada, Vancouver, British Columbia, personal communication). Since nutrient addition to waters is a novel concept in many areas, it is often advisable to post notices and conduct public meetings to explain the rationale and risks/benefits of the proposed treatments. Within the fisheries agencies, it is important to notify stock assessment personnel, area management staff, stewardship groups, and First Nations fisheries officers, particularly if salmon carcasses are used as the carbon and nutrient source. In British Columbia, provincial fisheries staff meet with regional Public Medical Health Officers, as required, to discuss planned treatments and nutrient formulations to alleviate concerns about potential nitrate and heavy metal addition to potable water sources.

Project Planning

One of the most important aspects of conducting a successful nutrient enrichment program is detailed project planning, which should start 1–2 years prior to nutrient treatment. This typically involves collection and analysis of background physical, chemical, and biological data from the candidate stream or lake, analysis of discharge patterns (rivers and streams), examination of epilimnetic and whole lake residence times, compensation depth (1% light level), and the duration and depth of thermal stratification (lakes and reservoirs). After these data are in hand, the final process is to develop an agency and public notification plan, preparing a permit application strategy (if required) and a well-designed monitoring plan. At least one full season of pre-fertilization data must be collected in order to characterize the nutrient status of the ecosystem in question. For project planning purposes, most nutrient enrichment programs can be described in terms of seven key variables:

1. Desired concentration of nutrients;
2. Nutrient formulation of fertilizer;
3. Seasonal timing of application;
4. Frequency of nutrient addition;
5. Location of application sites;
6. DIN:TDP ratio of nutrients to be added;
7. Application technique.

1. Desired Concentration of Nutrients

In streams and rivers, excessive periphyton biomass is reported to occur when SRP concentrations exceed 10 μg/L; therefore, target concentrations of SRP for stream and river fertilization (background plus nutrient additions) are in the 3–5 μg/L (ppb—parts per billion) range, or approximately one-third to one-half of potential nuisance concentrations, but high enough to be effective over several kilometers of stream. Uptake of SRP by attached bacteria and algae is very rapid, and concentrations can fall to below 1 μg/L within a kilometer of the addition source. Since nutrients are rapidly transformed into biomass accrual and will spiral to lower stream reaches, the actual concentration often cannot be measured in the water, and care must be taken to accurately apply P only at the pre-determined loading rate and not exceed it. Minimum target DIN concentrations for streams and rivers (background plus nutrient additions) are ~30–50 μg/L to ensure that DIN:TDP ratios remain ~10:1 on a weight:weight basis.

Because many oligotrophic lakes show co-limitation of N and P (Stockner 1987), river or stream ecosystems that originate from N-limited lakes may require additional N to prevent stream N-limitation. Fortunately, many river systems contain sufficient ambient concentrations of DIN, often originating from dense alder stands in riparian corridors (Volk et al., this volume), that they do not require additional nitrogen loading, thus significantly reducing fertilizer costs. In some cases, the concentration of DIN will vary during the season as the runoff gradually shifts from snowmelt to base groundwater flows. This reinforces the prerequisite for at least one year of pre-enrichment data collection to adequately characterize the temporal variation in ambient nutrient concentration and develop a site-specific enrichment strategy. Special attention should be directed towards not exceeding government regulatory agency standards for algal biomass. For example, in British Columbia streams and rivers, 50 mg/m^2 chlorophyll a (CHL) is the maximum concentration permitted under aesthetic considerations, and 100 mg/m^2 CHL is the maximum without detriment to aquatic life in streams (Nordin 1985).

When using salmon carcasses as a carbon and nutrient source, nutrient-loading density is often based solely on the availability of carcasses. More scientific approaches are recommended in which carcass nutrient loading is determined through quantitative estimation procedures. Methods to determine the carcass loading density include (1) analysis of historical escapement records, (2) back-calculation of desired in-situ nutrient concentration, (3) stable isotope analysis of lake and/or tree ring cores, or (4) comparison to stream systems in terms of fish per km of stream length. A promising new technique is the areal loading (kg of carcass per m^2) approach based on ^{15}N stable isotope saturation curves for juvenile salmonids (Bilby et al. 2001). This approach has been adopted in Washington State and results in the following maximum carcass density guidelines (Table 1).

Although this is a preliminary estimate based on a limited number of streams, it represents a sound ecological approach that can be experimentally derived for most river systems.

In lakes and reservoirs, the target concentration of P should be derived from a Vollen-weider-type loading model that incorporates mean depth and flushing rate and predicts the trophic state that results from various P loads (Vollenweider 1976, Stephens and Stockner 1983). Given the large literature on eutrophication and P loading to lakes,

TABLE 1. Draft Washington State NPDES carcasses loading guidelines.

