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Bed texture, food web structure, and juvenile salmonid rearing in North Coast California rivers

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Bed texture, food web structure, and juvenile salmonid rearing in North Coast California rivers

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Abstract

Excessive loading of fine sediments into western rivers has degraded spawning and rearing habitat for salmonids, and contributed substantially to their declines. Impacts on salmon redds have been studied extensively, but effects on juvenile rearing are less well documented. In a field experiment in the South Fork Eel River, we investigated the impacts of deposited fine sediment on juvenile steelhead. Our experimental design allowed us to isolate the effects of fine bed sediments from other covarying factors and to reveal the mechanisms of their effects. Increasing levels of embeddedness with deposited fine sediment (from zero to 100%) decreased growth and survival of juvenile steelhead trout. The nearly linear decreases in growth resulted from decreased food availability and metabolic costs of increased activity and intraspecific aggression. The invertebrate community changed from one of more available prey to one of unavailable burrowing taxa with higher levels of deposited fine sediment. Steelhead in more heavily embedded channels showed more continuous movement and aggression and higher incidence of injury. This study shows a direct impact of riverbed composition on salmonid rearing success, which has been identified as a life history bottleneckby models informing efforts to recover these populations.

Introduction and Problem Statement

Throughout California and the Pacific Northwest, stream and river systems draining into the Pacific historically supported large populations of anadromous fishes. These populations have declined throughout this region, and many rivers have lost one or more component species. Today, twenty-four salmonid ESUs in Western North America are listed under the Endangered Species Act. While these populations face numerous threats, the most common factor associated with anadromous salmon declines is habitat degradation.

Chief among the causes of river habitat degradation is the excessive loading of fine sediments. Deleterious fine sediment loading, caused by forest management practices, agriculture, mining, changes in climate, and in some rivers the lithology of soils of the watershed, is one of the most serious problems affecting river habitat quality. In the western United States, forest management activities, especially road construction, are the most important source of management-related sedimentation. Northern Coastal California rivers, such as the South Fork Eel, are particularly vulnerable to land management practices that increase fine sediment loading due to the steep dissected terrain and weak parent material of the drainages.

Investigations into the consequences of fine sediment loading for anadromous fishes have focused primarily on spawning and embryo survival. The effects of fine sediment deposition on salmonid redds have been well researched, both empirically and theoretically. Intrusion and accumulation of fine sediments into redds reduces embryo survival through decreased dissolved oxygen and water exchange and impeded emergence. Unfortunately, while data relating the sediment composition of riverbeds to the growth and survival of salmonid embryos are abundant and convincing, the same cannot be said for juveniles. Research on the influence of deposited fine sediments on juvenile salmonid growth and survival has consisted primarily of laboratory work and correlative field studies, drawing comparisons before and after or upstream and downstream of a fine sediment influx, or among rivers with differing bed compositions. Identification of the specific mechanisms responsible for changes in salmonid growth rates, survivorship, and composition has therefore been problematic. Similarly, most available data relating river substrate composition and the algal and invertebrate assemblages comprising the underlying foodweb have been obtained either from laboratory experiments or before/after, upstream/downstream, and whole river comparisons. While results are suggestive of the detrimental impacts of increased fine sediment deposition on juvenile salmonids and the plants and animals supporting them, a mechanistic understanding has been elusive. It is this information, however, that is crucial to interpreting and addressing salmonid declines and may enable managers to begin recovering populations of these fishes. According to a report recently published in *Science*, age structured matrix models indicate that this is the age class where improved survival will most affect populations (Kareiva et al 2000), and even modest reductions in juvenile mortality will reverse current population declines, regardless of adult dam passage and harvest.

