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Evaluations of Slow-Release Fertilizer for Rehabilitating Oligotrophic Streams

MEGAN S. STERLING

B.C. Conservation Foundation, #206-17564
56A Avenue, Surrey, B.C. V3S 1G3, Canada

KENNETH I. ASHLEY

Research and Development Section, British Columbia Ministry of Fisheries
2204 Main Mall, Vancouver, B.C. V6T 1Z4, Canada

Abstract.—A solid briquette fertilizer for use in the Pacific Northwest streams and elsewhere was identified from a variety of slow-release formulations (26 were tested with varying $N:P_2O_5:K_2O$ ratios and binders) using indoor trough and controlled field experiments. The use of a slow-release fertilizer is an innovative method for adding inorganic nutrients to nutrient-poor (oligotrophic) streams to increase autotrophic production and aid in the restoration of salmonid populations. A series of indoor trough experiments demonstrated that the majority of samples containing binders of molasses, hydrated lime, vegetable oil, bentonite, starch, acrawax, candle wax, and Daratak® XB-3631 (unpolymerized Saran™) dissolved too slowly. The fastest dissolution rates occurred with fertilizer briquettes having no binder or vegetable oil. Further trough and field studies using fertilizer with no binder and vegetable oil as binder examined the effects of varying $N:P_2O_5:K_2O$ ratios. Dissolution rates were varied by using different percentages of magnesium ammonium phosphate (MagAmP; its formula 7:40:0 $N:P_2O_5:K_2O$) and urea (46:0:0). Optimal continual nutrient release for a period of four months was achieved with a fertilizer formulation of 17:30:0 (percent by weight $N:P_2O_5:K_2O$), with a ratio of 75% MagAmP to 25% urea, and containing no binder. The dissolution rate for this product ranged from 4.6% to 6.6% per week (for field and trough experiments, respectively) in water of 0.15 m/s average velocity. These studies indicate that a slow-release fertilizer product can be manufactured to last approximately four months when applied in the spring to stimulate autotrophic production in nutrient deficient streams, thereby increasing forage and salmonid production.

Introduction

Pacific salmon accumulate nutrients while feeding and growing during their ocean rearing life stage. Marine-derived nitrogen, carbon and phosphorus, and organic matter of high nutritional value contained in eggs and carcasses are transferred to the freshwater environment by adult salmon returning to spawn (Bilby et al. 1996; Gresh et al. 2000). The return of spawning salmon and associated marine-derived nutrients (MDN) to freshwater ecosystems are important for sustaining primary productivity, salmon populations, and nontarget species (e.g., riparian vegetation, carnivores, and scavengers) in the Pacific Northwest's N- and P-limited freshwater ecosystems (Stockner 1987; Ashley and Slaney 1997; Cederholm et al. 2000).

The current decreased return of spawners and declining input of MDN to the Pacific Northwest's freshwater environment results from a number of factors, including overfishing, loss of freshwater and estuarine habitat, construction of dams, and water pollution from industrial activities (Slaney et al. 1996; Stockner and MacIsaac 1996). Generally, fewer salmon carcasses results in reduced primary productivity in nutrient limited systems and, hence, less food available for the next generation of salmon (Larkin and Slaney 1996). Smaller and weaker fish may have reduced ocean survival and lose their opportunity to spawn in their natal stream (Ashley and Slaney 1997; Gresh et al. 2000).

In order to counter the "negative feedback loop" of salmon productivity, nutrient additions to oligotrophic streams have been shown to effectively enhance ecosystem productivity, including growth and survival of juvenile salmonids (Perrin et al. 1987; Slaney and Ward 1993; Bilby et al. 1996; Ashley and Slaney 1997; Larkin and Slaney 1997). Liquid fertilizers traditionally have been the product of choice for stimulating the base of the food chain, but their use is limited to more accessible streams and rivers, and application is expensive due to the high cost of maintenance that is required (Ashley and Slaney 1997). Slow-release fertilizers have the advantage that a once-per-year or per-season application is much more operationally efficient than continuous drip or monthly applications of solid granular fertilizers.