Salmon species	Carcass loading
Coho/steelhead/cutthroat	0.15 kg m^2 bank full width
Pink/chum/sockeye	0.78 kg m^2 bank full width
Chinook	0.39 kg m^2 bank full width

it is not difficult to estimate the desired P load (nutrients plus background watershed loading) to ensure that the lake or reservoir remains within the permissible loading range. Nitrogen is then applied at sufficient rates to ensure that the epilimnetic DIN:TDP ratio remains greater than 10:1 on a weight:weight basis throughout the growing season. For example, in Kootenay Lake, British Columbia, the annual concentration of nutrients that were applied during the April–August treatment season (assuming a 0–20 m epilimnetic mixing depth) was 271 mg m^{2} (13.6 μg/L) of P and 1,191 mg m^{2} (59.5 μg/L) of N. This loading was sufficient to rebuild kokanee Oncorhynchus nerka escapement while maintaining excellent water quality conditions (Ashley et al. 1997). In the Federal Lake Enrichment Program (LEP), weekly phosphorus loads averaged 3.0 to 4.5 mg P m^{-2} $week^{-1}$ and yielded a weekly epilimnetic P enrichment of 0.2 to 0.7 μg/L over a 16–22 week growing season (Stephens and Stockner 1983; Stockner and MacIsaac 1996).

2. Nutrient Formulation

Salmon carcasses represent the ideal nutrient source as they contain a complex array of macro- and micronutrients, vitamins, and organic compounds, including highly unsaturated fatty acids or HUFAs. In terms of macronutrient analysis, most salmonids are between 0.3–0.4% by wet weight as P and 3.0–3.5% by wet weight as N and, hence, have close to a 10:1 TN:TP ratio on a weight:weight basis (Stansby and Hall 1965). The advantages of salmon carcasses as nutrient source is that they provide multiple pathways for transferring nutrients and energy into ecosystems (Wipfli et al. 1999), including direct consumption by numerous fish, amphibians, and terrestrial vertebrates (Cederholm et al. 2000; Jauquet et al., this volume). In addition, adult spawners distribute themselves freely throughout the watershed, a basic but underappreciated fact that becomes very evident when examining the logistics of redistributing thousands of kilograms of salmon carcasses in a drainage basin.

The reality of the current salmon crisis in the PNW is that sufficient numbers of salmon carcasses are not always available for distribution, particularly in basins where salmon runs have been severely depressed for many years. Under these conditions, the only option open to 'kick-start' population growth and restore ecosystem production is to examine alternate sources of nutrients. This is an important scientific and psychological step that often causes biologists to re-examine their basic understanding of the freshwater ecology and early life history of salmonids. Inorganic nutrients, while far from being a complete nutrient package, can increase salmonid production by stimulating autotrophic production at the base of the food web (Stockner and MacIsaac 1996; Ward et al., this volume). This bias against inorganic nutrients likely arises from confusion about the relative roles of allochthonous versus autochthonous carbon sources and resultant energy flows in forested stream ecosystems (Minshall 1978; Johnston et al. 1990).

A variety of inorganic nutrient formulations are suitable for lake and stream enrichment. Most formulations have been manufactured for agricultural use; hence, the accepted convention is to express the macronutrient content in terms of three numbers (e.g. 10-34-0 [ammonium polyphosphate]). These numbers refer to the percentage by weight of N, P_2O_5, and K_2O in the product. It is very important to note that phosphorus is expressed as percentage by weight as P_2O_5 and not as P or PO_4. This has caused much confusion when designing an enrichment program! To convert from percentage by weight of P_2O_5 to percentage by weight of P, one simply divides the percent P_2O_5 by 2.29 to obtain the percent P by weight. For example, 10-34-0 (ammonium polyphosphate) contains 34% P_2O_5 by weight and 14.8% P by weight (i.e., 34/2.29). Therefore, 10 kg of liquid 10-34-0 fertilizer contains 1.48 kg of P.

