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**ASSESSING THE EFFECTS OF MODERATELY ELEVATED FINE
SEDIMENT LEVELS ON STREAM FISH ASSEMBLAGES**

by

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ELEVATED FINE SEDIMENT LEVELS ON STREAM FISH
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ABSTRACT

The construction of the Redwood National Park highway bypass in 1989 created an opportunity to study the effect of moderately increased fine sediment on fish assemblages in natural streams. The bypass construction resulted in chronic addition of fine sediment into several tributaries of Prairie Creek and the Klamath River, California, while nearby tributaries remained unaffected. Streams affected by the bypass had higher concentrations of stored sediment within the streambed than unaffected streams (paired t-test, $p = 0.04$). Winter suspended sediment concentrations ranged from 2 mg/L to 102 mg/L and were also higher in bypass-affected streams than control streams (paired t-test, $P < 0.005$). I examined density, diversity, and growth of native stream fishes within five pairs of affected and control streams during the summer and winter of 1997. Bypass-affected and control streams contained similar densities of fish (paired t-test, $p = 0.69$) and similar diversity of vertebrates as measured by the dominance of the most common species (paired t-test, $p = 0.64$ for summer, $p = 0.23$ for winter). Total salmonid biomass, coho salmon (*Oncorhynchus kisutch*) biomass, and cutthroat trout (*Oncorhynchus clarki clarki*) biomass were not well predicted by the concentration of fine sediment in streambeds. Finally, summer-time growth of cutthroat trout in instream enclosures was also similar in bypass-affected and control streams (paired t-test, $p = 0.32$).

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INTRODUCTION

Many environmental factors, most notably poor land-use practices and expanding urbanization, have combined to push native California salmonid stocks to the brink of extinction (Nehlsen et al. **1991**). For instance, coho salmon (*Oncorhynchus kisutch*) populations within the state are probably less than 6% of what they were in the **1940's**, and there is every reason to believe the decline will continue (Brown et al. **1994**). Particularly in the Pacific Northwest, much research has focused on elevated suspended sediment concentrations that arise from logging and road building activities and the risk they pose to threatened Pacific salmon populations (Cederholm and Reid **1987**; Scrivener and Brownlee **1989**). This research has generally concluded that as sediment concentrations rise to very high levels, fish health (Newcombe and MacDonald **1991**) and reproductive success decline (Chapman **1988**). However, little research on stream fishes has focused on effects of moderate sediment concentrations common in many streams affected by human activities.

Sediment may affect stream fish by a variety of mechanisms. High concentrations of suspended sediment have been shown to lower the overall fitness of stream dwelling salmonids by disrupting normal feeding behavior (Berg and Northcote **1985**), reducing growth rates (Crouse et al. **1981**), and increasing plasma cortisol levels (Servizi and Martens **1992**). Increased sediment deposition can fill in pools and reduce the amount of cover available to fish, decreasing the

survival of juveniles (Alexander and Hansen **1986**). Excessive fine sediment in the streambed can interfere with proper development and emergence of salmonid fry, leading to lower fish recruitment (for review see Chapman **1988**). High levels of fine sediment in streambeds can also reduce the abundance of benthic invertebrates (Cordone and Kelly **1961**; Bjornn et al. **1977**), an important food source for juvenile salmonids.

Research investigating the effects of elevated sediment concentration on densities of stream fish has routinely focused on exceedingly high sediment levels. For example, Alexander and Hansen (**1986**) measured a **50%** reduction in brook trout (*Salvelinus fontinalis*) density in a Michigan stream after manually increasing the sand sediment load by a factor of four. In a similar study, Bjornn et al. (**1977**) observed that salmonid density in an Idaho stream declined faster than available pool volume after the addition of **34.5m³** of fine sediment into a **165 m** study section. Both studies attributed decreasing fish densities to the loss of rearing habitat caused by increased sediment deposition. However, streams subject to moderate sediment input may not experience dramatic morphological changes.

Similarly, research investigating physiological stress from suspended sediment has also focused on concentrations much higher than those typically found in streams subjected to moderate sediment input (for review see Newcombe and MacDonald **1991**; Bozek and Young **1994**). Redding et al. (**1987**) observed a temporary increase in plasma cortisol concentration in both

While the supply of sediment from the bypass into Prairie Creek and Klamath River watersheds has declined since the initial inputs, recent observations suggest that sediments from the bypass continue to modify stream habitat. Pool sediment depths in bypass-affected streams near their confluences with Prairie Creek were approximately ten times greater in 1996 than in 1990 (L. Ollivier, Redwood Science Laboratory, Arcata CA 95521; personal communication).

This study compares fish assemblages in streams affected by the bypass with nearby unaffected streams. The specific objectives are to contrast fish diversity, density and summertime growth and survival of coastal cutthroat trout (*O. clarki clarki*) in streams with varying fine sediment conditions.

STUDY AREA

Study streams were located in the Prairie Creek and lower Klamath River drainages of northwest California (Figure 1). Rainfall in this area averages about 127 cm annually, with 75% of the rain occurring from November through March. I identified five pairs of streams each consisting of one stream affected by the bypass and another unaffected by the bypass. I based these pairings on the similarity of tributaries in longitudinal position within the drainages and in watershed area. The pairs of streams provide the basis for measuring the effects of the bypass on sediment concentration and biological characteristics by paired t-tests.

Prairie Creek and its tributaries are representative of the old-growth redwood (*Sequoia sempervirens*) dominated watersheds that were once common throughout northwestern California. The Prairie Creek watershed has largely been spared the intensive logging and urban development that have altered much of the forested landscape of California. Of the six Prairie Creek tributaries studied, only the Boyes Creek and May Creek watersheds have experienced substantial logging (both watersheds were last logged in the 1960's). Stream channels in the drainage typically consist of cobble and gravel, and large woody debris is common. Stream canopy is composed largely of old-growth and second-growth redwood, with bigleaf maple (*Acer macrophyllum*), spruce (*Picea sitchensis*) and red alder (*Alnus rubra*) also present. Prairie Creek

