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Effects of Suction-Dredge Gold Mining on Benthic Invertebrates in a Northern California Stream

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Abstract.—The effects on benthic invertebrates of mining with two suction dredges were investigated in 1983 by using artificial-substrate samplers in Big East Fork Creek, a tributary to Canyon Creek in northern California. The samplers were placed in Big East Fork Creek above and below the dredge site and in Canyon Creek above and below the confluence of Big East Fork Creek. The effects of dredging on invertebrates varied with taxa and were site-specific at the level of dredging during the study. Total numbers of invertebrates that colonized samplers and their diversity indices did not differ significantly between Big East Fork and Canyon creeks or above and below dredges in either creek. Numbers of invertebrates peaked earlier in samplers below the dredges. In Big East Fork Creek, shredders were more abundant above than below dredges, whereas gatherers were more abundant below dredges. Filterers rapidly colonized samplers below dredges and were later displaced by siltation. Shredders were more abundant above dredges in Big East Fork Creek and less abundant above dredges in Canyon Creek. Sediment and organic matter fractions in samplers were higher below than above the dredges. Habitat variables (water depth and velocity, organic matter, sediment) accounted for 17–75% of the variation observed in abundance of common taxa. In drift samples, numbers of gatherers were higher below than above dredging sites; numbers of other functional feeding groups were similar. Sedimentation rates in Big East Fork Creek were higher below than above the dredging sites. Sedimentation rates in Canyon Creek were similar above and below Big East Fork Creek. High water flows and bed-load movement in winter filled dredge holes and flushed sediment from the study site.

Suction-dredge gold mining has increased in California in recent years as a result of high gold prices and the versatility of the portable suction dredge. The effects of dredge mining on aquatic populations and habitat in anadromous streams are poorly documented. The effects on invertebrates generally appear to be temporary and site-specific. Griffith and Andrews (1981) reported that less than 1% of 3,623 invertebrates entrained through a dredge were dead or injured 1 d later, and that dredged stream areas were recolonized after 38 d. Harvey (1986) observed that suction-dredge mining in California Sierra streams had only localized effects on turbidity, but that benthic invertebrate communities were significantly altered by dredging. Alterations were localized and associated with changes in the degree of embeddedness of cobbles and boulders. Thomas (1985) found that dredging caused significant local alterations in the abundance of benthic invertebrates in a Montana stream, but he noted that recolonization occurred within 1 month. He also found that concentrations of suspended sediment returned to background levels 11 m below a dredge. Our objectives were to assess the effects of two suction dredges on benthic invertebrates, on the relative rates at which invertebrates colonized artificial substrates, on diel invertebrate drift rates, and on sedimentation and selected water quality characteristics above and below dredging in streams used by anadromous fishes.

Study Site

Canyon Creek is a fourth-order, moderate-gradient (2–5%) stream that flows into the Trinity River at Junction City, California. It drains 168 km^2; summer low flows are 0.28–1.4 m^3/s, and winter high flows are near 42 m^3/s. Big East Fork Creek is a high-gradient (up to 15%), third-order stream that enters Canyon Creek 18 km upstream from the confluence of Canyon Creek with the Trinity River. Low summer flows in Big East Fork Creek range from 0.11 to 0.20 m^3/s. Annual precipitation in the Canyon Creek area for water year 1982–1983 (October 1, 1982, to September 30, 1983) was 180% of the mean, based on a 45-year period from 1931 to 1975 (California Department

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of Water Resources 1983). California requires a permit for all dredge mining and designates open areas and seasons. Dredging is permitted in Canyon Creek from June 1 to September 15; the diameter of the nozzle is restricted to 15.2 cm or less. Dredging is permitted until October 15 on Big East Fork Creek. No dredging occurred on Canyon Creek above Big East Fork during the study. Canyon and Big East Fork creeks have been extensively mined in the past. Canyon Creek provides important spawning and rearing habitat for chinook salmon *Oncorhynchus tshawytscha*, coho salmon *O. kisutch*, and steelhead *O. mykiss*.

Methods

We used artificial-substrate baskets to sample sites designated as follows: site B1, Big East Fork above dredges; site B2, Big East Fork below dredges; site C3, Canyon Creek above confluence of Big East Fork; and site C4, Canyon Creek below confluence of Big East Fork. Professional miners operated two suction dredges (hose diameter, 10.2 cm) on Big East Fork from August 3 to October 4, 1983. The diameter and depth of the cone-shaped dredge holes were measured at the end of the dredging season.