The molecular formulation that the P and N occur in can also vary among fertilizers. The P always exists in a phosphate molecule (PO_4^{-3}), as elemental phosphorus does not occur naturally on earth (Emsley 2000). The P can also occur in long chains as polyphosphate (as in 10-34-0), and bioassay experiments indicate that polyphosphate is a better P source for lake and stream fertilization, as the time required for hydrolysis of the poly-P bonds acts as a slow-release agent that favors small-sized phytoplankton with rapid uptake capabilities (Suttle et al. 1988, 1991). Nitrogen in inorganic fertilizers can be obtained in a variety of formulations including nitrate alone (e.g., granular $CaNO_3$), as ammonia-nitrate blends (e.g., granular 34.5-0-0 ammonium nitrate), as urea alone, or as urea-ammonium nitrate blends (e.g., liquid 32-0-0 and 28-0-0). Most phytoplankton and periphyton must synthesize the enzyme nitrogenase before NO_3^- can be utilized, but ammonium can be directly utilized and, hence, is the preferred form of N for aquatic ecosystems.

One of the most frequently asked questions by biologists and the public regarding the use of inorganic nutrients is the concern about heavy metal contamination of fertilizer products. The phosphorus in inorganic fertilizers is derived from phosphate rock that is mined from several principal phosphate deposits around the Earth. Each ore body has a characteristic signature of heavy metals that is unique to the geology of the ore deposit. An emerging concern is that all of the Earth's high quality phosphate rock deposits have already been mined and that the concentration of heavy metals is increasing in the remaining deposits as the phosphate industry extracts lower quality ore (Driver et al. 1999). For example, the concentration of mercury is highest in Chinese ore, whereas cadmium and chromium tend to be highest in Idaho phosphate deposits (Table 2).

Therefore, careful scrutiny of the ore source can significantly reduce heavy metal concentrations in the phosphate fertilizer. An alternate but more expensive approach for reducing heavy metal concentrations is to specify food grade (human consumption) or feed grade (animal consumption) phosphate in the fertilizer. The slow-release stream fertilizer used in British Columbia is manufactured with food grade phosphate (Sterling and Ashley, this volume). Pharmaceutical grade phosphate is the purest type of phosphate; however it so expensive that it is suitable only for small mesocosms or laboratory scale experiments.

Storage and Handling

Fertilizers. Solid fertilizers absorb moisture; hence, they need to be stored in a cool, dry place to prevent caking. The nutrients in liquid fertilizers (e.g., 10-34-0) will precipitate or 'salt out' in cold weather when mixed with higher concentrations of nitrogen fertilizer (e.g., 32-0-0). The resultant jelly-like precipitate will clog pumps and small orifices, and it is a troublesome problem to rectify. In practice, 28-0-0 has proven to be less prone to precipitate when blended with 10-34-0. Ideally, supplies of fertilizer should not exceed seasonal requirements so that all liquid fertilizer is used during the treatment season and winter storage is not required. Most solid and liquid fertilizers are quite corrosive, and standard safety precautions should be taken when handling the various products. Most metallic and ferrous compounds corrode very quickly when exposed to fertilizer (e.g. phosphoric acid and ammonium polyphosphate), and care must be taken to thoroughly clean equipment soon after use. Ammonium nitrate is extremely explosive if exposed to sparks or open flames and fuel oil and should be handled very carefully and never transported or stored near fuel oil or an ignition source.

Carcasses. Salmon carcasses have a limited 'shelf life' due to exponential mass loss and must be applied to lake, stream, and riparian habitat as soon as they become available; hence, the need for good project planning and close attention to

TABLE 2. Concentration of heavy metals in various phosphate ore deposits. Note: table taken from Driver et al. 1999.

Country	Deposit	P_2O_5	As	Cd	Cr	Hg	U	V
		wt %	mg/g	μg/g	mg/g	μ/kg	mg/g	mg/g
Israel		32	5	25	227	130	150	200
Jordan		32	8	5	92	48	78	70
Morocco	Bu Craa	35.1	Nr	37.5	Nr	Nr	75	Nr
	Louribga	32.6	13.3	15.1	200	855	88	106
	Youssoufia	31.2	9.2	29.2	255	120	97	200
Togo		36.7	10	58.4	101	365	94	60
USA	Florida	31.9	11.3	9.1	60	199	141	108
	Idaho	31.7	23.7	92.3	290	107	107	769
	N. Carolina	29.9	11.2	38.2	158	233	65	26
South Africa		39.5	11	<2	Nr	Nr	9	17
Tunisia		29.3	4.5	39.5	144	Nr	44	27
Senegal		35.9	17.4	86.7	140	270	67	523
Australia		28.9	14	4	35	75	84	63
Syria		31.9	4	3	105	28	75	140
China		31	26	2.5	33	4,990	22.8	80

Nr = not recorded

logistics are keys to a successful carcass treatment plan. Decomposition rates for salmon, derived from a single exponential regression, range from $k = -0.033$/day to $k = -0.061$/day (Chaloner et al. 2002). Rainbow trout decompose at 1.5%/day at 4.2°C and 4.9%/day at 8.6°C (Minshall et al. 1991). If carcass distribution is delayed, the carcasses can be frozen for application at a later date; however, each should be individually frozen on racks and not be frozen in aggregate or in plastic bags, as they will be difficult to separate for later use. Commercial freezing is relatively inexpensive and is a plausible alternative if adequate freezer capacity is un- available.

