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Pacific salmon and sediment flocculation: nutrient cycling and intergravel habitat quality

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Abstract Salmon-derived sediment flocs form during post-spawning die-off when organic matter from salmon carcasses combines with fine inorganic suspended sediments. These flocs deliver salmon derived nutrients to the stream bed where they enter the stream's trophic network. To assess the influence of these mixed origin sediments on salmon stream benthic habitat, a re-circulating flume was constructed and seeded with gravel of a similar size to that from regional natal salmon streams. Flume conditions for water depth, velocity, and suspended sediment were also similar to regional natal salmon streams. Following the addition of salmon organic matter, intergravel habitat quality was observed to change in three ways: (i) the proportion of silts (10–63 μm) increased, (ii) the carbon to nitrogen ratio decreased, and (iii) the biological oxygen demand of sediments increased. These preliminary results provide direct evidence that salmon derived organic matter influences the composition of inorganic sediments in, and the habitat quality of, the streambed.

Key words British Columbia; flocculation; intergravel habitat; nutrient cycling; Pacific salmon; sedimentation

INTRODUCTION

There is considerable interest in the role that Pacific salmon play in the nutrient and energy balance of their natal watersheds, because the organic matter released into the stream from salmon carcasses can be the most significant annual input of organic material (Naiman *et al.*, 2002). This infusion of salmon-derived organic matter is significant because Pacific salmon gain up to 90% of their biomass at sea (Willson, 1997) but return to their natal streams to spawn and die thereby transporting these marine derived nutrients (MDN) to freshwater systems. These nutrients support the productivity of the natal watershed's aquatic and terrestrial ecosystems (Naiman *et al.*, 2002; Bilby *et al.*, 2003; Johnston *et al.*, 2004). This balance is not well understood and may be negatively affected by fishing or habitat alteration due to watershed development activities. Scheuerell *et al.* (2005) determined, using a mass balance approach, that the decline in spawning chinook (*Oncorhynchus tshawytscha*) populations of the Snake River Basin (Washington, USA) led to an export of nutrients from the basin. That is, as the ratio of spawning fish to smolts declined, smolts removed more nutrients than were brought to the basin by spawners. They postulate that a continued decline in spawners with time may lower the ability of the watershed to support juvenile salmon. Although the importance of MDN in supporting natal watershed ecology is recognized, the method of its delivery in aquatic environments and the fate of salmon breakdown products on stream channel morphology and benthic ecology have received limited attention.

The combination of inorganic sediment with salmon detritus through the process of flocculation has the potential to alter the transfers of both materials through the aquatic system (McConnachie & Petticrew, 2006). This paper investigates the fate of salmon breakdown products on benthic ecology by assessing the influence of salmon organic matter (SOM) on the composition of streambed sediments and the intergravel habitat quality.

Sediment flocs comprise a significant portion of the suspended sediment load in most rivers (Droppo, 2001) but have been noted to vary seasonally in composition and shape as a function of the type and quantity of organic and inorganic material available (Petticrew, 2005; McConnachie & Petticrew, 2006). Flocs are integral to investigations of sediment and nutrient transport in rivers because they are wholly different from their sub-components having a different shape and density. They act as the delivery agent for inorganic and organic material to the streambed.

Flocculated fine sediments that incorporate sockeye salmon (*Oncorhynchus nerka*) breakdown products including MDN, have been observed in gravel stored sediments of productive salmon bearing streams in the interior of British Columbia, Canada. This seasonal study, which evaluated the structure and composition of gravel stored sediment before, during, and following the return of ~14 000 spawners found that flocs had a relatively higher density and settling velocity during the peak spawning period than during the salmon die-off. The physical reworking of the stored fine sediment during active spawning and the inclusion of a higher proportion of salmon-derived organic matter during die-off were suggested as explanations for these differences (Petticrew & Arocena, 2003). Stable isotope analysis (^{13}C and ^{15}N) identified an increased content of salmon-derived nutrients in suspended sediments at these sites during the salmon die-off in the same year (McConnachie & Petticrew, 2006).

Flocs observed in the water column settle onto and infiltrate into the streambed near salmon redds during the low flow periods that are typical during the spawning period. Once captured within the streambed matrix, flocs can block intergravel pore spaces similar to inorganic particles reducing intergravel water flow and quality. In addition, aerobic bacteria that are either attached to the floc or that reside in the streambed may digest the organic matter fraction of the floc, further depressing local oxygen concentrations (Storey *et al*., 1999). This balance between nutrient source, supply, storage, and recycling will influence the long-term ecological success of a stream's salmon populations.