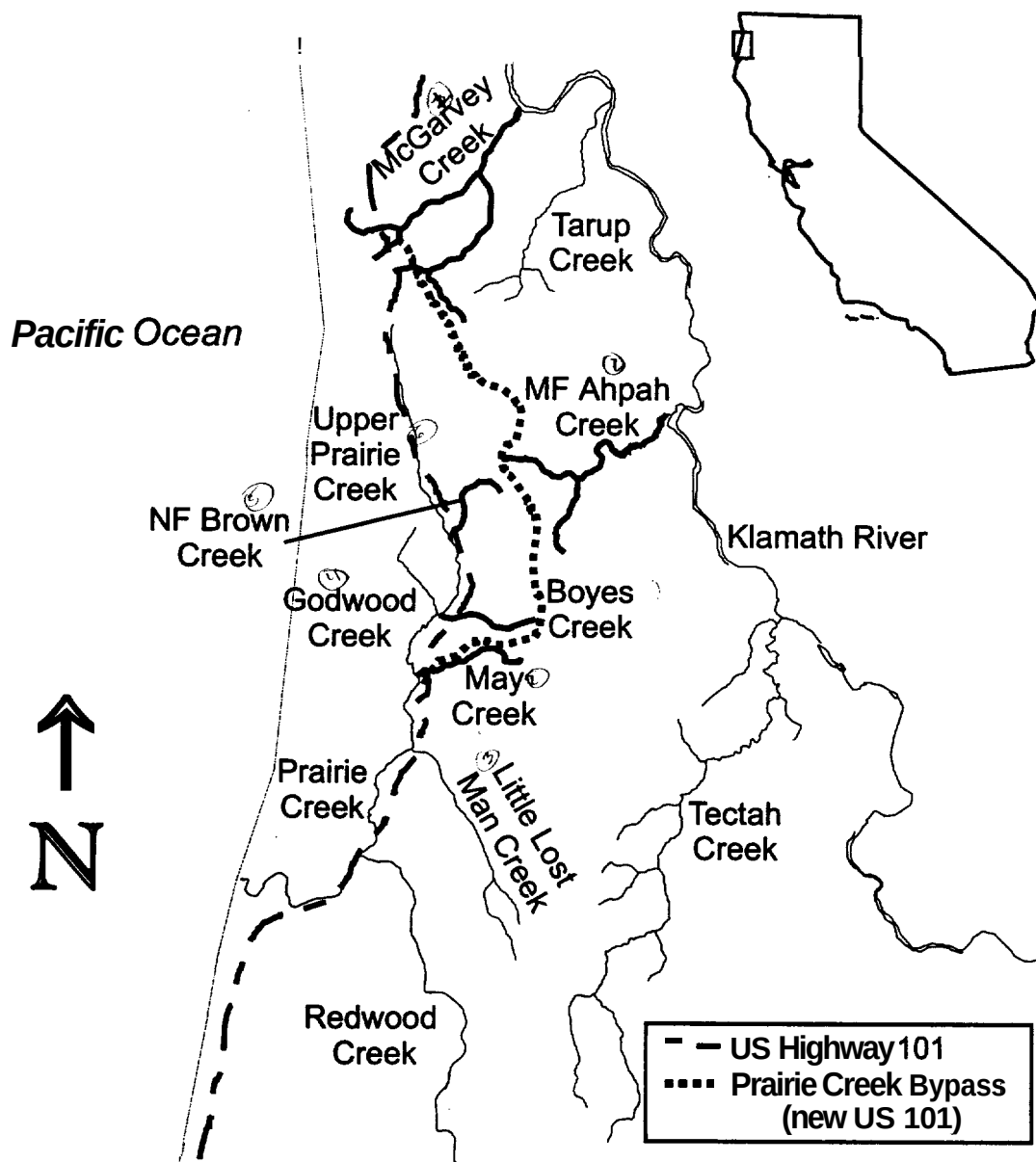


Figure 1. Study streams in Prairie Creek and lower Klamath River basins, Humboldt County, California. Streams affected by the 1989 highway construction appear in bold.

historically supported large runs of anadromous salmonids including coho salmon, chinook salmon (*O. tshawytscha*), and steelhead trout. Within the Prairie Creek drainage, the following affected / control stream pairs were included in the study: May Creek / Godwood Creek, Boyes Creek / Little Lost Man Creek, and North Fork Brown Creek / Upper Prairie Creek.

The Klamath River tributaries selected for my study are first and second order streams characterized by steep gradients and cobble / gravel substrate. Second-growth conifer species ranging from 5 - 50 years-old dominate the hillslopes. Riparian areas are dominated by red alder. Coastal cutthroat trout was the only fish species in the Klamath study reaches. Affected / control stream pairs in the lower Klamath River were: McGarvey Creek / Tarup Creek and Middle Fork Ahpah Creek / Tectah Creek.

METHODS

Sediment Conditions

Sediment conditions in each of the ten study streams were quantified by measuring two variables: summer fine sediment concentration stored within the streambed and suspended sediment concentration during high discharge in winter. To measure fine sediment concentration stored in the channel, I used an index based on disturbing a fixed area of the stream bed and catching the resulting suspended sediment in downstream traps (Mahoney and Erman **1984**). In one pool tail in each stream, I placed nine circular traps (three rows of three traps each) with the lid positioned approximately 5 mm above the stream bed surface (Figure 2). Prior to placement in the stream bed, each trap (8.4 cm diameter by 2.5 cm deep) was filled with clear water and marbles (to reduce possible resuspension of trapped sediment) and fitted with a tight lid. Once depth and velocity were recorded at each trap location, lids were carefully removed starting at the upstream row and working downstream. After all lids were removed, a known volume of streambed (30 cm length x 60 cm width x 10 cm depth) located 25 cm above the first row of traps was disturbed for 2 minutes with a hand trowel. I recorded the average width of the sediment plume during the excavation process. The lids were replaced once the plume had dissipated and the traps carefully removed from the streambed. Trap contents were transferred into 125 ml bottles and treated with a dilute solution of hydrochloric acid to inhibit