3. Seasonal Timing of Application

The seasonal timing of inorganic nutrient application in temperate lakes corresponds to the normal ice-free growing season that coincides with the period of stable thermal stratification in dimictic and warm-monomictic lakes. A 20–22 week application window from late April to early September is standard for most lakes and reservoirs in southern British Columbia (Stephens and Stockner 1983; Stockner and Ashley, this volume). This period would be reduced accordingly at higher elevations or latitudes as the growing season shortens. Nutrients can be added at a constant application rate throughout the growing season or 'front-end' loaded to apply more phosphorus and less nitrogen during the early part of the season when concentrations of DIN in most systems are at maximum levels. The 'front end loading' concept is intended to simulate spring freshet conditions for phosphorus loading and substantially increase spring production on the tail of the 'freshet' P-input. Ever increasing loads of N, as the season progresses, compensates for the rapid spring biological uptake and gradual depletion of epilimnetic DIN; this regimen also matches phytoplankton production to the seasonal patterns of the early copepod and later cladoceran population increases (Stockner and MacIsaac 1996). This loading pattern results in a late spring peak in P input, which then declines to a constant summer loading and eventually to a reduced late summer loading (Figure 1). If sufficient ambient epilimnetic DIN concentrations are present to sustain production through the growing season without periods of depletion, then nitrogen applications can start at very low rates in the spring, with only slightly higher rates throughout the summer. This strategy is designed to prevent DIN limitation and decrease the likelihood of colonial cyanobacteria (blue-green algae) blooms that are often associated with N depletion or low N:P ratios (Smith 1983; Pick and Lean 1987).

In rivers and streams, the seasonal timing of application depends on the nutrient source being considered. If salmon carcasses are used, the general rule is to apply them at the same time as the historic salmon runs (i.e., mimic nature). If inorganic nutrients are being used, the principle is to apply the nutrients during the summer growing season, which will vary depending on latitude and elevation. In British Columbia, the standard practice is to begin applying nutrients on the descending limb of the hydrograph. In southern rivers, such as the Keogh River on northern Vancouver Island, this can be as early as late April. In more northern systems that exhibit snow-melt freshets in late May and June (e.g., Mesilinka River), nutrients are typically applied in early July and sometimes as late as mid-July depending on the magnitude and duration of the freshet period.

4. Frequency of Nutrient Addition

Lakes. There is a paucity of information on the 'optimal' or best frequency of nutrient addition to rivers (Ashley and Slaney 1997), but there have been some studies on application frequency to lakes to optimize production (Stephens and Stockner 1983). The basic principle is to add nutrients as often as technically feasible without exceeding economic or logistic constraints (resources). In lakes, laboratory experiments have demonstrated that more frequent pulses of light nutrient loads favor smaller-sized phytoplankton (e.g., picoplankton), as their greater surface area to volume ratio permits rapid nutrient uptake (Suttle et al. 1987). Less frequent weekly loadings with higher loads initially stimulate picoplankters but gradually tend to favor larger-sized nano- and micro-phytoplankton that have slower uptake rates but larger internal P storage capabilities (Suttle et al. 1987). After several decades of lake enrichment, weekly application rates have provided the best community production responses, and these have proven to be logistically the most feasible application frequency for lake fertilization (Stockner 1987; Stephens and Stockner 1983; Stockner and MacIsaac 1996; Ashley et al. 1999). In some cases, due to unique