Objectives and Procedures

Our objective was to investigate the mechanistic responses in growth and survival of juvenile steelhead trout and in the structure and dynamics of the river foodweb supporting them to increasing fine sediment deposition. This species is particularly vulnerable to degradation of rearing habitat because of its long river residence time; while most salmonids rear in one year, steelhead may spend up to three years in natal streams and rivers before traveling to the ocean. We combined manipulative and observational experiments, conducted over two years in the South Fork Eel River at the Angelo Coast Range Reserve. During the first year, we conducted an in-channel manipulation of riverbed sediment composition in which we explored the influence of increasing deposited fine sediment on the growth and survival of juvenile steelhead trout, on algal accrual and availability, and on invertebrate abundance and diversity. During the second year, we examined the abundance and feeding behavior of steelhead trout in riffles and pool tail-outs with differing bed compositions. After several weeks of observations of free living fish over naturally occurring heavily sedimented and clean (‘free stone’) square meters of river bed, we reverse engineered these habitats. This entailed vacuuming fine sediments out of embedded substrates with a bilge pump, and adding fine sediments to formerly clean substrates until they were embedded at levels typical of natural river reaches in the South Fork Eel that were impaired by fine sediment loading. We subsequently observed fish in these modified areas to compare their habitat use and behavior in these sites before and after habitat manipulation.

Experimental Manipulation-

From June through August 2000, we studied the effects of increasing deposited fine sediments on juvenile steelhead trout and the food web supporting them in artificial channels in the river. The experiment consisted of six experimental treatments, fully embedded substrate (5/5ths embedded); 4/5ths embedded, 3/5ths embedded, 2/5ths embedded, 1/5th embedded, and 0/5ths embedded, replicated four times in a randomized-block design. We placed six flow-through channels side-by-side in the tail-outs of each of four pools along the river, with each channel in a tail-out assigned to one of the six embeddedness regimes. The channels, open at the upstream and downstream ends and measuring two meters long by one meter wide by one and a half meters tall, were constructed of vinyl flooring, anchored by four pieces of conduit pipe secured to rebar hammered into the riverbed. We collected and sifted ambient gravels through a 6 mm sieve to obtain a matrix of pebbles, gravel, and cobbles, lacking fines, and filled each channel to a depth of 15 cm. We then embedded the 5/5ths treatment with fines from the adjacent dry channel, in measured quantities, until only the upper surface of the coarse matrix was visible. This quantity was designated as 5/5ths embedded, and scaled back incrementally to 0/5ths. Fines were then added to each other treatment as calculated. This novel experimental design allowed us to manipulate levels of deposited fine sediment while keeping other conditions (e.g. drift, flow, light, temperature, etc.) at ambient and similar levels across treatments, thus minimizing confounding influences and increasing the likelihood that observed effects were due to treatment.

After channel substrates were embedded according to treatment, we allowed twenty-five days for insect colonization and algal accrual. We then sealed the upstream and downstream ends of each channel with 6 mm mesh *Vexar* screen to prevent immigration and emigration of steelhead trout, but maintain natural flow and drift levels and allow prey (invertebrates and roach and stickleback fishes) passage in and out of the channels. Each channel was stocked with two steelhead trout seined from the river. The length and weight of all fish were recorded just prior to stocking (weight range 0.585 to 2.970 grams; length range 34 to 54 millimeters). Fish placed in a given channel were size matched such that their size difference was at least 3mm and at most 12mm in length and at least 0.350g and at most 1.300g in weight. Size matching was necessary to ensure the establishment of a dominance hierarchy and minimize aggression and injury.

The steelhead trout were enclosed for 46 days, during which time they were monitored every other day. Whenever a fish was injured (presumably due to a garter snake or conspecific attack) it was monitored twice daily until it died and then was promptly removed and replaced with a fish of similar size. After 46 days, the length and weight of each was again recorded before it was returned to the river.

Response Variables-

1. Growth of juvenile steelhead trout - As mentioned above, we recorded changes in the length and weight of each fish over the course of the experiment.