The artificial-substrate samplers measured 25.4 × 10.2 × 6.4 cm. They were constructed of 13-mm-mesh hardware cloth and were filled with cleaned stream cobble graded from 2 to 4 cm in diameter. The samplers were randomly placed at each sample site and were buried flush with the stream bottom in water with similar depths, velocities (2% or less), and substrates. We buried 28 samplers each at sites B1 and B2 in Big East Fork Creek on August 31 and September 1, and we removed 7 at random from each site after 2, 4, and 6 weeks; 14 samplers each were similarly buried at sites C3 and C4 in Canyon Creek on September 1 and 2, and 7 were removed at random from each site after 4 weeks. High streamflows prevented removal of samplers from each site 1 month after dredging stopped. Water depth and velocity were measured at each sampler with a top-set wading rod and a pygmy flowmeter. Samplers were carefully removed and placed in a bucket to retain organic matter and sediments; they were dismantled in the bucket, and benthic invertebrates, organic matter, and sediment were separated from the sampler cobble by rinsing the sample through a 1.27-cm-mesh Tyler sieve. The rocks and associated organic matter from the samplers were immersed in an irritant solution (Britt 1955) to dislodge clinging organisms. Samples were concentrated by pouring the supernatant through a number 70 Tyler sieve and were then preserved in 70% ethanol.

We separated invertebrates and organic matter from sediment by density flotation, using a 200-g/L sugar solution (Slack et al. 1973). Organic matter and sediment were dried in an oven at 100°C for 24 h and weighed. Invertebrates were keyed to the lowest readily identifiable taxonomic level. The taxa were also divided into functional feeding groups—predators, shredders, grazers, filterers, and gatherers (Merritt and Cummins 1984).

The Shannon–Weiner diversity index H' (Wilhm and Dorris 1968) was used to determine diversity per sampler. The equitability index e' (Platts et al. 1983) was used to examine the evenness of allotment of individuals among taxa. All benthic invertebrate data were log-transformed, and normality was examined with a G-test (Sokal and Rohlf 1981) and frequency histograms. Homoscedasticity of transformed data was verified with the Hartley F-max test (Sokal and Rohlf 1981). A two-way analysis of variance (ANOVA) was performed on functional group data from Big East Fork Creek for treatment (above and below the dredge) versus time (periods of 2, 4, and 6 weeks), with seven replicates. A separate two-way ANOVA was performed on functional group data for week four from Big East Fork and Canyon creeks for treatment (above and below dredge, with creeks pooled) versus creek (Big East Fork and Canyon creeks, with treatments pooled), with seven replicates. The Bonferroni approximation (Ramsey 1980) was applied to ANOVA significance levels to account for dependence among measured variables (Willig et al. 1986). Descriptive statistics and ANOVA were computed with the SPSS programs CONDESCRIPTIVE, ANOVA, and ONEWAY (Nie et al. 1975) and on the BMDP program 5D (Dixon 1981). The relation of abundance of common taxa captured in samplers to physical habitat variables (water depth and velocity, organic matter, sediment) was estimated by multiple-regression analysis with BMDP program 1R (Dixon 1981).

Kick samples, taken from similar stream habitats downstream from samplers during each removal period, were treated in the same way as the artificial-substrate samples. Percentage composition of functional groups and diversity indices in kick samples were compared with the percentages in artificial-substrate samples. We collected invertebrates at sampler sites on October 8 for 0.5 h at 1000, 1400, and 2200 hours with drift nets that were secured in the water column with the top of the net slightly submerged to avoid excess leaf clutter. Drift nets had a 930-cm^2 area with 1.14 meshes/mm. Drift samples were treated in the same way as artificial-substrate samples.

At each transect, discharge and temperature were recorded and a water sample was taken. Water temperatures were monitored with recording thermographs throughout the study. Water samples were refrigerated, and turbidity and conductivity were measured within 4–24 h.

Cans (15.2 cm in diameter) filled with washed stream cobble graded from 2 to 4 cm were used to measure sedimentation rate. We buried 16 cans flush with the stream bottom in transects across artificial-substrate sampler sites. Two cans were removed at each site after 4 weeks and at each Big East Fork site after 6 weeks (site B1, 50 m and 100 m above dredges; site B2, 40 m and 113 m below dredges). The site 113 m below the dredges on Big East Fork was 5 m upstream from the confluence with Canyon Creek. High streamflows prevented measurement of siltation after the dredging season. Sediment samples were sieved with a 6.35-mm-mesh Tyler screen to separate sediments from cobble. Sediments were sieved to the following fractions (mm): 0.208, 0.104, 0.063, and <0.063 (fines). Sediment fractions were dried at 100°C for 24 h and weighed.