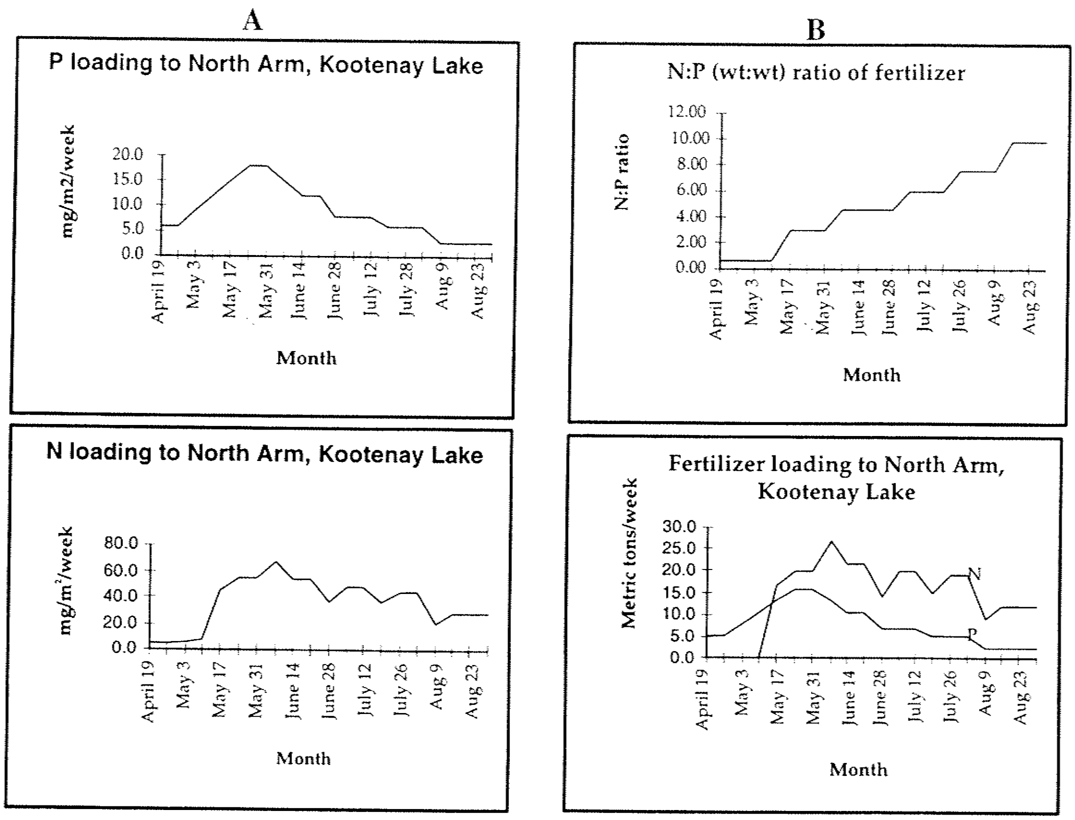

FIGURE 1. Example of a 'front end' nutrient-loading schedule for Kootenay Lake, British Columbia. A. Weekly areal P and N loading rates; B. Variation in weekly N:P ratio and weight (tonnes) of fertilizer added.

application opportunities, nutrient additions have been made several times per day from regularly scheduled ferry runs with a positive plankton response (e.g., Arrow Reservoir; Pieters et al., this volume). Innovative low-cost techniques for continuous nutrient loading to small lakes or embayments of large lakes have included placing bags of granular fertilizer in tributary streams to slowly dissolve (Milbrink and Holmgren 1981) or by using floating screen bottomed boxes near the lake center and allowing wave action to gradually dissolve solid granular fertilizer and distribute the nutrients throughout the lake (Ashley and Johnson 1989). The temperature and turbidity of inflowing streams must be examined first to determine if the resulting density will enter the epilimnion or plunge to an intermediate depth with a resultant loss in effectiveness of nutrient delivery.

Streams. In streams, the frequency of application depends primarily on the predominant nutrient sources (e.g., groundwater, carcasses, and alder). Ideally, salmon carcasses should be added at the same frequency as they once occurred in the river system, mimicking natural events. Historically, many rivers received multiple escapements that could start as early as April and last until late fall. Economics, logistics, and availability will likely determine the best frequency for carcass application. When applying inorganic nutrients to streams, the same rule applies as additions to lakes (i.e., more frequent, weekly applications are preferred). This is intended to prevent accumulation of nuisance algae and also to avoid large doses of fertilizer where the ammonia component could reach concentrations potentially toxic to fish.

In practice, simple gravity-fed drip systems have proven difficult to regulate due to constant clogging of the fine orifice valves with fertilizer precipitate. In addition, daily variations in air temperature affected fertilizer drip rates, thus under or overapplying nutrients. Three innovative application systems have been developed to facilitate nutrient addition to streams:

(1) Flow proportional fertilizer injection systems that use a pressure sensor to determine real-time stage-discharge information; programmable peristaltic pumps then inject the exact amount of fertilzer to attain the desired concentration, thus providing constant application rates. These systems were accurate and reliable but energy intensive; hence, photovoltaic pannels should be incorporated into the system to extend the operating time of the pump batteries;

(2) Pre-programmed units similar to (1) above, designed for metering fertilizer into snowmelt dominated river systems to which fertilizer was added at 20-minute intervals following a pre-programmed exponential decay curve for nutrient loading (Wilson et al., this volume);

(3) The most promising technique for constant application has been the development of slow-release inorganic nutrient briquettes (Sterling et al. 2000). Briquettes are added annually by hand or helicopter, thus allowing once-per-year treatments that are particularly useful in remote regions (Sterling and Ashley, this volume).