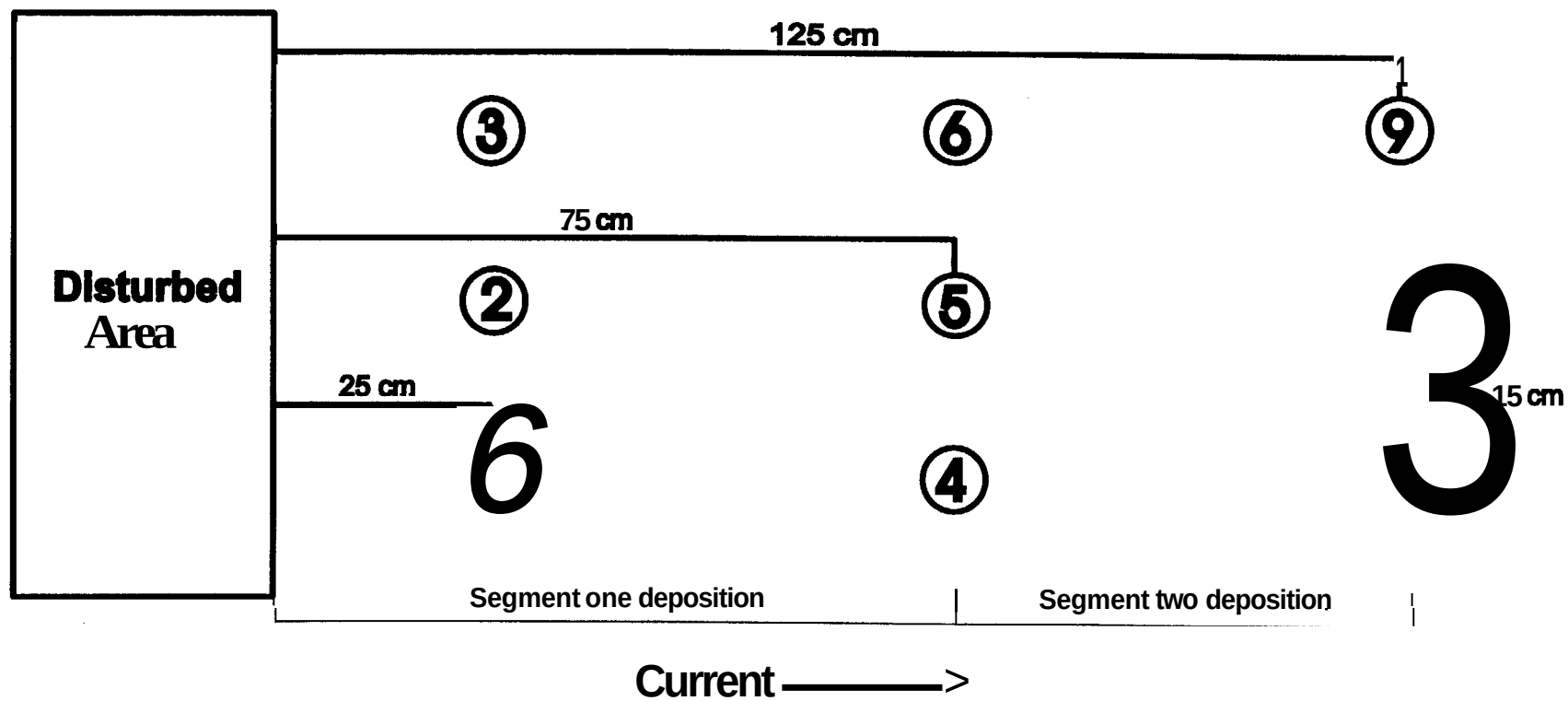


Figure 2. Arrangement of sediment traps used to determine sediment index (following Mahoney and Erman 1984)

bacterial growth. In the laboratory, samples were separated into fine and coarse sediment using a 0.3 mm sieve. The fine sediment was vacuum-filtered onto 1 mm glass-fiber filter paper prior to drying and weighing.

I determined the concentration of fine sediment present in the original disturbed area by combining sediment deposition occurring from the origin to row two (segment one) and deposition from row two to row three (segment two). Deposition beyond row three was assumed to be negligible.

$$\text{sediment concentration within streambed} = \frac{(\text{Segment one dep. (mg/cm)} + \text{segment two dep. (mg/cm)}) \times W \text{ (cm)}}{\text{volume of stream bed disturbed (18000 cm}^3\text{)}} \text{ (mg/cm}^3\text{)}$$

where

$$\text{Segment one deposition (mg/cm)} = \frac{Z_2 \left(\frac{N_1^2}{N_2} - N_2 \right)}{-\log_e \frac{N_2}{N_1}} \quad \text{Segment two deposition (mg/cm)} = \frac{Z_{3-2} N_2}{-\log_e \frac{N_3}{N_2}}$$

W = average width (cm) of the sediment plume over the traps

Z₂ = distance (cm) from origin to second row of traps

Z₃₋₂ = distance (cm) from second to third row of traps

N_i = mean sediment deposition (mg/cm²) per trap in the ith row

The computed average deposition for each segment was multiplied by the corresponding downstream length (75 cm from origin to row 2, 50 cm from row 2 to row 3) and then summed to produce the total deposition per unit width (mg/cm) occurring from the origin to row 3. Multiplying the total unit deposition by the average width of the sediment plume and dividing by the original area disturbed produces the approximate sediment concentration (mg/cm³) originally present in the disturbed volume of streambed. I compared this sediment index in bypass-affected and control streams using a paired t-test.

I collected grab samples of suspended sediment on February 22, 1998 during high discharge following a rainstorm. A flow-duration curve using Little Lost Man Creek daily discharge data indicated that the discharge during this event is exceeded approximately 15 days per year. The sampling procedure entailed submerging a 125 ml bottle approximately 10 cm below the water surface near the thalweg. I later vacuum-filtered (Gelman glass-fiber filter; pore size 1 mm), dried and weighed each sample to provide an estimate of suspended sediment concentration in mg/L. By sampling several hours after peak discharge, I hoped to eliminate the extreme variability in suspended sediment which can result when sampling near the peak of the hydrograph. Suspended sediment concentration in bypass-affected and control streams was compared using a paired t-test. I also tested for significant correlation between the sediment index and winter suspended sediment concentrations. All sediment data were log transformed prior to statistical analysis.

Fish Density and Diversity

I sampled fish density and diversity in all ten streams from May - September 1997 (summer) and from February - May 1998 (winter / spring). In summer, time between sampling of stream pairs did not exceed 10 days. For summer sampling, two approximately 50-m reaches per stream were chosen using a representative reach approach. I avoided reaches with unusual habitats (i.e. braided channels, unusually large pools, or excessive LWD accumulation).

Block nets were placed at the upper and lower boundaries of each study reach and fish and amphibians sampled by three-pass backpack electrofishing. All fish and amphibians captured were anesthetized using CO₂, identified, weighed to the nearest 0.01g, and measured to the nearest mm (fork length (FL) for salmonids, snout/vent for Pacific giant salamanders (*Dicamptodon tenebrosus*), body length for red-legged (*Rana* aurora) and yellow-legged frogs (*R. boyler*), and total length for sculpin (prickly sculpin, *Cottus asper* and coastrange sculpin, *C. aleuticus*), threespine stickleback (*Gasterosteus aculeatus*), Klamath smallscale sucker (*Catostomus rimiculus*), Pacific lamprey (*Lampetra tridentata*) and tailed-frog (*Ascaphus truer*) tadpoles). Young of the year steelhead and cutthroat were both categorized as "trout" because they are difficult to distinguish in the field. I calculated fish biomass (g/m²) from population estimates obtained using the Zippin successive removal method (Zippin 1958).

For the winter / spring sampling, I randomly selected one of the two original 50-m reaches in each stream and then used the same methods employed in summer. Due to access problems, Middle Fork Ahpah Creek was sampled on May 5, 1998, several weeks later than the other nine streams in the study (February 26 - March 18, 1998).

