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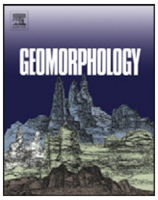

Biogeomorphic impacts of migration and disturbance: Implications of salmon spawning and decay

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A B S T R A C T

Geomorphologic processes often involve a biotic element that acts to regulate landform development. This biotic element can be plant or animal-based with a feedback that ultimately benefits the ecology of the organism. Pacific salmon (*Oncorhynchus* sp.) are an example of an animal biogeomorphic agent exhibiting such feedbacks and, because of long migrations from the sea to freshwater spawning grounds, are a species of interest that act on both local and regional scales. Upon returning to their natal streams, salmon generate a dual disturbance, resuspending large amounts of sediment as they construct nests while at the same time generating a substantial nutrient pulse through post-spawn die-off and decay. The retention and export of these nutrients are of importance to any hypothesized productivity boost driven by the marine derived nutrients (MDNs). Using experimental enclosures in the Horsefly River spawning channel in north-central British Columbia, our objectives for this study were to i) quantify the magnitude of organic and inorganic sediment export and retention from an active-spawning area and ii) determine the contribution of fine sediment MDN storage. Using a suspended sediment mass balance model, marine isotope enrichment and a time series of gravel bed sediment infiltration, we found strongly linear relationships between sediment infiltration and marine-derived nutrient enrichment. Elevated suspended sediment produced by salmon redd (nest) construction acted as an effective vector for MDN infiltration into the gravel bed. This study demonstrated that localized patterns of sediment deposition are regulated by salmon activity which in turn act to control MDN storage within, and release from, the gravel bed. Furthermore, this study demonstrates the ability of a biogeomorphic agent like salmon to establish a feedback mechanism that creates favorable conditions which ultimately benefit the organism.

1. Introduction

Instances of solely abiotic processes driving landform dynamics are rare, occurring on Earth in only very extreme climates (Corenblit et al., 2011). Instead, the vast majority of geomorphic processes have some biotic element that helps to regulate landform change which in turn has an ecological feedback to the original biotic element (Corenblit et al., 2011). For example, Pollen-Bankhead and Simon (2010) found that riparian soil structure was stabilized by plant root networks thereby retaining local habitat for future plant colonization and providing stable bank conditions along rivers. Examples of these local feedbacks are not limited to plants because zoogeomorphic (animal driven) processes are also recognized as significant drivers of landform change (e.g. North American beaver dams Naiman et al., 1994). Such local zoogeomorphological feedbacks generated in conjunction with large migrations across landscapes and ecosystem boundaries suggest that zoogeomorphic processes have the potential to alter and regulate regional and local nutrient flow (Vanni, 2002; Quinn, 2005; DeVries, 2011). For example, within their natal streams Pacific salmon cause seemingly opposing ecological forces of physical disturbance (via sediment resuspension) and nutrient subsidy (via post-spawn decay). These ecological forces have been demonstrated to impact abiotic and biotic elements (Rex and Petticrew, 2008; Albers and Petticrew, 2012) within spawning streams revising the role thought to be played by sediment and nutrients during the salmon's freshwater lifecycle.

Fine sediments, including clay and silt-sized particles, have been recognized as important delivery and storage vectors for nutrients and contaminants (Owens et al., 2005). In the case of Pacific salmon, ecologically important nutrients are transferred from marine environments to freshwater spawning habitats via the bodies of returning salmon (i.e. marine-derived nutrients (MDNs)). The coincident processes of fine sediment resuspension from redd (nest) construction and the pulse of nutrients to the water column from fish die-off result in salmon organic matter combining with inorganic silts and clays to provide a vector for the retention and storage of nutrients in the spawning gravels (Rex and Petticrew, 2008; Petticrew et al., 2011). In the water column the sediments form structures, known as flocs, that settle more quickly

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than their constituent particles (Petticrew et al., 2011). Once stored on, or in, the gravel bed, flocs increase the potential for localized biological production through longer period and greater amounts of intergravel retention allowing for organic matter processing (Wotton, 2007). Flocs, however, contribute an unknown amount to the overall MDN storage potential of spawning habitats.

The heavier inorganic (mineral) framework of flocs acts as a substrate for bacteria and salmon organic matter such that the resultant particles are more likely to settle out of the water column closer to the point of resuspension rather than be flushed downstream. Most studies have focused on MDN sequestration into benthic biofilms and periphyton (e.g. Moore and Schindler, 2008) but have remained largely silent on potential delivery vectors. The occurrence of this salmon–sediment floc generation and delivery mechanism has been clearly shown in the laboratory (Arkinstall, 2005), flumes (Rex and Petticrew, 2008) and the field (McConnachie and Petticrew, 2006) but the rate of exchange of MDN between the water column and gravel bed remains unclear. The temporal and spatial significance of these sediment vectors on gravel bed storage of MDN has not been quantified, thereby restricting our ability to estimate the impact of gravel bed storage of MDNs on biological productivity in these habitats. The objectives of this study are to i) quantify the magnitude of inorganic and organic sediment export and retention from an active-spawning area and ii) determine the contribution of fine sediment MDN storage and its effects on habitat conditions.