Target Slow-Release Fertilizer Characteristics

The ideal slow-release fertilizer briquette should consistently and uniformly release a chosen nutrient concentration at the appropriate N:P ratio. Briquette size should be large enough to avoid fluvial transport or burial in sand, yet dissolve over a period of approximately four months. Binders should be natural or biodegradable and strong enough for aerial application, and the briquette should resemble stream substrate to avoid vandalism. Phosphorus quality must be food grade to ensure that trace metal concentrations meet the most stringent water quality criteria.

Slow-Release Fertilizer Development

The first slow-release fertilizers used in British Columbia were introduced to the Keogh River on northern Vancouver Island. They consisted of crushed barley and agricultural fertilizer pellets. Barley was less effective than the agricultural fertilizer pellets and was labor-intensive to introduce (Perrin et al. 1987). In 1983, a solid prill, slow-release fertilizer with a soybean resin coating (Osmocote™, Sierra Chemical Ltd., Milpitas, California) was used, but the briquettes dissolved too quickly, releasing the nutrients immediately after application, even with the thickest coating. They also fractured during aerial application, and the cost was 2–4 times higher than conventional granular agricultural blends (Johnston et al. 1990).

In 1994, slow-release fertilizers developed by I.M.C. Vigoro (Winter Haven, Florida), Cominco Fertilizers (Calgary, Alberta) and Sierra Chemical (Milpitas, California) were tested (Pons 1995). I.M.C. Vigoro's product, using MagAmP (magnesium ammonium phosphate) and Daratak® XB-3631 (unpolymerized Saran™: vinylidene chloride-acrylic acid-2-ethylhexyl acrylate polymer) as a binder, proved to be the most suitable for stream fertilization, based on these trials. Chemical and physical factors affecting phosphorus bioavail-ability (as PO_4^{3-}), as well as the response of periphyton growth to nutrient additions, were determined for I.M.C. Vigoro's product (Sterling 1997; Sterling et al. 2000).

Successful aerial and hand application of I.M.C. Vigoro's slow-release fertilizer (3 μg/L dissolved inorganic phosphorus) occurred from 1995 to 1997 in a variety of B.C. streams (Mouldey and Ashley 1996). Diatom and invertebrate production was enhanced in a matter of weeks and lasted 3–12 months, as anticipated. However, I.M.C. Vigoro discontinued manufacturing the fertilizer in 1997.

In 1999, another fertilizer company (Lesco Inc., Rocky River, Ohio) was identified as capable of manufacturing slow-release fertilizer briquettes with characteristics similar to I.M.C. Vigoro's product. This paper examines the dissolution rate characteristics of Lesco's products in order to determine an optimal slow-release fertilizer for use in candidate Pacific Northwest streams chosen for nutrient supplementation to aid in salmon restoration.

Methods

The dissolution rates of 26 formulations supplied by Lesco Inc. were evaluated during exposure to a range of water temperatures and velocities in indoor troughs and a constructed side channel. Four key characteristics were considered: binder type, duration of nutrient addition, N:P ratio, and metal concentrations.

1. Binder Type

An ideal binder will not fracture during aerial application and will release nutrients uniformly over time. Binder formulations tested ranged from no binder to combinations of molasses, hydrated lime, vegetable oil, bentonite, starch, water, acrawax, candle wax, methocel cellulose, and Daratak®.

2. Duration of Nutrient Addition

Ideally, the fertilizer should last approximately four months when applied in late spring or early summer in the Pacific Northwest. Dissolution rate of the briquettes was altered by varying the magnesium ammonium phosphate (MagAmP; 7:40:0 $N:P_2O_5:K_2O$) and urea (46:0:0) proportions, which ranged from 85.75% MagAmP and 14.25% urea to 75% MagAmP and 25% urea. Urea dissolves quickly upon contact with water and produces a "Swiss cheese" effect in the briquette that enhances the dissolution rate.

