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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 A 4.8696(a) W696.6()-86.85694

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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 (McConnachie and Petticrew, in press; Petticrew, 2005). 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 (*Onco ync ne*) 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 *e* ., 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				

near zero (Clesceri *e* , 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.

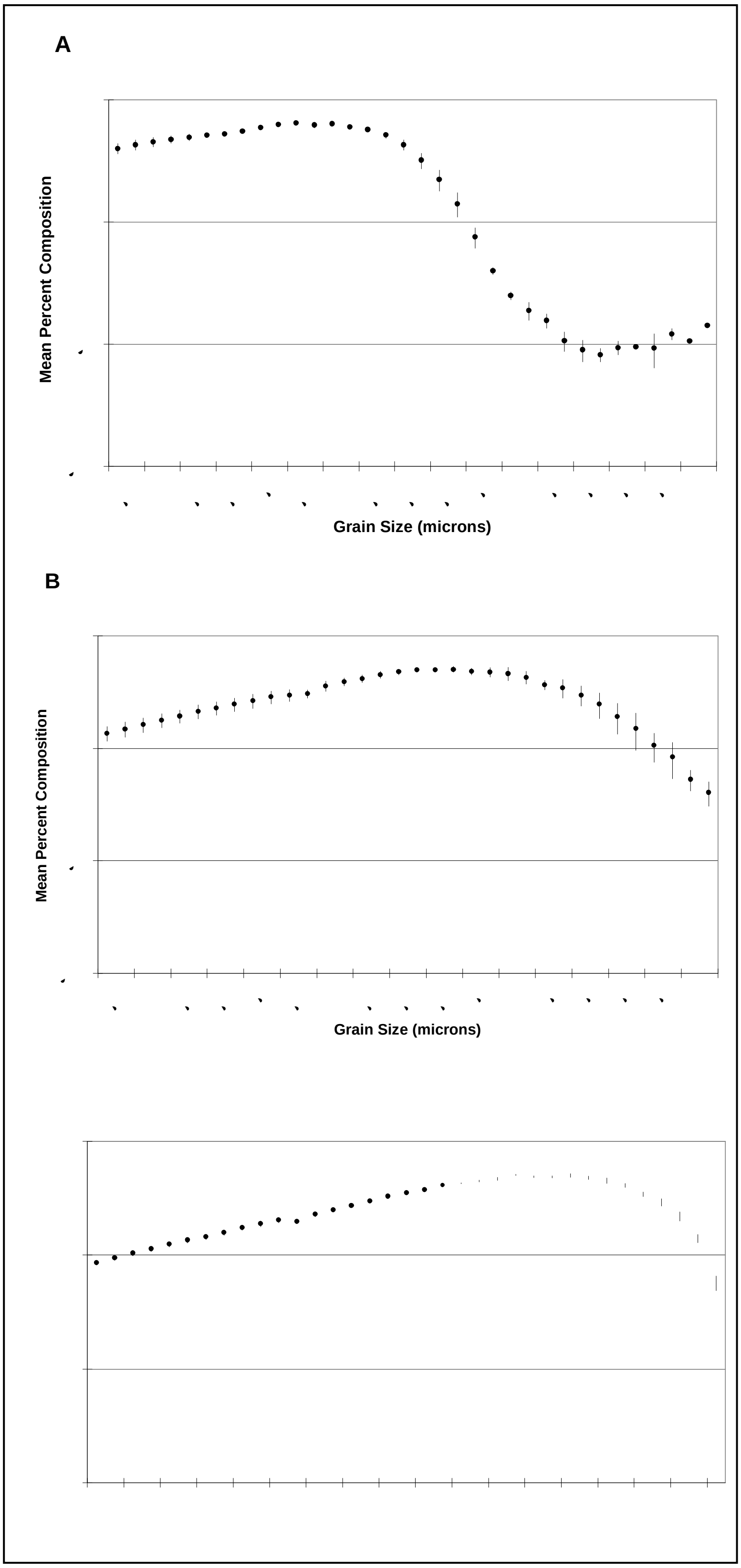

Fig. 2 Mean percent composition and standard error (*n* = 3) for fine grained sediments captured in infiltration bags during the baseline (A), sediment only (B), and salmon and sediment (C) exposure periods.

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