METHODS

In 2004, a salmon rearing channel measuring approximately 36 m × 2 m × 1 m was converted to a re-circulating flume at the Quesnel River Research Center in Likely, British Columbia. The flume was seeded to a depth of 0.4 m with washed 1–2.5 cm crushed gravel. Experimental flume conditions of water depth and velocity (10–20 cm and 5–10 cm s^{-1}), suspended sediment (<5 mg L^{-1}) and SOM (30–100 g m^{-2}) were similar to those identified in a previously studied salmon-bearing stream in the Stuart-Takla region of British Columbia (Table 1). The study period extended over six days

Table 1 Flume sampling dates (n = 3 infiltration bags) and the amount of sediment and salmon added to the flume on that day (blanks indicate no addition).

Date in 2004	Sample type	Sediment added (g)	Sediment concentration (mg L^{-1})	Salmon added (g)	Cumulative salmon organic matter (g m^{-2})
31 August	Background				
1 September	Pre-spawn	32	1.7		
2 September	Sediment + Salmon 1	26	1.5	2470	41
3 September	Sediment + Salmon 2	63	3.3	2114	76
4 September	Sediment + Salmon 3	25	1.4	2559	118
5 September	Post-spawn				

from 31 August 2004 to 5 September 2004, which coincided with the early salmon run in the Quesnel River. Sediments and SOM were added to the flume in a sequence similar to the spawning cycle, namely the pre-spawn (sediment only), die-off (sediment and SOM), and post-die-off (re-circulation of suspended sediment and SOM following all additions). Sediments were from the Stuart-Takla study area and were mechanically dispersed while SOM came from the anaerobic decomposition of six pink salmon (*Oncorhynchus gorbuscha*) (9 kg total weight) over a period of three weeks.

The flume's water column was sampled for turbidity, temperature, and conductivity. Water column turbidity, conductivity, and temperature were collected using a Yellow Springs Instruments (YSI) 6920 multi-parameter probe that collected samples on a 15-min interval.

The streambed was sampled for fine sediment composition (<2 mm) including flocs, biological oxygen demand, and nutrients (C and N). Gravel-stored fine sediment samples were collected with infiltration bags, which captured sediments settling on the streambed surface and infiltrating through the streambed in horizontal directions (Lisle & Eads, 1999; Rex, 2002). Each of the 15 infiltration bags installed was buried to a depth of 25 cm in a column of reference gravel consisting of flume material that was pre-screened to remove sediments less than 2 mm. During retrieval, the infiltration bags were brought up through the column of reference gravel capturing both the reference gravel and other material of less than 2 mm that had settled during the exposure period. These samples were sieved through a 2-mm screen and sub-samples of the liquid fraction were collected for absolute particle size determination, carbon and nitrogen ratio, and biological oxygen demand. Effective particle size determination was determined through the photography of samples added to a settling column and image analysis using Northern Exposure (Empix Imaging Inc.). These latter data will be presented in future publications.

The absolute particle size of captured inorganic fine sediments, both water column and streambed, was analysed at the Bedford Institute of Oceanography using a Coulter counter as per Milligan & Kranck (1991). The biological oxygen demand (BOD) of streambed sediments was determined by measuring oxygen concentrations on a daily basis for a period of seven to nine days, or until dissolved oxygen levels had reached near zero (Clesceri *et al.*, 1998). BOD samples were incubated in the flume and then a laboratory water bath of the same temperature as the flume (~10°C). Carbon and nitrogen filters were analysed in the UNBC Central Equipment Lab using mass spectrophotometry.

RESULTS

Water column responses to salmon OM and sediment

The water column showed immediate and marked increases in turbidity (up to 700% above background) and conductivity (up to 5% above background) with additions of sediment and salmon tissue. Turbidity responses were short-lived, returning to background conditions within hours of the sediment or salmon addition (Fig. 1). Conductivity increased by approximately 15% over the course of the study due to the addition of sediment and salmon electrolytes (Fig. 1). Temperature patterns exhibit a diurnal pattern with higher temperatures recorded during the day, except when water was added to keep the channel suitably deep.