2. Behavior of juvenile steelhead trout – Throughout this experiment, we conducted focal individual surveys of fish inside the enclosures. We selected a vantage point from which the entire channel could be monitored and then remained motionless for five minutes before observations were recorded. The fish’s activities (i.e. moving, holding, prey inspection, prey attack, aggressive intraspecific encounter, non-aggressive intraspecific encounter) were then recorded continuously for ten minutes.

3. Pre- and post-manipulation channel usage – For ten days prior to sealing the upstream and downstream ends of the channels and ten days following the removal of the upstream and downstream mesh walls, we monitored the open channels for juvenile steelhead usage.

4. Food web effects – We collected data relating bed composition to aquatic invertebrate abundance and diversity, periphyton production, and prey fish (stickleback and juvenile roach) abundance in the channels. We sampled aquatic invertebrates in the channels and from the adjacent riverbed once prior to stocking the juvenile steelhead, once during the experimental manipulation, and once after removing the steelhead. In order to collect these samples, we plunged a circular aluminum corer (20 cm diameter) through the sediment to the channel floor and collected all material contained within. At each sampling period, we repeated this three times per channel, and collected and pooled the invertebrates from each subsample. We sampled periphyton in the channels, and counted prey fish abundance in the channels on five occasions prior to stocking, ten occasions during the manipulation, and five occasions after removing the steelhead.

5. Channel sediment characterization – After removing all invertebrates from the sediment cores as described above, we collected the sediment from each sample. After drying the sediment samples, we sifted each into twenty size classes, recording the volume and mass of each size class of sediment for every sample.

Results

Steelhead growth decreased steeply and roughly linearly with increasing fine sediment concentration (Fig. 1). With increasing fine sediment, invertebrate assemblages shifted from available prey organisms (i.e. epibenthic grazers and predators) to unavailable burrowing taxa (Fig. 2), so that steelhead confined to channels with higher levels of sedimentation experienced lower food availability than those in less embedded channels. Deposited fine sediments also increased steelhead activity. At higher levels of embeddedness, fine sediments filled spaces under and between coarse cobbles, producing a flat and featureless bed. As interstitial refuges and prey declined, steelhead spent less time sheltering behind or under cobbles and more time actively swimming (Fig. 3a). Steelhead also exhibited higher levels of intraspecific aggression, including attacks (Fig.3b), as prey availability and visual separation between fish decreased with higher fine sediment levels. As a result, more heavily embedded channels had a higher incidence of fatal injury (logistic regression, $P < 0.05$, n = 24) (Fig. 4). These results are presently under review (Suttle et al., submitted).

Results from the second year, in which open areas of substrate were observed, then reverse engineered to re-arrange embeddedness conditions, are still being analyzed. Habitat use by fish was strongly influenced by the content of fine sediments in the bed, however, and cleaning or supplementing fine sediments in given streambed areas subsequently increased or decreased, respectively, the use of those areas by juvenile steelehead (Power et al., in preparation).

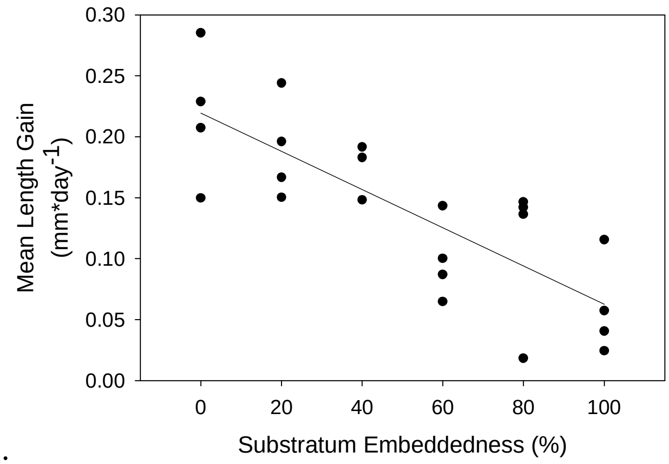

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Figure 1. Effects of manipulated substratum embeddedness on the growth of juvenile steelhead trout (R^2 = 0.63, P < 0.0001). Changes in growth in mass were similar (R^2 = 0.59, P < 0.0001). Analyses of relative growth, which accounts for differences in initial size, and of instantaneous growth rate produced similar linear patterns (R^2 = 0.52, P = 0.0001 and R^2 = 0.53, P < 0.001, respectively). One experimental channel with 40 percent substratum embeddedness contained no fish that survived the minimum 25 days and is thus excluded from the analysis.