3. N:P Ratio (for Application in Both N- and P-Limited Streams).

Streams are considered N-limited when the N:P atomic weight ratio is less than 10:1, co-limited when N:P is between 10:1–20:1, and P-limited when N:P is greater than 20:1 (Borchardt 1996). The formulations that were tested had N:P ratios ranging from 7:40 to 17:30.

Metal Concentrations. The presence of metals in the manufactured fertilizer product is based on the purity of the phosphoric acid source. Some metals of concern are lead, nickel, cadmium, arsenic, magnesium, and mercury. Their concentrations were closely monitored by analytical laboratory analyses before the fertilizer products were tested in the field.

4. Indoor Trough Studies to Determine Dissolution Rates

Indoor channels located at a trout hatchery in Abbotsford, B.C., were used to determine the dissolution rates of a variety of fertilizer briquettes. Fertilizer supplied by Lesco Inc. contained 12% magnesium, 7% nitrogen, and 40% P_2O_5 by weight, existing as the $MgNH_4PO_4 \cdot H_2O$ compound. Briquettes were formed by compressing ~9 g of fertilizer with a variety of binders.

Hatchery-heated water (14.0°C) and well water (9.5°C) were used but had a flow restriction, limiting water temperature of 13.0 ± 0.5°C to a velocity of 0.30 ± 0.03 m/s. Variations in temperature and velocity were obtained by mixing heated water and groundwater sources, as well as adjusting the trough slopes. Water velocity was measured using a Marsh McBirney, Inc. Model 2000 Portable Flowmeter. Temperature gradients across the troughs were eliminated by water hose positioning.

Plexiglas troughs, modeled after Bothwell (1983, 1988), were equipped with various dams at the head of the troughs to reduce visible turbulence. A total of three troughs were used, each containing four to six wires strung with six to eight fertilizer briquettes. The briquettes were drilled, individually weighed, and strung, separated by 5-mm diameter plastic beads, onto galvanized wire. Extra beads were strung on each end of the wires to keep the briquettes from the slower-moving water at the trough edges. Each sampling day, the briquettes furthest downstream were removed, air-dried for two weeks at 17.5°C, desiccated, and weighed to determine dissolution rate. Sampling varied according to the number of briquettes available but took place over a period of two months and occurred 1, 2, 3, 4, 6, and 8 weeks after the briquettes were introduced to the flowing water.

Initial Screening of Fertilizer Samples

Initially, 18 samples were provided in two batches and tested in June 1999. The first trial (samples A–J; Table 1) contained two briquettes per sample (sampled at 4th and 8th week). A second trial[1] (samples K–R) contained six briquettes per sample and were sampled at 1, 2, 3, 4, 6, and 8 weeks.

Dissolution Rates of Fertilizer Samples

A third trial of slow-release fertilizer samples involved 16 combinations of nutrients and binders. These briquettes were sampled from the troughs at 1, 2, 3, 4, 6, and 8 weeks. Variations in fertilizer formulation (A0 to D3) were achieved by using different percentages of magnesium ammonium phosphate (MagAmP; 7:40:0) and urea (46:0:0). The letter in the fertilizer identification represents the binder (A = none; B = Daratak® and vegetable oil; C = vegetable oil; and D = mo-

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[1] The fertilizer binders and N:P ratios were withheld for the second trial in order to conduct a blind study.

lasses, hydrated lime, and vegetable oil), and the number indicates the proportion of MagAmP and urea as $N:P_2O_5:K_2O$ (0 = 12.55: 34.3: 0; 1 = 13.44: 33.4: 0; 2 = 14.80: 32.0: 0; and 3 = 16.75: 30.0: 0).

Controlled Field and Indoor Trough Studies

Griffin Channel, a man-made side channel of North Vancouver's Mosquito Creek, was used for the field testing (trial four). The three trials of indoor trough dissolution rate experiments reduced the number of fertilizer samples to be tested in the field to six types. All four fertilizer samples with no binder (A0, A1, A2, A3) and two with vegetable oil binder containing the highest concentrations of urea (C2 and C3) were selected and tested simultaneously in the field and troughs to determine if briquette dissolution in the controlled environment was similar to the field environment.