Using individual streams as the basic units of observation, I compared characteristics of the fish assemblages in affected and unaffected streams using paired t-tests. Total salmonid biomass was contrasted across all 5 pairs of streams. On Prairie Creek, differences in coho salmon, young-of-the-year (YOY)

trout, and 1+ trout biomass within stream pairs (bypass-affected/ control) were analyzed with paired t-tests. I separately analyzed coho salmon and YOY trout because they were the most abundant fish in the Prairie Creek drainage. A similar approach was used on the Klamath River tributaries, where a t-test was used to compare differences between bypass-affected and control streams in age 1+ and YOY cutthroat trout biomass. Again, I examined YOY cutthroat trout biomass because they were the most abundant fish in the upper reaches of the Klamath River tributaries. In both study drainages, I analyzed 1+ trout biomass because it might best reflect the quality of winter habitat, which may limit salmonid populations in streams (Cunjak **1996**). Because the ten streams represented a broad range of sediment conditions, I also performed regression analysis of coho salmon biomass (for Prairie Creek streams) and total salmonid biomass (for all ten streams) versus sediment concentration.

In addition to fish biomass, I analyzed diversity of the vertebrate assemblages within the ten study streams using an inverse of species dominance. This measure of diversity has been used previously in salmonid-dominated, coastal watersheds of the Pacific Northwest (Reeves et al. **1993**). Following Reeves et al. (1993), I used the Berger-Parker index $d = N_{\max} / N$ to estimate dominance, where $N_{\max}$ is the number of individuals of the most abundant species and N is the total number of individuals in a sample (Berger and Parker **1970**). I again used a paired t-test to compare vertebrate dominance in the assemblages within the bypass affected / control stream pairs, and

electrofishing, field crews measured several physical characteristics of the study

woody debris (LWD) volume was estimated by measuring all dead wood at least 1 m long and 0.3 m in diameter within the bankfull channel of each reach. Cover was estimated as the area of habitat providing overhead protection from predators (i.e. LWD, undercut banks, etc.) for fish 80 mm FL. I also recorded percent canopy readings from mid-channel at the 10, 25 and 40 m points along each reach using a densiometer. Four canopy readings were taken at each point (facing upstream, downstream, and toward the left and right banks) and all twelve readings averaged. Differences in canopy, LWD volume, cover, % silt, average stream depth and average stream width were analyzed using paired t-tests.

Salmonid Growth and Survival During Summer

I measured coastal cutthroat trout growth and survival over a six week period during July / August 1997 in stream enclosures on all six Prairie Creek

study streams. Three or four approximately 10-m-long sections were chosen on each stream, with each section containing a pool and about 2 m of the adjacent upstream riffle. Metal stakes were driven into the streambed at the upper and lower boundaries of each section, and 6-mm plastic mesh was fastened to the rebar with plastic ties. About 15 cm of the underwater edge of the mesh was buried in the substrate. Once the mesh fences were in place, I removed all fish from each enclosure by electrofishing. Electrofishing continued until at least two successive passes yielded no fish. Cutthroat trout (60-100 mm FL) were then gathered from the surrounding area. I weighed, measured, photographed, and clipped the adipose fin of each fish included in the experiment before placing them in enclosures. Fish were weighed on an electronic balance to the nearest 0.01 g. Cutthroat trout were stocked in each enclosure at a rate of one-half the average salmonid biomass (g/m^2) for Prairie Creek study streams. Average salmonid biomass was derived from electrofishing data gathered earlier in the study. The relatively low stocking rate was used to 1) provide favorable conditions for growth, and 2) allow for declining flows and subsequent reductions in habitat area within the enclosures over the course of the experiment. During the experiment, leaves and detritus were removed from the screens at least once per week. Otherwise, fish were left undisturbed. At the end of the experiment, fish were recovered from each enclosure by electrofishing and identified, weighed, measured and photographed prior to release. I also measured the average depth and surface area of each enclosure at the end of the experiment.

To estimate weight change of fish in each stream, I first averaged the individual percentage weight gains of fish within each enclosure, then averaged the three or four enclosures in each stream. I analyzed these results using a paired t-test. Recognizing the broad range of sediment conditions in the study streams, I also regressed percentage growth on the sediment index. Data from three of the nineteen enclosures in the experiment were compromised due to movement of fish. Data from these enclosures were excluded from the analysis.

RESULTS

Sediment Index

Bypass-affected and control streams had different amounts of fine sediment stored in the stream bed (Table 1; paired t-test on log transformed data, $n = 5$, $p = 0.04$). The difference in sediment concentration within pairs of control and bypass-affected streams ranged from 43 % for Middle Fork Ahpah / Tectah to 158 % for McGarvey / Tarup (affected - control / control). There was significant variation in the sediment index within the two groups of streams. Sediment conditions in the four Klamath tributaries exhibited greater variation than Prairie Creek tributaries. The percentage of silt substrate was also significantly higher in bypass-affected streams than in control streams (Table 2; paired t-test, $n = 5$, $p = 0.05$). Other physical characteristics did not differ between bypass-affected and control streams (Table 2; paired t-tests; $n = 5$, all $p > 0.24$).

Winter suspended sediment concentrations ranged from 2 mg/l (Upper Prairie Creek) to 102 mg/l (McGarvey Creek) and were higher in bypass-affected stream than control streams (paired t-test on log transformed data, $n = 5$, $p < 0.01$). However, winter suspended sediment samples were not strongly correlated with fine sediment stored in the stream bed (log-transformed data, $n = 10$, $r^2 = 0.12$).

Table 1. Sediment index, winter sediment concentration, and sediment study site physical data for Prairie Creek and Klamath River tributaries (September 1997 through February 1998). Mean velocity and depth represent mean conditions over all nine sediment traps during sediment sampling.

Stream pairs	Treatment	Sediment Index (mg/cm ³)	winter suspended sediment conc. (mg/L)	Mean velocity (cm/s)	Mean depth (cm)
Little Lost Man	control	5.12	18	5.78	18.56
Boyes	bypass-affected	7.89	92	5.33	8.11
Godwood	control	2.43	3	14.28	10.28
May	bypass-affected	4.56	20	11.67	10
Uppper Prairie	control	4.71	2	7.89	7
North Fork Brown	bypass-affected	7.26	6	6.89	15.22
Tarup	control	8.26	22	6.89	7.11
McGarvey	bypass-affected	21.33	33	8.78	8.56
Tectah	control	3.60	50	9.22	16.89
MF Ahpah	bypass-affected	5.16	102	12.33	18.44

Table 2. Summer physical characteristics of study streams.

