

# Delivery of marine-derived nutrients to streambeds by Pacific salmon

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Marine fish that migrate to freshwater rivers to spawn



# LETTERS

Bacteria attached to salmon organic matter aid in ocs formation via EPS that adhere the salmon organic matter and clay components similar to EPS processes observed in the formation of non-salmon-organic-matter-based ocs<sup>13,44</sup>. These ocs-residing bacteria may increase benthic bacterial numbers and are at least partially responsible for salmon-organic-matter mineralization. The ume study showed that there were significant differences in the concentration of gravel-bed bacteria between treatments, with the lowest being observed during the baseline, clay and salmon exposures and the highest concentrations being observed during the salmon-plus-clay exposure ( $F(3,8) = 67.71$ ,  $df: (3, 8)$ ,  $p < 0.01$ ). Attached bacterial numbers exceed the free-floating, unattached bacterial counts because they reside on the ocs (Fig. 4), which settle faster and/or remain trapped in the gravels. The role of attached bacteria in forming ocs with inorganic particulate matter is supported by the absence of a significant increase in gravel-bed bacterial concentration following the addition of salmon organic matter alone. Further, large ocs observed in the water column during the salmon exposure were less dense than the salmon-plus-clay treatment owing to their lower inorganic content, and did not enter the gravel-bed as readily (for example Fig. 2b). These lower levels of gravel-stored 'salmon-only' particles are associated with significantly lower concentrations of benthic bacteria, which increase dramatically following the salmon-plus-clay treatment, concurrent with the significant increase in EPS (Fig. 3). Stage two, ocs sedimentation, is shown here to be mediated by the presence of salmon organic matter and its associated bacterial populations.

The addition of salmon-organic-matter-based ocs to the ume's gravel-bed resulted in the delivery and storage of marine-derived nutrients to the gravel-bed. Nutrient enrichment of the gravel-bed and ocs dissociation was found to occur in the presence of salmon plus clay. Specifically, there was a significant decrease in the carbon-to-nitrogen ratio of captured gravel-bed sediment from approximately 15:1 to 10:1 ( $F(3,4) = 30.87$ ,  $df: (3, 4)$ ,  $p < 0.01$ ) following the addition of salmon plus clay. These values align with field information from O'Neil Creek, which identified a decrease in the carbon-to-nitrogen ratio in suspended particulate matter from more than 15:1 to approximately 11:1 at the same time that the salmon nitrogen (<sup>15</sup>N) signal peaked. Similarly, in the recirculating ume, the delivery of salmon organic matter to the streambed is identified by nitrogen enrichment, and it confirms that ocs generated from salmon organic matter observed in the water column are delivered and retained within the gravel-bed of the recirculating ume. Stage three, MDN enrichment and release, can be identified by the shift in the carbon-to-nitrogen ratio of gravel-bed sediment samples.

The biophysical mechanisms of nutrient and organic-matter cycling through marine and freshwater environments are necessary prerequisites to understanding the ecology and ensuring the sustainability of the resources they provide. Similar to ~~the~~ this work highlights the importance of microbial communities in local energy and nutrient utilization processes, but here we identify the important role they play in delivering and retaining marine-derived materials to freshwater streambeds through the process of ocsulation. This investigation has demonstrated that salmon-organic-matter-based ocs formed in the water column and settled onto the streambed in the presence of clay and attached bacteria. Once captured in streambed interstices, these nutrients and organic matter stimulate microbial community development and enter the benthic food web. Our results indicate that the ocs feedback loop proposed here is an ecologically important mechanism for delivering and retaining marine-derived nutrients for later cycling in natal Pacific salmon streams.

Fish-habitat-restoration activities that singularly focus on physical habitat modification or natal-stream fertilization may be

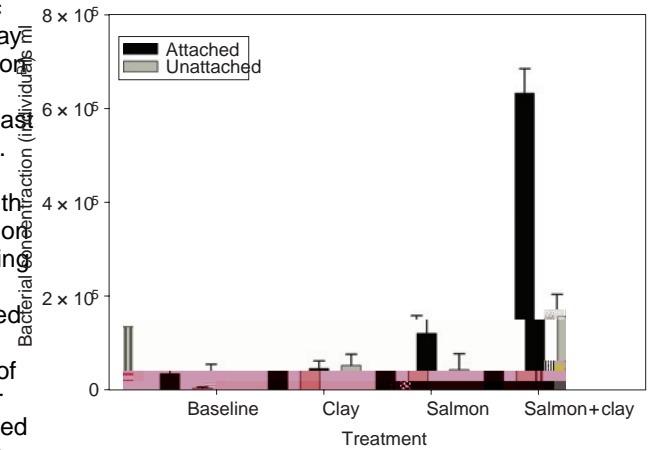


Figure 4. Treatment means for attached and unattached bacterial concentrations from gravel-bed sediment collected in the recirculating ume. The mean of three samples per treatment, with the error bars representing one standard error of the treatment mean.

Water-column particle size, gravel-stored sediment settling studies, and gravel-stored sediment EPSD and APSD data were collected using a LISST-ST (ref. 23). The LISST-ST collects particle-size information using laser light scattering and transmissometry. Water-column particle-size measurements were collected *in situ*.