Results

We recovered 56 artificial-substrate samplers that contained 94 taxa altogether (8 to 35 taxa per sampler). The mean number of invertebrates per sampler from Big East Fork after 2, 4, or 6 weeks was not different above and below the dredges. Numbers initially increased below dredges sooner than above dredges and then declined at both sites (Figure 1). Mean Shannon–Weiner diversity and equitability indices per sampler increased with time, but they were not different above and below dredges (Figure 1). Mean percentage of shredders per sampler was significantly higher ($F = 68.8$; df = 1, 36; $P < 0.001$) above than below dredges, and gatherers and filterers were significantly higher ($F = 9.6$; df = 1, 36; $P < 0.005$ and $F = 13.2$; df = 1, 36; $P < 0.001$, respectively) below than above dredges (Figure 2). No significant differences were observed in mean percentage of predators and grazers in samplers. Mean number of annelids and dipterans per sampler were higher below than above dredges, but numbers of plecopterans were higher above than below dredges (Figure 3). Mean numbers of ephemeropterans and trichopterans did not differ by site or time.

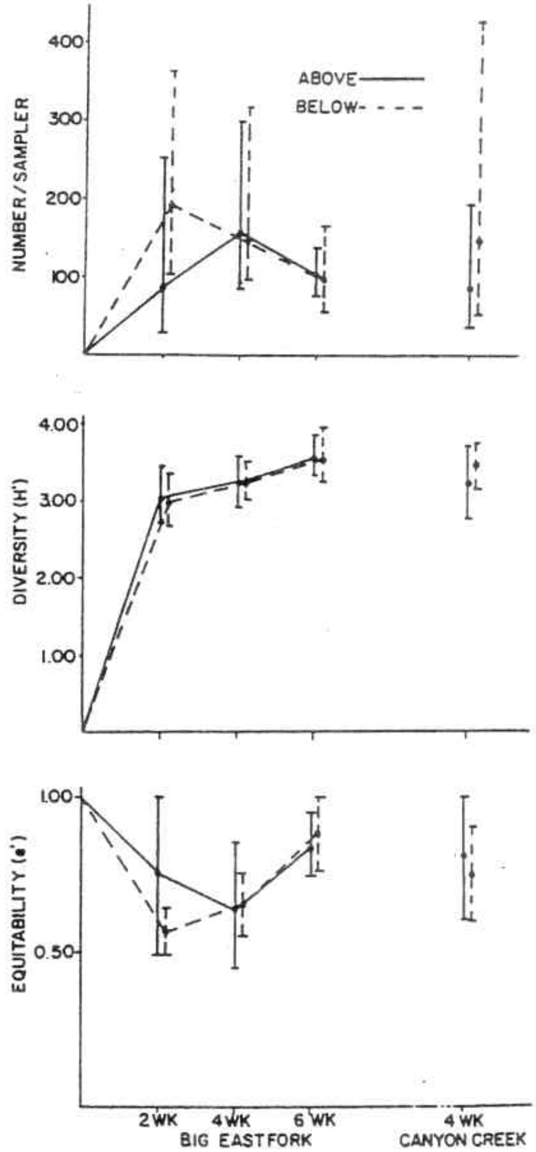

FIGURE 1.—Back-transformed means and 95% confidence limits for numbers of invertebrates, Shannon–Weiner diversity index, and equitability index per artificial-substrate sampler above and below dredges in Canyon Creek basin, California. Means are for seven samplers. WK = week.