2. Materials and methods

2.1. Study site and preparation

We utilized an artificial salmon enhancement stream, the Horsefly River spawning channel (HFC), to examine the biogeomorphic impacts of salmon spawning. The HFC is in the Horsefly watershed (52° 19′N/121° 19′W), located within the Cariboo region of British Columbia, Canada (Fig. 1a). Further details on channel characteristics, in addition to the results of a separate portion of this same study can be found in Albers and Petticrew (2012). For the present paper, we utilized the HFC in an upstream–downstream paired treatment approach where a control enclosure (10 m × 20 m) was kept free of salmon and an active-spawn enclosure of the same size was loaded with salmon to simulate natural spawning conditions. The gravel bed was cleaned of fine sediment and weed growth prior to the start of the experiment ensuring a consistent baseline. Cleaning was accomplished by raking the gravel bed to a depth of 30 cm using a large fork mounted on a bulldozer. This resuspended fine material and weed biomass were then flushed downstream and pumped out of the HFC. Water flow into the channel was controlled by a large siphon supplying water from an upstream settling pond which is connected via a side channel to the Horsefly River. Discharge in the HFC was monitored through a combination of staff gauge readings and a pressure transducer (Unidata 8007 WPD) and applied to a calibrated rating curve. The rating curve was estimated by measuring flow velocity at 0.6 of the depth at 1 m intervals across the channel and at a range of representative stage heights (n = 4).

The introduction of sockeye salmon (*Oncorhynchus nerka*) into the HFC was regulated by a downstream gate off the mainstem of the Horsefly River. Sockeye salmon were loaded into the active-spawn enclosure (Fig. 1b) by opening the portion of the downstream exclusion fence which separated the experimental area from the rest of the channel. The control enclosure, which was located immediately upstream of the active-spawn enclosure, was intended to remain free of fish as a spatial control although some live fish did escape into this enclosure. These fish were removed from the control enclosure to mitigate any upstream spawning influences. Salmon were counted in the field or, when densities were too high for this approach to be feasible, counts were made from photographs.

2.2. Suspended sediment

Two automatic water samplers (Teledyne ISCO, Inc.) were placed streamside with the sampling tube located in the thalweg of the HFC at 0.6 of the depth near the rear of both the control and the active-spawn enclosures (Fig. 1b) to sample for suspended sediment. Water was sampled from each enclosure every 3 h, eight times per day (except where noted) into two sample bottles to form two 12 h composite samples. Water samples were later filtered with glass fiber filters, dried at 60 °C for 12 h, weighed, ashed at 550 °C for 2 h and weighed again. Organic and inorganic estimates of suspended sediment concentration were derived from this process.

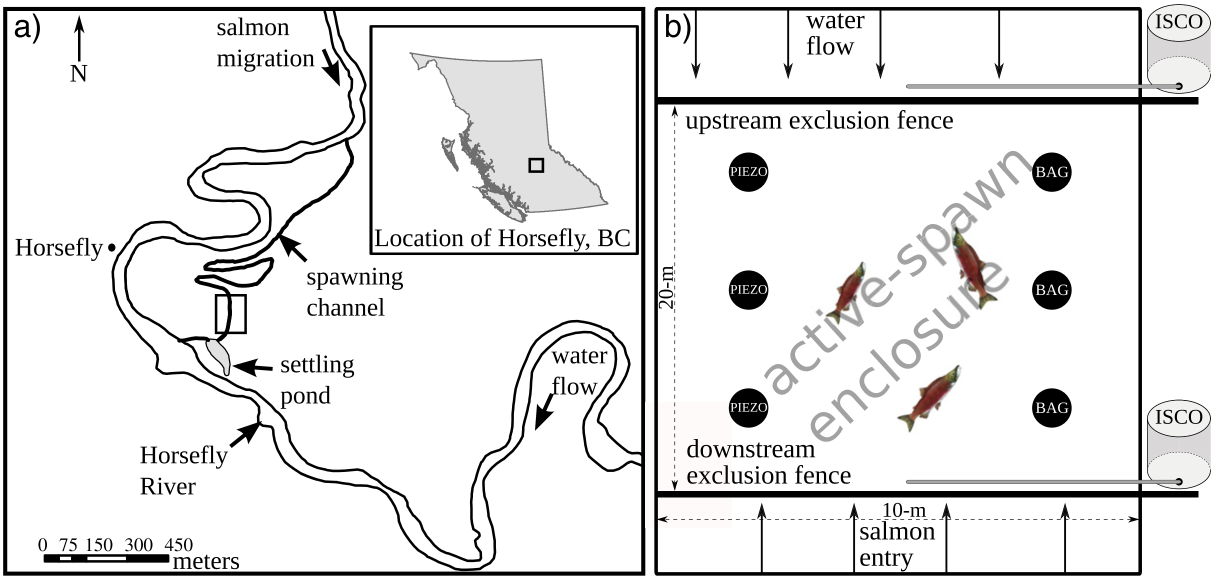

Fig. 1. a) Horsefly River, British Columbia. Experimental section of the HFC is indicated by the black box in the spawning channel. b) Schematic of fence, piezometer, ISCO and infiltration bag placement in the active-spawn enclosure. Figure is not drawn to scale.