The trough experiments were set up as in previous studies (Sterling 1997; Sterling et al. 2000). For the field studies, the briquettes were drilled, individually weighed, and labeled with a colored and numbered tag attached by galvanized wire. Approximately 1,000 individually-labeled briquettes were placed in riffle sections of the stream with a velocity of 0.15 ± 0.05 m/s and a temperature range of 3.6 ± 0.1°C to 5.2 ± 0.1°C; trough water velocities were set at 0.15 ± 0.04 m/s to match the field conditions, and temperature was 9.5 ± 0.1°C. Riffle velocities greater than 0.25 m/s were avoided because the briquettes are transported downstream where they settle in pools. Sterling et al. (2000) determined that temperature did not have a significant effect on dissolution rate of the fertilizer briquettes.

Eight briquettes were removed from the trough and thirty were randomly removed from the stream every two weeks. Sample numbers for the field study decreased near the end of the experiment because of difficulty locating the briquettes (some were buried and others were very well camouflaged). Sampling occurred for both trough and field studies at 2, 4, 6, and 8 weeks.

Results

Initial Screening of Fertilizer Samples

Ideally, after eight weeks, the fertilizer briquettes should dissolve by approximately 60%. In trial one, the majority of samples A–J had very slow, average release rates after eight weeks in the trough (13–32%). Sample G dissolved too quickly and fell off the wire before the first sampling at four weeks. None of these slow-release fertilizer samples were deemed promising.

In trial two, the majority of samples (K, L, N, O, P, Q, and R) had dissolution rates that were too slow (12–18%) with the exception of sample M (formulation withheld), which showed the most promise since 42% dissolved after eight weeks. The results from these two trials were provided to Lesco Inc. and were used to develop further samples that were tested.

Dissolution Rates of Fertilizer Samples

The average percent weight lost in trial three of the 16 different briquettes formulated from combinations of four binder types and four combinations of urea and MagAmP after eight weeks ranged from 17% to 55%. The slowest dissolution occurred with the Daratak™ and vegetable oil binder (B series), followed by molasses, hydrated lime, and vegetable oil binder (D series). The fastest occurred with no binder (A series) and vegetable oil binder (C series).

The dissolution rate of the briquettes was increased by increasing the proportions of highly soluble urea in the fertilizer (fertilizer identification numbers 2 and 3). Upon contact with the water, the urea dissolves creating a more porous briquette and increases the surface area in contact with the water. An initial 'pulse' of urea should not be a concern because urea is a long-chain molecule that takes time to break down (via bacterial decomposition) to nitrate, and previous experiments using urea in fertilizer have produced positive results because of its effective bacterial stimulation (Stockner and MacIsaac 1996).

Controlled Field and Indoor Trough Studies

Four fertilizer samples with no binder (A0, A1, A2, A3) and two with vegetable oil containing the highest concentrations of urea (C2 and C3) were tested simultaneously in the field and trough experiments during trial four. These compositions had the highest dissolution rates of the 16 samples tested in the previous batch and were also ideal because of their natural ingredients:

magnesium, ammonia, phosphate, and vegetable oil (canola oil).

In both the field and trough studies (Figures 1 and 2), the briquettes without binder (A series) had slower, more consistent release rates, as demonstrated by the linear dissolution rates compared with briquettes with vegetable oil binder (C series). A consistent release rate is favored for a slow-release fertilizer product. As with trial three, the dissolution rate of the fertilizer briquettes was proportionate to urea concentration.

Briquette dissolution rate was found to be similar in both the field and trough environments. The slow-release fertilizer that lost approximately 60% of its weight after eight weeks and had the most consistent dissolution in the field and trough was sample A3. Its dissolution rate (determined by slope calculation) ranged from 4.6% per week to 6.6% per week (53.3% to 63.6% after eight weeks) for field and trough experiments, respectively, in water of constant velocity (0.15 m/s). The increase in dissolution rate of the C2 and C3 products after six weeks (Figure 2) was potentially due to structural weakening of the briquette.