5. Location of Application Sites

Streams. The location of application sites depends mainly on the nutrient source(s) being applied. In anadromous salmon ecosystems, carcass applications should cover as much of the adult spawning habitat as feasible, and most intensive applications should be well away from stream mouths and estuaries so that nutrient spiraling works effectively throughout the length of the anadromous salmon use zone. The presence of large woody debris (LWD) will significantly improve carcass retention (Cederholm et al. 1988); hence, application zones can be modified somewhat to take advantage of differential LWD availability in logged and unlogged sections of the same river system. In areas where agricultural or anthropogenic input of nutrients has raised ambient concentrations of nutrients above limiting values, carcasses can be applied in riparian zones, thus enriching the terrestrial portion of the nutrient shadow without contributing to excessive enrichment of the aquatic ecosystem.

When using inorganic nutrients, the principle factors influencing the location of nutrient addition are the logistics of delivering nutrients to the application site(s) and the nutrient spiraling length of the ecosystem. In practice, these two factors should be integrated whenever possible to optimize the treatment plan. In remote regions, the cost and logistics of delivering large quantities of liquid fertilizer is often the critical factor when deciding whether to proceed with a nutrient enrichment project. If there are adequate sites for liquid fertilizer tank storage, then the application sites should be located to function in concert with the inherent nutrient spiraling characteristics of the stream or river to provide the most ecologically effective nutrient enrichment. If the geography of the site location precludes establishment of liquid fertilizer tank farms, slow-release fertilizer, although more expensive, can be used in a manner consistent with nutrient spiraling distances. If the increased cost of the slow-release fertilizer exceeds the project budget, then it is preferable to defer the project until additional funds are obtained or logistical constraints removed, rather than proceeding with a precarious and ecologically risky treatment plan.

In streams, the gravitational flow of water downhill displaces nutrients considerable distances downstream as nutrients are taken up by autotrophic and microbial biomass and recycled or 'spiraled' through the biota and back to the water (Mulholland 1996). Experiments involving radioactive $^{32}PO_4$ applications to streams have confirmed that spiraling does occur and that the distance traveled is dominated by the water component (i.e., water velocity). Increasing the uptake of nutrients from the water may reduce spiraling distance. For example, filter-feeding invertebrates, through capture of seston, may impede downstream transport of organic matter and effectively reduce spiraling distance (Minshall et al. 1985). In addition, some nutrient cycling does take place within the boundary zones created by benthic algae that does not involve downstream displacement and, hence, is an alternative pathway to nutrient spiraling (Mulholland 1996). Evidence from river fertilization experiments indicates that increased periphyton and presumably heterotrophic microbial biomass can extract sufficient nutrients from the water to shift P-limited systems to N and P co-limitation; hence, spiraling length has likely been reduced by increasing the biomass and effective nutrient uptake capacity of the biological community (Slaney et al. 1994; Wilson et al., this volume). An example of an integrated treatment plan is the Keogh River that flows for 30 km from source to ocean (Ward et al., this volume). The prescription for the Keogh required ~1,000 kg of slow release fertilizer, and previous enrichment experiments (Slaney et al., this volume) indicated a spiraling distance of ~6 km. Therefore, 200 kg of slow-release fertilizer was applied at the start of the Keogh River, and four additional 200-kg treatments applied at 6-km intervals moving downstream towards the mouth of the river. This approach avoids excessive single-site enrichment effects by distributing nutrients in a manner that is ecologically consistent with each river's inherent spiraling distance. Additional research is required to further our understanding of nutrient spiraling and enrichment practices.

Lakes. Nutrient application to most lakes targets pelagic phytoplankton and ultimately the zooplankton forage-base of sockeye salmon or land-locked kokanee. Therefore, on larger water bodies (>100 ha), nutrient application is on transect lines toward the center of the lake and well away from lake littoral margins (>500 m from shorelines) and outflow river mouths (e.g., Ashley et al. 1999). If shore spawning is a prevalent feature of the salmon run, then treatment can include application over the littoral zone as well as near shore pelagic. It is important to disperse the nutrients over as wide an area as possible so that dilution by epilimnetic water prevents 'pooling' and sinking of concentrated fertilizer into the metalimnion. Dye studies have confirmed that horizontal dispersion in small lakes is consistent with previous observations in oceans and large lakes (Lawrence et al. 1995); hence, wind-driven circulation will distribute nutrients over a large area, albeit at a rate considerably slower than the biological uptake of nutrients in the water column. Shore-based water pumps have been successfully used in small lakes to spray a dilute liquid fertilizer mixture ~10 m offshore; however, this must be done frequently enough to avoid harmful concentrations of ammonia in the treatment zone (Johnson et al. 1999). Again, a tradeoff between logistics, cost, and ecological principles will determine the most effective location for nutrient application.