Stream pairs	Treatment	% canopy	LWD vol (m ³ /m ²)	cover for fish (% of stream bottom)	% silt	mean depth (cm)	mean width (m)
Little Lost Man	control	93.1	0.23		0	13.09	5.6
Boyces	bypass-affected	95.4	0.01	7.75	8.9	12.51	2.7
Godwood	control	94	0.16	5.34	1.5	13.85	3
May	bypass-affected	93.5	0.16	11.00	10	11.82	2.5
Upper Prairie	control	95.4	0.41	8.14	0	9.3	1.5
North Fork Brown	bypass-affected	91.4	0.06	4.76	6.4	11.15	2.4
Tarup	control	98.2	0.26	2.72	14.5	10.73	2.5
McGarvey	bypass-affected	97.7	0.33	7.11	42.3	8.26	3.2
Tectah	control	95.9	0.30	6.56	5	8.12	2.1
MF Ahpah	bypass-affected	95.2	0.34	12.41	11	9.71	2.1

Diversity/ Density of Fish

Fish species captured in Prairie Creek tributaries included coho salmon, steelhead trout, coastal cutthroat trout, prickly sculpin, coastrange sculpin, three-spine stickleback, and Klamath smallscale sucker. Both ammocoetes and adults of Pacific lamprey were also collected. Amphibians frequently collected included Pacific giant salamanders and tailed frogs. Yellow-legged and red-legged frogs were rare. The only vertebrates collected in the Klamath tributaries were coastal cutthroat trout, Pacific giant salamanders, and tailed frogs. ~~Smallmouth bass were also collected in the Klamath tributaries.~~

~~Relative abundance of fish species in both sampling seasons in Prairie Creek~~

~~Results~~ Dominance of coho salmon within the six Prairie Creek tributaries ranged from 0.28 and 0.58 during summer and 0.31 and 0.55 during winter. Diversity of vertebrate assemblages, measured as the inverse of dominance, did not differ between the five pairs of bypass-affected and control streams in summer or winter (paired t-test, $n = 5$, $p = 0.64$ for summer, $p = 0.23$ for winter). Overall, the fine sediment index did not predict vertebrate diversity in the study streams (Figure 3; $n = 10$, $r^2 = 0.09$, $p = 0.41$).

During summer, I found similar salmonid biomass in bypass-affected and control streams (Figure 4; paired t-test, $n = 5$, $p = 0.69$). Separate analyses of tributaries in the **two** drainages yielded similar results. Bypass-affected streams in Prairie Creek contained a higher summer biomass of coho salmon and YOY trout than control streams, but the difference was not significant (Figure 5; paired t-test, $n = 3$, $p = 0.09$ for coho salmon, $p = 0.82$ for young of the year trout).

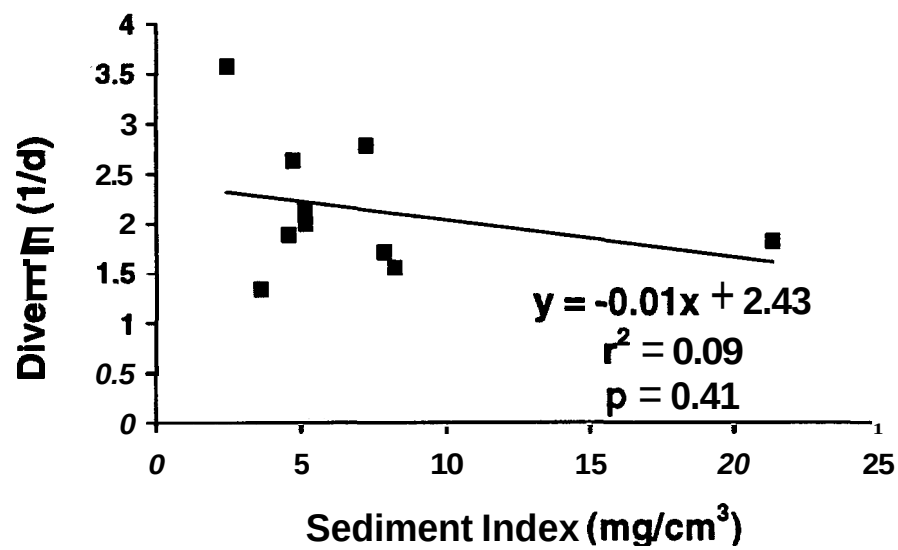


Figure 3. Regression analysis of summer diversity (1/dominance) versus sediment index in Prairie Creek and Klamath River tributaries, northern California.

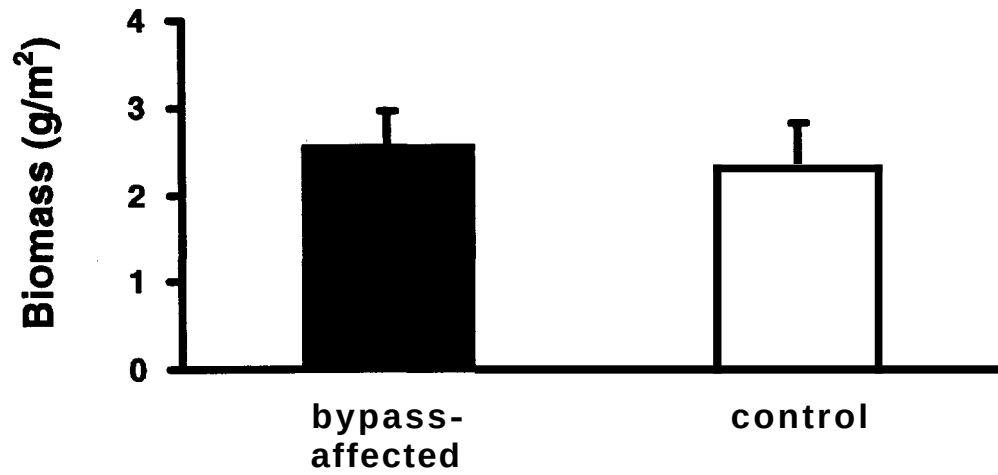


Figure 4. Total salmonid biomass in Prairie Creek and Klamath River tributaries.