Discussion

Indoor trough and outdoor field testing of proprietary slow-release fertilizer products (Lesco Inc.) suggests that a formulation of 75% MagAmP and 25% urea with no binder (sample A3) is acceptable for instream use. It possesses characteristics that make it suitable for nutrient rehabilitation of the Pacific Northwest's oligotrophic streams. The briquette dissolves uniformly, and after eight weeks exposure, approximately 60% of the initial weight is lost, which is within the target dissolution rate.

The highest urea concentrations resulted in briquettes with the fastest dissolution rate. In addition, the 9-g briquette size is adequate for providing nutrient release over four to five months without being washed downstream by average summer flows in smaller streams. They can be

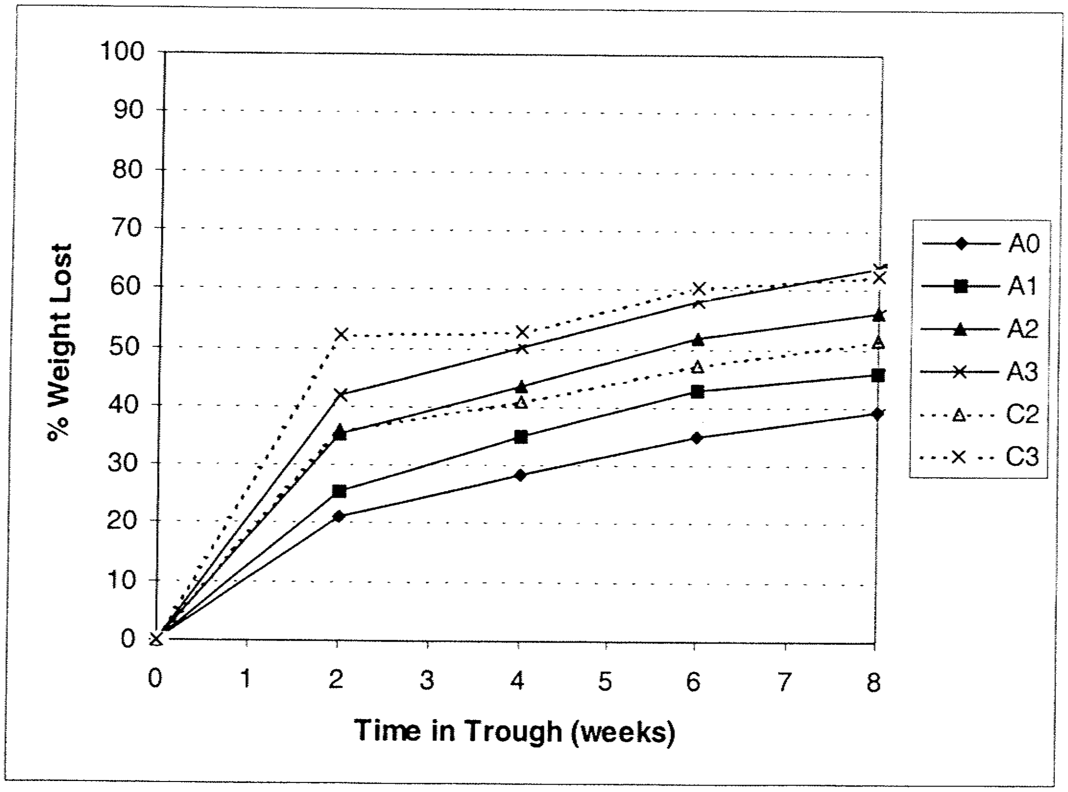

FIGURE 1. Average percent weight lost versus time for trough study (samples A0–A3, C2, and C3).