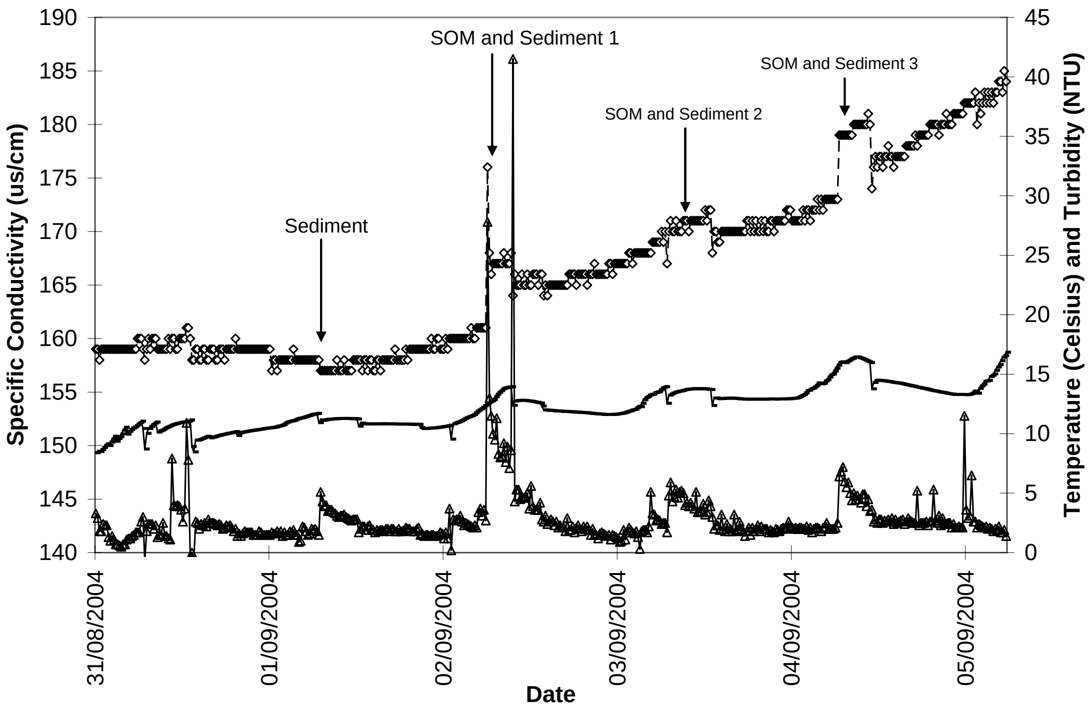

Fig. 1 Water column conditions in the re-circulating flume during the study period. Specific conductance is denoted by the open diamond, temperature by the line, and turbidity by the open triangle.

Streambed sediment composition

The composition of the fine streambed sediment changed over the course of the study showing a trend of larger silt fractions (10–63 μm) in the infiltration bag samples