6. N:P Ratio of Nutrient Blend

Once the desired concentration of N and P has been determined, the ratio of ambient nitrogen to phosphorus (i.e., N:P ratio) must be calculated to determine whether the system is limited by more than one macronutrient. The Redfield ratio, which is the cellular atomic ratio of C, N, and P in marine phytoplankton, provides a benchmark for assessing nutrient limitation, most commonly between N and P (Borchardt 1996). N:P ratios can be calculated as total nitrogen divided by total phosphorus (e.g., TN/TP); however, the utility of this calculation is limited due to the large percentage of refractory N and P incorporated in the TN and TP analyses. It is much more informative to compare the N to P ratios of biologically available nutrient, and the best approximation for this is the DIN/TDP ratio (Stockner and MacIsaac 1996).

Ambient N:P atomic ratios greater than 20:1 are considered P limiting, less than 10:1 is N limiting, and between 10 and 20:1, the distinction is equivocal (Borchardt 1996). Atomic weight ratios can be converted to weight:weight ratios by multiplying by the atomic weight of the element in question. For example, a 10:1 N:P atomic weight ratio is equivalent to a 4.5:1 N:P weight:weight ratio (e.g., $10 \times 14/1 \times 31 = 4.5$, where 14 = atomic weight N, 31 = atomic weight P). Minimum target N:P ratios (weight:weight) should be at least 7.5:1 (i.e., 30 µg/L NO_3-N + NO_2-N + NH_3-N/4 µg/L SRP; ambient concentration plus added nutrients) to ensure the system does not become co-limited by N.

The ambient N:P ratio will vary as a function of the drainage basin's underlying bedrock geology, as modified by the existing topography and precipitation regime. As a general rule, productivity and nutrients tend to be lower in coastal waters where the underlying geology is mainly erosion resistant granites and rainfall is high (Stockner 1981). In British Columbia, the interior plains, except for the northeast, are composed mainly of nonmetamorphosed sedimentary and volcanic rocks; hence, interior lakes, rivers, and streams usually have a higher concentration of dissolved ions (TDS) and higher productivities and ambient nutrient concentrations (Stockner 1987), although many examples of nutrient deficient interior streams are known as well (Slaney et al., this volume). In parts of Washington and Oregon, the geology has been heavily influenced by volcanic activity that often results in higher concentrations of phosphorus but low concentrations of dissolved inorganic nitrogen. Many of these systems are naturally nitrogen-limited (e.g., Sandy and Clackamas rivers, Mt. Hood area; D. Shively, U.S. Forest Service, Mt. Hood National Forest, unpublished data).

In British Columbia, many coastal streams (e.g., Adams River, Big Silver Creek, Keogh River) usually have soluble reactive phosphate (i.e., SRP) concentrations less than 1 μg/L and adequate dissolved inorganic nitrogen (i.e., DIN) greater than 30 μg/L, whereas some interior streams (e.g., Blackwater River) have 27 μg/LP and less than 5 μg/LDIN. Rivers that span two or more biophysiographic regions may exhibit blended nutrient regimes as a ratio of their respective watershed areas and water yields. Thus, it is possible to have a productive system on the coast (e.g., Dean River) because the majority of the nutrients are derived from an interior basin. Similarly, lake-headed river systems can significantly modify downstream nutrient regimes, owing to the uptake, retention, and bioassimilation of nutrients within the lake, although to some extent this is compensated for in the immediate outlet zone due to washout of lake seston. For example, the Nechako River, which flows across the B.C. interior, is both N- and P-limited due to its large coastal drainage basin and large headwater lakes, whereas the Nation River is N-limited due to the presence of headwater lakes.