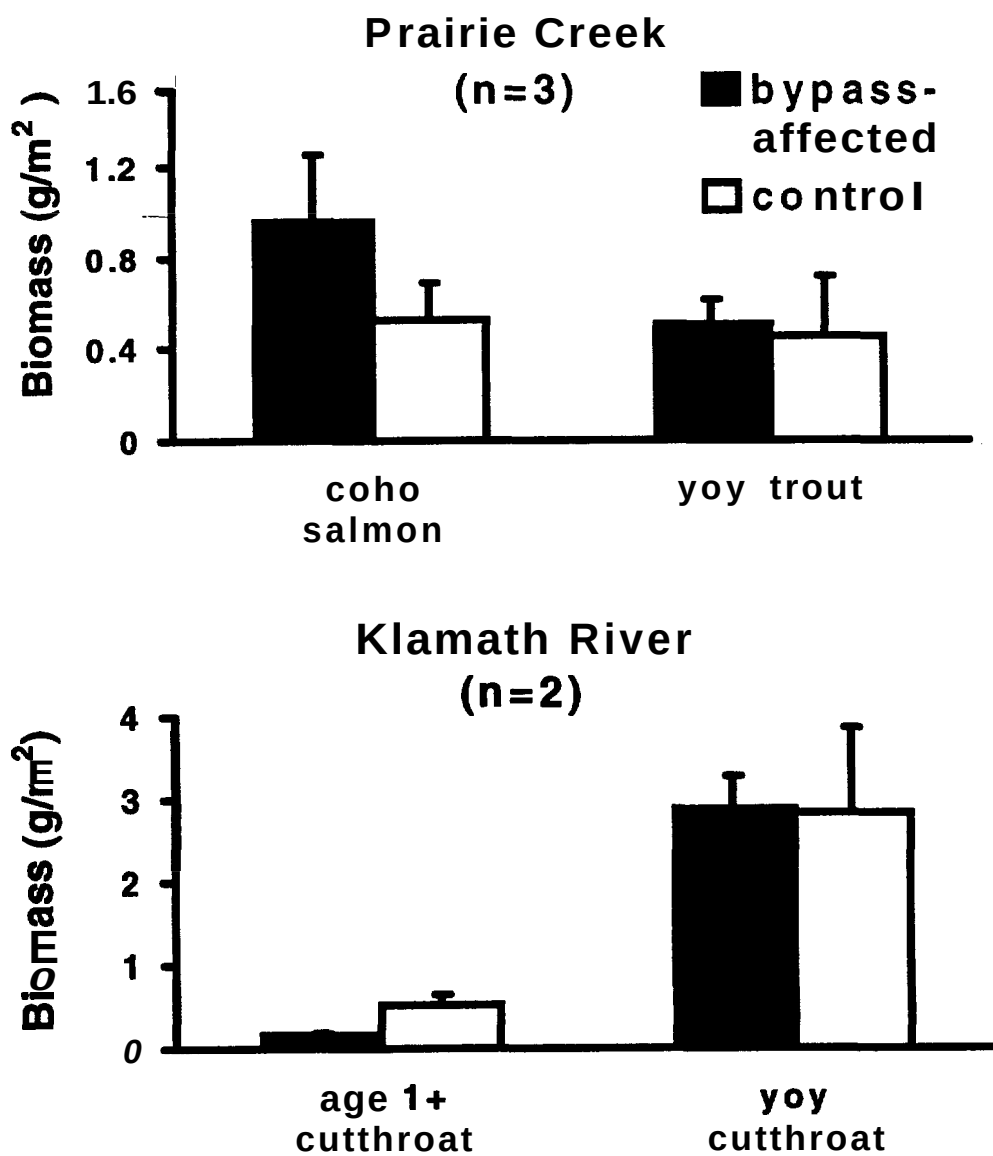


Figure 5. Summary of salmonid biomass for Prairie Creek and Klamath River tributaries, northern California.

Summer cutthroat trout biomass in the Klamath tributaries did not differ between affected and control streams (Figure 5; paired t-test, $n = 2$, $p = 0.25$ and $p = 0.98$ for age 1+ and YOY cutthroat, respectively). Neither total salmonid biomass (Prairie Creek and Klamath River tributaries combined) nor coho salmon biomass (Prairie Creek tributaries) were well-predicted by the sediment index during summer (Figure 6; $n = 10$, $r^2 = 0.11$, $p = 0.36$ and Figure 7; $n = 6$, $r^2 = 0.38$, $p = 0.19$).

Fish density remained similar between bypass-affected and control streams in winter. Winter salmonid biomass was significantly lower than summer biomass in Prairie Creek and Klamath river tributaries combined ($n = 10$, winter average 1.20 g/m^2 , summer average 2.48 g/m^2 ; paired t-test, $n = 10$, $p = 0.003$). Winter coho salmon biomass in Prairie Creek and overall salmonid biomass both tended to be higher in bypass-affected streams, though not significantly so (paired t-test, $n = 3$, $p = 0.23$ for coho salmon biomass in Prairie Creek tributaries; $n = 5$, $p = 0.15$ for total salmonid biomass). Likewise, age 1+ trout densities were generally higher in bypass-affected streams during the winter, but not significantly so (paired t-test, $n = 5$, $p = 0.67$).

Summer Growth and Survival

Growth and survival of cutthroat trout in enclosures was similar in bypass-affected and control streams (Figure 8; paired t-test, $n = 3$, $p = 0.32$). However, growth in enclosures was well-predicted by sediment index (Figure 9; $n = 6$, $r^2 =$

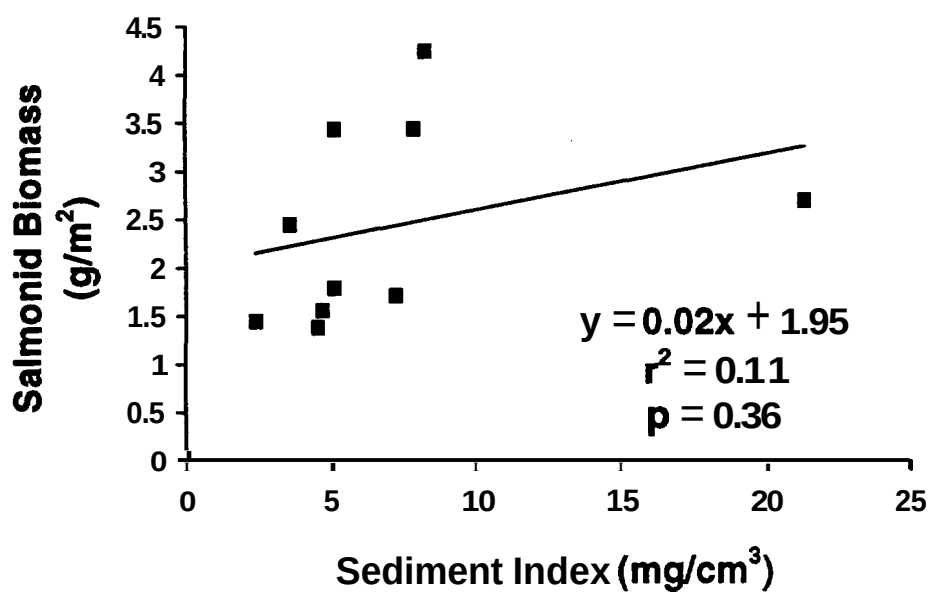


Figure 6. Regression analysis of total salmonid biomass versus sediment index in Prairie Creek and Klamath River tributaries, northern California.