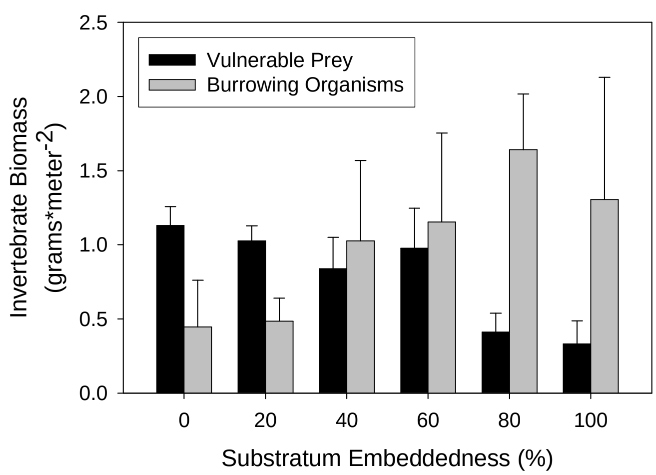

Figure 2. Biomass of invertebrates from sediment core samples taken at experiment's end (mean $\pm$ s.e.). There were significant linear relationships between fine sediment and the biomass of individual functional groups of invertebrates. As fine sediment increased, biomass of vulnerable prey declined (R^2 = 0.42, P < 0.001) and biomass of unavailable burrowing organisms increased (R^2 = 0.23, P = 0.02). A similar pattern was found in the pre-stocking samples taken June 30th; there was a significant and negative relationship between fine sediment and vulnerable prey biomass (R^2 = 0.35, P = 0.003) and a significant and positive relationship between fine sediment and burrowing organism biomass (R^2 = 0.37, P = 0.002). Fine sediment had no influence on the biomass of armoured grazers. Similar taxon-specific responses to fine sediment have been observed in other studies (Bjornn et al. 1977, Mebane 2001).