7. Application Techniques

The topic of nutrient application often receives the least amount of research attention, yet is one of the most important aspects of an effective nutrient enrichment program. A scientifically correct program can fail if the logistical aspects of nutrient application have been improperly planned. Conversely, a logistically correct application program may be ineffective if it is not ecologically sensible. Hence, the application technique must be appropriate for the specific characteristics of each treatment project. Tables 3 and 4 summarize some of the general observations to date, gathered from projects that have been successful and those that have not. Two general rules emerge: (1) attempt to mimic nature whenever possible; (2) be cognizant of the density differential between the nutrients being added and the water body in question. Slight differences in density will cause nutrients, either in the form of liquid fertilizer or dissolved from solid granular fertilizer to rapidly sink; hence, it is important to dilute the fertilizer to avoid its sinking through the epilimnion. Dilutions in the order of 10,000:1 have been used to avoid this problem (G. Lawrence, University of British Columbia, Vancouver, personal communication). Finally, be creative; nutrient enrichment is a relatively new field and many new techniques have yet to be discovered. Just ensure that ecological principles and logistical constraints receive equal consideration and are not at odds with each other.

Once the specifics of the application technique has been resolved, a summary table of the seven key variables should be developed and reviewed to ensure that the plan is enrichment plan is technically sound (Table 5).

Conclusions

There are a variety of application techniques available to fisheries managers seeking to enhance the production of salmonid rearing habitat. After a minimum 1–2 year pre-treatment study, one must carefully consider the specific requirements of the ecosystem, N or P or co- limitation of autotrophic production, and then select the technique that is best suited for the ecosystem. Be creative; try to mimic the arrival of the anadromous salmon 'nutrient pump' where applicable, and proceed to write the nutrient prescription so as to assure a well-balanced seasonal N:P ratio in receiving wa-

TABLE 3. Summary of nutrient application techniques for lakes and reservoirs.

Nutrient source	Application techniques	Issues
Salmon carcasses	Manual or aerial application in littoral zones	Logistics of transport and application, transplant permits, seasonal availability of carcasses
Granular fertilizer	Aerial (fixed or rotary wing), tug-barge, shore based spray, lake center dispersion	Logistics of transport, delivery, mixing, storage and application, density differences
Liquid fertilizer	Aerial (fixed or rotary wing), tug-barge, shore based spray, lake center dispersion	Logistics of transport, delivery, storage, spill containment and application, density differences
Slow-release solid fertilizer	Manual or aerial (rotary wing) application in littoral or reservoir drawdown zones	Logistics of transport and application, density differences, seasonality of reservoir drawdown

TABLE 4. Summary of nutrient application techniques for streams and rivers.

Nutrient source	Application techniques	Issues
Salmon carcasses	Manual or aerial (rotary wing) application	Logistics of transport and application, transplant permits, seasonal availability of carcasses, public and agency notification
Granular fertilizer	Automatic application stations	Logistics of transport, delivery, mixing, storage and application, nutrient spiraling distance, public and agency notification, energy sources
Liquid fertilizer	Manual drip stations, flow proportional or pre-programmed (snow-melt systems only) injection systems	Logistics of transport, delivery, storage, spill containment and application, nutrient spiraling distance, public and agency notification, en ergy sources
Slow-release solid fertilizer	Manual or aerial (rotary wing) application	Logistics of transport and application, nutrient spiraling distances, cost, public and agency notification

ters that have sufficient dissolved N to assure the production of edible phytoplankton/periphyton and to avoid the occurrence of nuisance colonial cyanobacteria in lakes or mats of colonial greens in streams. One must develop a prudent application strategy that insures that nutrient additions are well dispersed in stream or within the epilimnion and are applied at an appropriate frequency extending over a time period sufficient to illicit a response (e.g., weekly additions for lakes over a 22-week period). Finally, one must proceed to notify appropriate authorities well in advance of first nutrient applications and secure the necessary permits, which should include a requirement to monitor the ecosystem responses throughout the duration of the application period and for one year after cessation of supplementation.

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TABLE 5. Examples from the Kootenay Lake and Keogh River fertilization programs listing the seven key variables of nutrient enrichment.

Key variable	Kootenay Lake	Keogh River
1. Concentration of applied nutrients	P = 271 mg/m^2 (13.6 μg/L); N = 1,191 mg/m^2 (59.5 μg/L) in 0–20 m epilimnion	5 μg/L P, 3.7 μg/L N
2. Nutrient formulation	Blend of 10-34-0 and 28-0-0 liquid agricultural fertilizer	7-40-0 slow release fertilizer
3. Seasonal timing of application	3rd week in April to end of August	Late spring
4. Frequency of nutrient addition	Weekly, Monday morning	Single application in late spring
5. Location of application sites	10-km zone in the center of the North Arm	River source and 6-km intervals
6. N:P ratio of nutrient blend	Seasonally adjusted at 3–4 week intervals from 0.67:1 to 7.5:1 (wt:wt basis)	0.4:1
7. Application technique	Tug/barge, surface spray + propeller mising travelling at 5 km/hr	

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