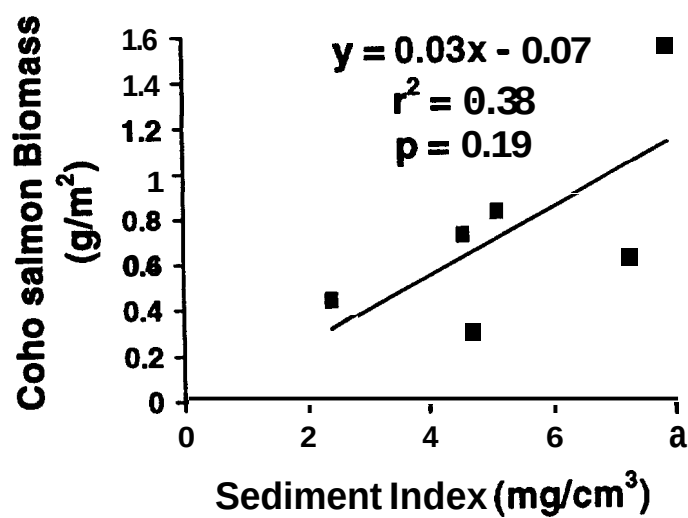


Figure 7. Regression analysis of coho salmon biomass versus sediment index in Prairie Creek, northern California.

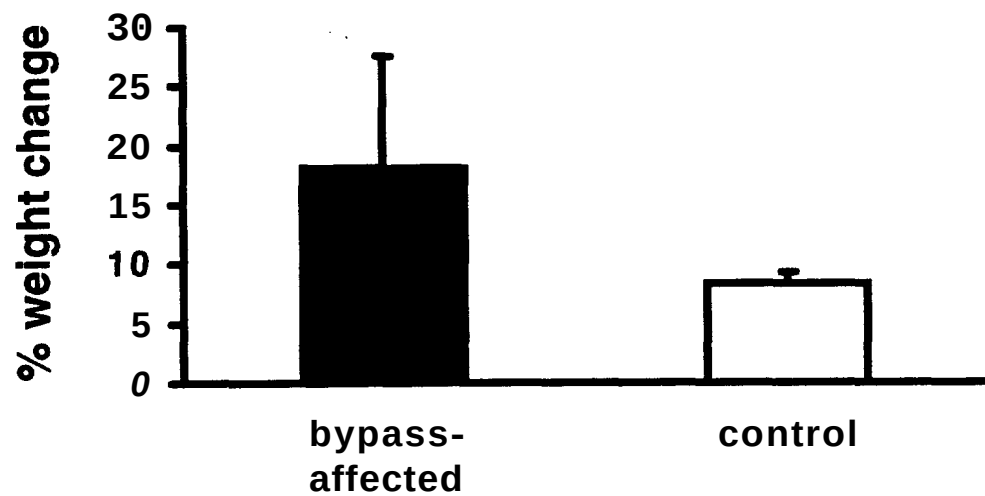


Figure 8. Summer growth of cutthroat trout in bypass-affected versus control streams in the Prairie Creek drainage, northern California. Percentage growth was determined by stocking fish within mesh-enclosed stream sections at one-half natural density. After six weeks fish were removed and the average percentage growth was computed for each study stream.

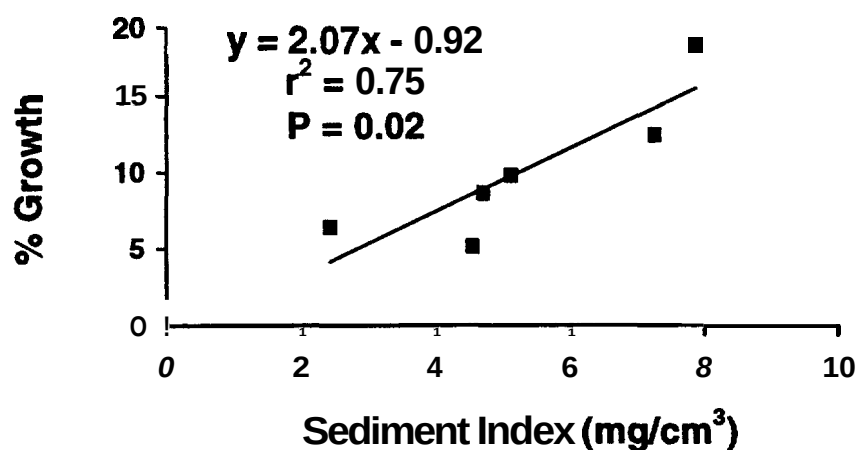


Figure 9. Regression analysis of percentage growth versus sediment index in Prairie Creek tributaries, northern California. Percentage growth was determined by stocking coastal cutthroat trout within mesh-enclosed stream sections at one-half natural density. After six weeks fish were removed and the average percentage growth was computed for each study stream.

0.75, $p = 0.02$). Average weight change of cutthroat trout ranged from 5.2% for May Creek to 18.3% for Boyes Creek. Weight change varied dramatically among experimental units in Little Lost Man and May creeks with fish losing weight in one enclosure in both streams. Fish gained weight in all the enclosures in the other four study streams. Due to movement of fish in and out of enclosures, one enclosure in Boyes Creek and two in Godwood Creek were eliminated from the analysis.

DISCUSSION

This study revealed no relationship between moderately increased instream fine sediment and stream fish biomass or diversity. Streambed fine sediment concentrations in bypass-affected streams ranged from **4.6** to **21.3** mg/cm³. In contrast, watersheds logged without riparian buffers investigated by Mahoney and Erman (1984), generally had higher instream sediment concentrations (**13** to **88.3** mg/cm³). Similarly, suspended sediment concentrations in the streams I studied were also below levels previously predicted to cause fish mortality (Newcombe and MacDonald 1991). The highest suspended sediment concentration I measured, combined with the assumption that this concentration occurs about **15** days per year, yields a stress index of 5 on a scale of **1 - 15** (*sensu* Newcombe and MacDonald (1991): log (concentration x duration)). Newcombe and MacDonald's review of sediment effects suggests that this stress index value would result in reduced feeding rates and impaired homing, but would not cause physiological stress or immediate mortality.

Several mechanisms linking sediment and fish health may operate only at high levels of fine sediment input. For example, elevated suspended sediment concentrations known to directly harm salmonids commonly exceed 2000 mg/L. Chronic exposure to suspended solids at concentrations between 2000 and 4000 mg/L can cause physiological changes that are characteristic of sublethal stress, such as increased plasma cortisol levels in the blood and lowered immunity to

infection (Redding et al. 1987). Bergstedt and Bergersen (1997) observed significantly more gill abnormalities and fin abrasions in salmonids living at sediment concentrations approaching 4000 mg/L below a sediment sluicing dam, compared to fish living above the dam. Bozek and Young (1994) documented asphyxiation of cutthroat trout in a Montana stream where sediment concentrations reached 9,680 mg/L. At the moderate sediment levels I encountered, however, measurable effects of suspended sediment on fish health appear unlikely.