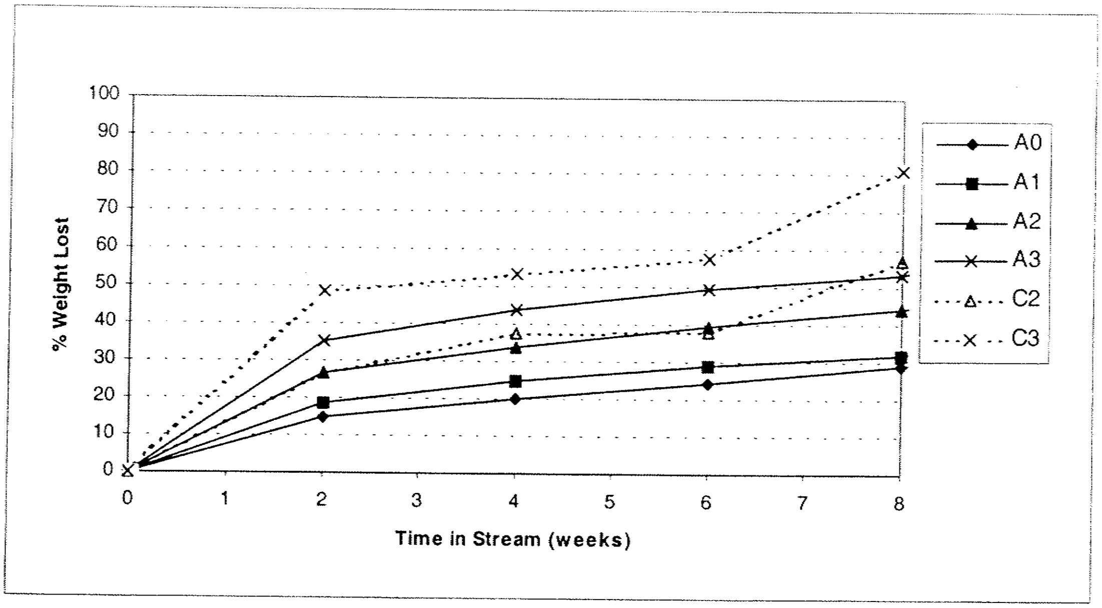

FIGURE 2. Average percent weight lost versus time for field study (samples A0–A3, C2, and C3).

hand-placed or distributed by aerial application in more remote systems.

These field experiments also demonstrated that the ideal location for briquette placement is around similar or slightly smaller-sized cobble substrate. This ensures that the briquettes are not buried in sand, nor washed away by larger flow events, since they are placed with substrate of similar size ensuring their perseverance at that stream location.

After the fertilizer briquettes are in contact with water for a few weeks, they become very well camouflaged due to a thin layer of biofilm, and they become darker from water saturation. This feature is advantageous because there is no concern of vandalism or alterations to the nutrient addition regime (i.e., frequent replacement of briquettes).

Based on the four considerations described in "Methods," the following is a summary of research findings to date:

1. The preferred fertilizer type is without any binder;
2. To achieve nutrients lasting approximately four months, the highest urea concentration (25%) is preferred, with the briquette dissolving at a rate of approximately 4.6% per week to 6.6% per week for field and trough experiments, respectively;
3. The preferred N:P ratio for P-limited streams is 7:40% by weight. A high nitrogen product (i.e., 40:7:0) is currently under development;
4. To ensure that there are no metal concentrations that would be of concern for drinking water and aquatic life purposes, a food grade phosphoric acid source (used for making the fertilizer product and often the source of metal contamination) should be used.

The results of this research pose several avenues for future investigations: 1) develop high nitrogen briquette for nitrogen limited river systems; 2) confirm that N and P release is constant over time to ensure that N or P does not become limited by uneven dissolution rates; 3) conduct a toxicity bioassay to verify that the briquettes are an environmentally safe product; and 4) paired carcass and slow-release fertilizer study, to compare if inorganic N and P additions are adequate for stimulating primary production or if the addition of organic minerals, vitamins, and lipids from carcasses, are also required.

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