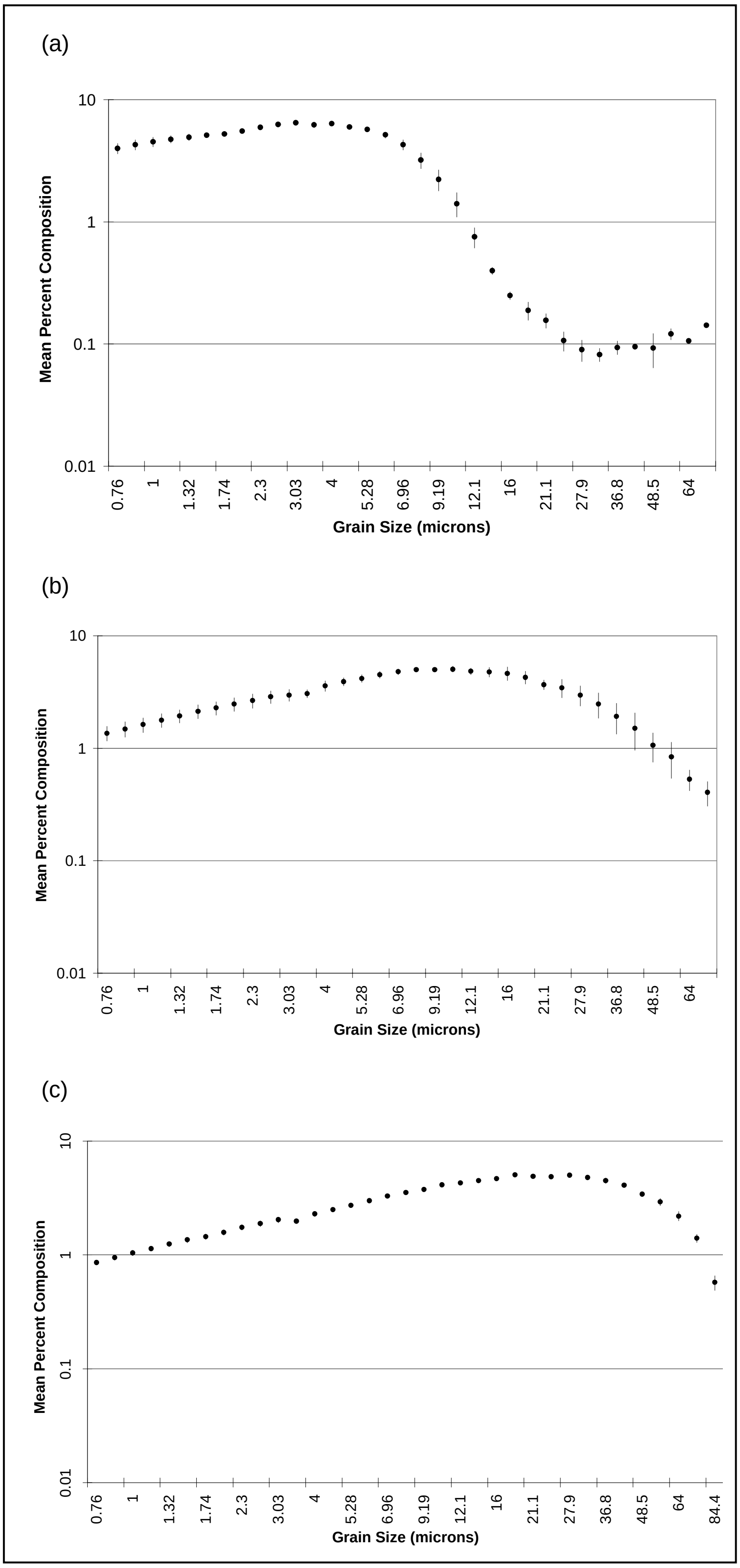

Fig. 2 Mean percent composition and standard error (n = 3) for fine grained sediments captured in infiltration bags during: (a) the baseline, (b) sediment only, and (c) salmon and sediment, exposure periods.

following the addition of SOM and sediment (Fig. 2). Initial streambed sediments had a D_{50} of 2.6 μm, sediment only samples had a D_{50} of 8.0 μm, and the final SOM and sediment samples had a D_{50} of 14.0 μm. Similarly, the proportion of sediment greater than 10 μm increased with only 2.4% of the initial streambed sediment exceeding 10 μm, 37.3% of the sediment only samples, and 57.5% in the SOM and sediment samples.

Habitat quality indictors: carbon to nitrogen ratio and biological oxygen demand

The post-salmon addition sediment samples have a significantly lower carbon to nitrogen ratio than the background and sediment addition infiltration bag samples (p = 0.0001, Fig. 3). Similarly, the BOD samples exhibit a considerably different trend between the background, sediment, and salmon and sediment samples. The initial stream-bed samples and sediment-only BOD samples decreased to 60% oxygen saturation within nine days (Fig. 4). The three salmon and sediment samples had lower starting oxygen concentrations than the background and sediment samples and decreased to near zero within seven days.