As with fish health, significant impacts on fish habitat probably require much higher sediment concentrations than I encountered. Large additions of fine sediment can significantly decrease available pool volume, which in turn may lower juvenile fish density. Bjornn et al. (1977) observed that salmonid density declined at a faster rate than pool volume when the latter was reduced by over 50% following the introduction of fine sediment into a natural stream. Similarly, Alexander and Hansen (1986) increased the normal **bedload** in a Michigan stream by a factor of four, transforming the channel into one continuous run devoid of **pools** and riffles. Several years after the introduction of sediment, brook trout abundance had decreased by half. However, these large additions of sediment produced changes in pool morphology and volume unlike conditions in Prairie Creek and lower Klamath River streams during this study. Average depths within study reaches were 10.7 cm for bypass-affected and 11.0 cm for control streams, suggesting that pool volumes were similar in the two groups. **In**

addition to reducing pool volume, increased sediment loads may reduce habitat complexity by simplifying the substrate. Habitat complexity can be positively related to fish diversity (Gorman and Karr **1978**). However, the overall similarity in habitat (average stream depth, LWD volume, and fish cover) between stream pairs in this study (Table 2) suggests that differences in fish density and diversity as a result of differences in habitat complexity would not be expected.

High levels of fine sediment in spawning gravel may hamper salmonid reproduction via decreased embryo survival and fry emergence. This in turn could have a negative effect on salmonid production and (or) standing crop (for review see Chapman **1988**). However, high fry mortality is common in anadromous salmonid populations. Any reduction in density of YOY fish resulting from high levels of inter-gravel sediment could result in decreased competition, increased growth, and greater survival among remaining fry (McFadden **1969**). Magee et al. (**1996**) saw no difference in cutthroat trout recruitment in streams with high fine sediment concentrations versus adjacent undisturbed streams. This was attributed in part to higher juvenile survival at low densities. Movement among tributaries by YOY fish may also obscure any effects of locally poor reproduction. Klatte and Roelofs (**1997**) documented higher spring outmigration of juvenile coho salmon in Godwood Creek than in the three bypass-affected streams of Prairie Creek in this study: on average over 7 times greater for age 0+ fish and 1.5 times greater for 1+ fish. However, in this study summer density of juvenile coho salmon in Godwood Creek was one-third that of Boyes Creek, a

bypass-affected stream characterized by elevated instream sediment levels and particularly low out-migration. These data suggest migration of YOY fish from areas of high to low recruitment may mitigate stream-level effects of elevated fine sediment on reproductive success, or that summer densities are not limited by abundance of alevins.

In contrast to extreme levels of suspended sediment, which can be lethal, moderate levels can be advantageous and even preferred by juvenile fishes (Cyrus and Blaber 1987). Gregory and Levings (1998) compared predation rates by piscivorous fish on migrating juvenile salmonids in the Harrison (<1 NTU) and Fraser (27-108 NTU) rivers of southern British Columbia. The authors found that predation on juvenile salmonids by piscivorous fish was reduced in turbid compared with clear water, mainly by reduced encounter rates between predator and prey. In addition to possibly increasing survival, the moderate turbidity in some Prairie Creek tributaries may reduce outmigration of juvenile salmonids.

Large amounts of fine sediment may decrease the abundance and production of benthic invertebrates (Cordone and Kelly 1961; Crouse et al. 1981), thus limiting food available to many stream fish. However, the availability of terrestrial insects in streams with dense riparian vegetation may mask any negative effects of reduced aquatic prey because terrestrial invertebrates often comprise a significant portion of the diet of juvenile salmonids (Cada et al. 1987; Nakano et al. 1999). Furthermore, riparian areas consisting of dense shrub and

broad-leaf species (particularly alder) can generate greater terrestrial input than comparable old-growth habitat (Wipfli 1997). The enclosures used to quantify

expected. The relatively high weight gain as compared to the control stream recorded in Boyes Creek (18.3%) may reflect the close proximity of the enclosures to productive riparian areas.

Though a significant difference in summertime growth between bypass-affected and control streams was not apparent, growth rates were positively correlated with sediment index. This result is supported by a significant correlation between growth measured during the experiment and summer salmonid biomass in the same streams ($n = 6$, $r^2 = 0.89$, $p < 0.01$). These results are not easily interpreted. One possibility is that fish more effectively prey on benthic invertebrates when the substrate is moderately embedded. Brusven and Rose (1981) documented 90-95% predation on benthic invertebrates by sculpin during 24 hour tests involving sand substrate, over twice the predation that occurred over sand substrate with unembedded cobbles. Greater success preying on benthic macroinvertebrates could translate into greater fish growth, and would explain the positive relationship between sediment and growth that I observed.

Results from this study contrast with observations in 1990 and in **1996** of lower amphibian densities in streams affected by the Prairie Creek bypass

(Welsh and Ollivier 1998; Welsh and Ollivier 1999). Sampling immediately after the initial addition of sediment might have revealed a strong relationship between sediment concentration and fish density. However, differences between amphibians and fish in use of pool habitat might best explain the discrepancy between the 1996 amphibian data and 1997 fish data. Pool-dwelling amphibians, particularly the Pacific giant salamander, tend to reside under cobbles, and thus would be severely affected by increased substrate embeddedness (Welsh and Ollivier 1998). Juvenile salmonids predominantly reside in the water column and would be more affected by a loss of pool volume than an increase in substrate embeddedness (Bjornn et al. 1977). Greater substrate embeddedness within pools was observed in bypass affected streams during the 1996 amphibian sampling. However, significant changes in pool area and volume were not detected during my sampling, suggesting the loss of preferred habitat was greater for amphibians. Furthermore, juvenile coho salmon spend a short time (typically 1 year) rearing in freshwater before migrating to saltwater, whereas most stream amphibians are long-lived and highly philopatric (Welsh and Ollivier 1998). For this reason, poor stream habitat may more strongly affect amphibians than coho salmon.

Though I found no apparent effects of moderate sediment levels on fishes, the continuing sediment input occurring within the Prairie Creek watershed affords a unique opportunity to further study the effects of moderate sediment conditions on production and diversity of stream fish. Studies examining feeding

behavior as well as within-stream migration patterns of juvenile salmonids in Prairie Creek streams would prove useful in better understanding the effects of elevated sediment on stream fish assemblages. Future studies investigating effects of elevated fine sediment on stream fish assemblages focused on sub-lethal sediment intensities higher than the moderate conditions encountered in this study would be particularly valuable.

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