a

b

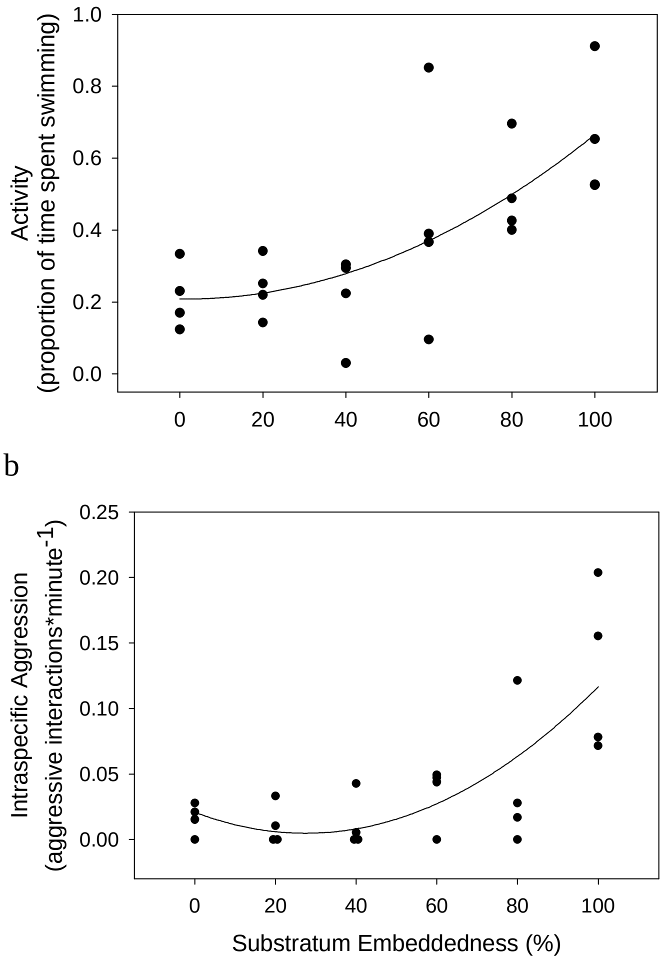

Figure 3. Behavior of steelhead parr in experimental channels. Data represent mean values for each experimental channel. (*a*) Fish activity. Presented is the best-fit line from 2nd order polynomial regression (R^2 = 0.45, P = 0.004). The difference in activity between steelhead in 100% embeddedness channels and those in 0% embeddedness channels translates to a 47% higher energy expenditure, based on metabolic data for the same size class of sockeye salmon (*O. nerka*) under similar environmental conditions (Brett and Glass 1973), energy equivalents of animal oxygen consumption (Elliot and Davison 1975), and assuming a standard twelve-hour period of nightly inactivity. (*b*) Intraspecific aggression. Presented is the best-fit line from 2nd order polynomial regression (R^2 = 0.56, P = 0.0002).

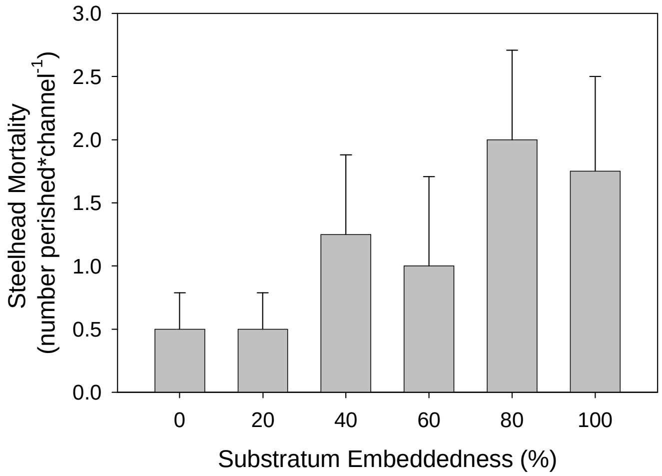

Figure 4. Steelhead mortality in experimental channels (mean ± s.e.). Data represent the number of steelhead that died per channel per treatment. Because dead fish were immediately replaced, statistical analysis was performed using logistic regression on the binary response variable mortality/no-mortality for each channel, with experimental channels as the unit of replication (n = 24).

Conclusions

It is widely known that salmonid stocks decline when land use increases fine sediment delivery to gravel bedded rivers (Bisson and Sedell 1984, Reeves *et al*. 1993, Waters 1995), but mechanistic understanding of the role of fine sediment in these declines has been restricted to the embryo stage. We observed decreases in steelhead growth and survival with increasing fine sediment deposition, associated with lower prey availability and higher activity, aggression, and risk of injury. Declines in growth rates lower survival of salmonids and other fishes (Werner and Gilliam 1984, Walters and Korman 1999). Larger body size confers higher survival of over-wintering (Quinn and Peterson 1996) and smolting (Thedinga and Koski 1984, Ward and Slaney 1988, Yamamoto et al. 1999) juvenile salmonids. Recent demographic models indicate that these juveniles may be the best age classes to target for effective conservation measures. Even modest reductions in juvenile mortality (*i.e.* 6 – 11%) are predicted to reverse population declines in Snake River chinook salmon (*Oncorhynchus tshawytscha*), regardless of adult dam passage success and egg survival (Kareiva et al. 2000). Differences in growth and survival imposed by fine sediment could therefore have important population-level impacts.