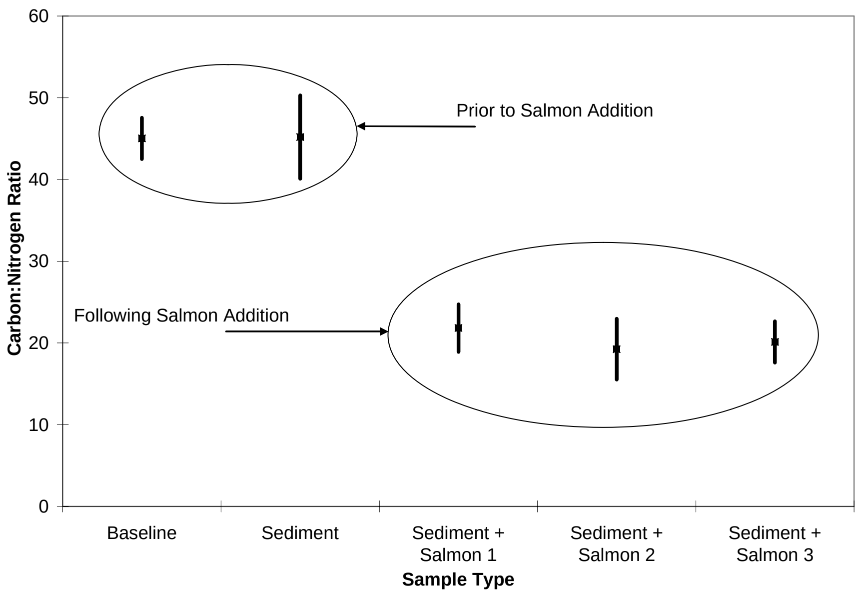

Fig. 3 Carbon to nitrogen ratios for infiltration bag samples collected during the baseline, sediment only, and salmon and sediment additions. The graph shows the mean and standard error about the mean (n = 3).

DISCUSSION

The timeframe for mixed sediment (inorganic and organic matter) storage is of ecological importance because of its role in nutrient cycling and habitat quality, as well as its geomorphic importance due to its influence on sediment conveyance through watersheds. This study demonstrated that SOM added to the water column will increase the proportion of silt particles delivered to the streambed. Further, the delivery of SOM enriches the streambed, as shown by the reduction in the carbon to nitrogen

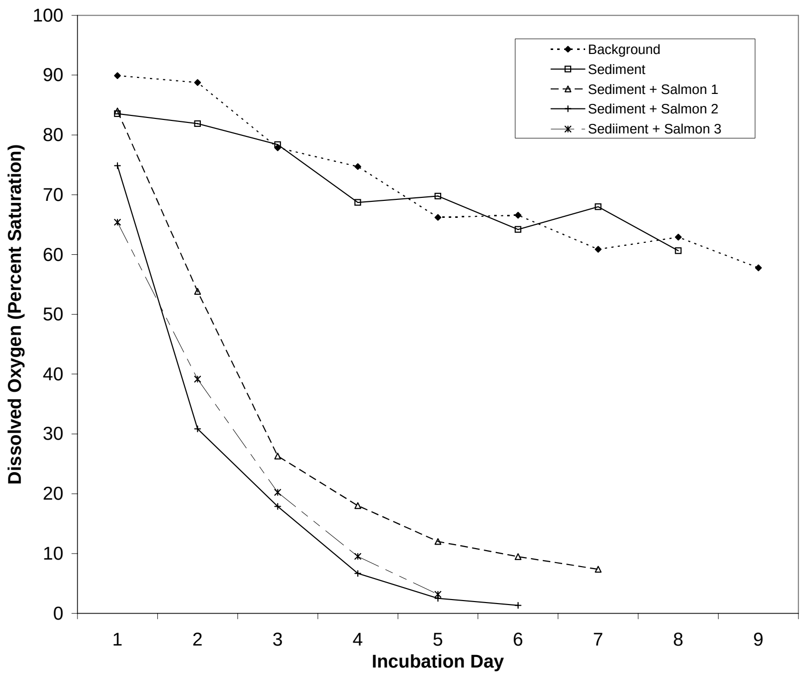

Fig. 4 Biological oxygen demand curves for background, sediment, and the salmon and sediment samples (*n* = 3). These data have been temperature corrected.

ratio, which in turn increases microbial respiration. As microbial respiration increases the BOD will also increase, depressing intergravel oxygen. This sequence of events shows that the interaction of spawning Pacific salmon and background suspended sediments during die-off affects intergravel habitat quality, which may in turn influence the breeding success of the returning salmon. While the literature has shown that intergravel habitat conditions can be affected by the quantity of inorganic sediments (Chapman, 1988), this work and others (Petticrew, 2006; McConnachie & Petticrew, 2006) has shown that both the quantity and quality of organic content in settled solids is also important. Clearly a balance between the amount of organic matter retained in the gravels for local recycling of nutrients and the amount of sediment (organic and inorganic) collected in the gravel pores must be maintained for optimal fisheries habitat. Ongoing research in experimental flumes and planned research in a local spawning channel will describe the process of floc formation and further clarify the role of flocs in stream nutrient retention.

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