The number of invertebrates and the diversity index per sampler were not different between Big East Fork and Canyon creeks or above and below the dredges in either creek after 4 weeks (Figure 1). Mean percentage of filterers was significantly higher ($F = 13$; df = 1, 24; $P < 0.005$) in Canyon Creek than in Big East Fork (Figure 2). Shredders were more abundant above the dredges in Big East

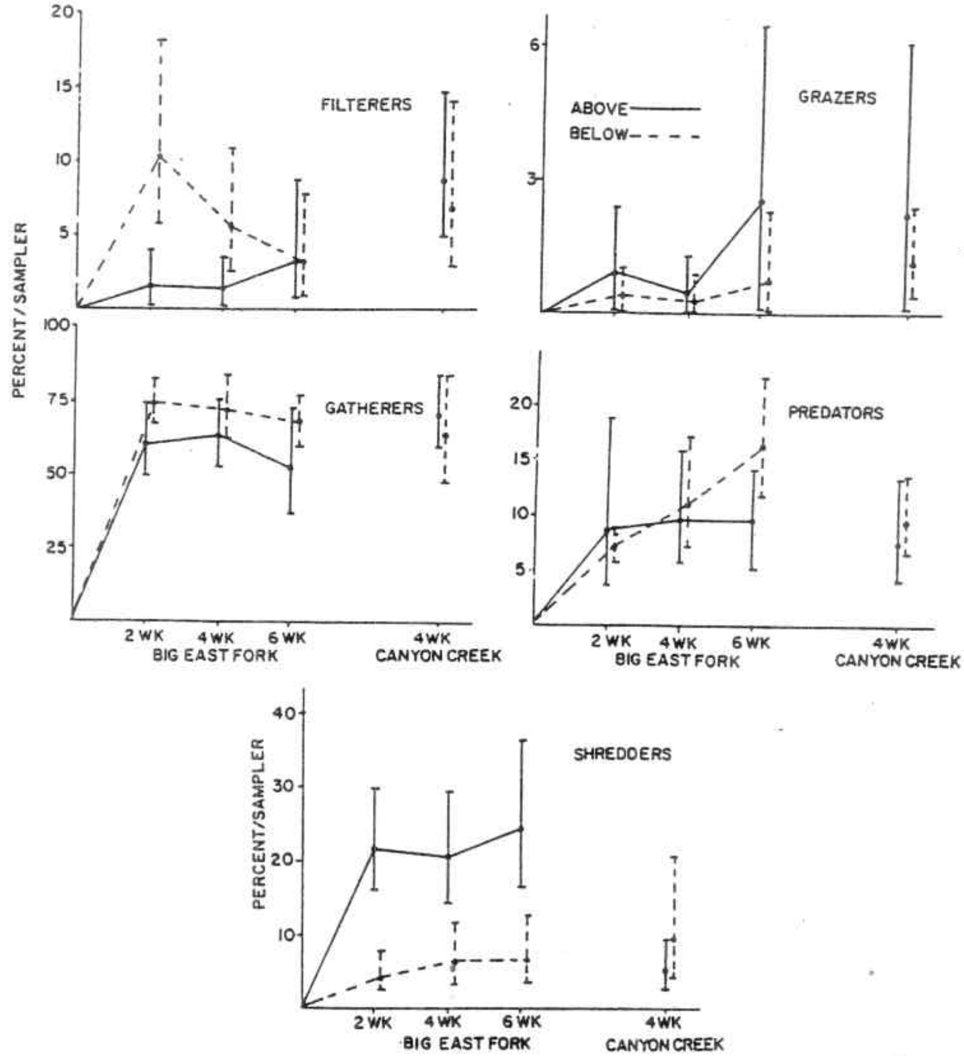

FIGURE 2.—Back-transformed mean percentages and 95% confidence limits for filterers, gatherers, grazers, predators, and shredders per artificial-substrate sampler above and below dredges in Canyon Creek basin, California. Means are for seven samplers. WK = week.

Fork and less abundant above the dredges in Canyon Creek ($F = 13$; df = 1, 24; $P < 0.005$). Mean percentages of predators, grazers, and gatherers were not significantly different for creek or site (Figure 2). The mean number of annelids per sampler did not differ between creeks but was higher below than above dredges in both streams (Figure 3). The mean number of dipterans per sampler was higher in Big East Fork, and the number of ephemeropterans per sampler was higher in Canyon Creek (Figure 3). Trichopterans were more abundant below than above dredges in both creeks (Figure 3). The number of plecopterans per sampler did not differ between creeks or sites (Figure 3).

The sediment and organic matter content in samplers was higher below than above dredges in both creeks (Figure 4). Sediment levels in samplers were relatively higher in Canyon Creek than in Big East Fork below dredges after 4 weeks of colonization. Habitat variables (depth, velocity, organic matter, and sediment) accounted for 17–65% of the variation observed for common taxa in samplers, and all regression models were significant ($P < 0.05$) except for *Ameletus* sp. (Table 1).

Most taxa collected in kick samples were also

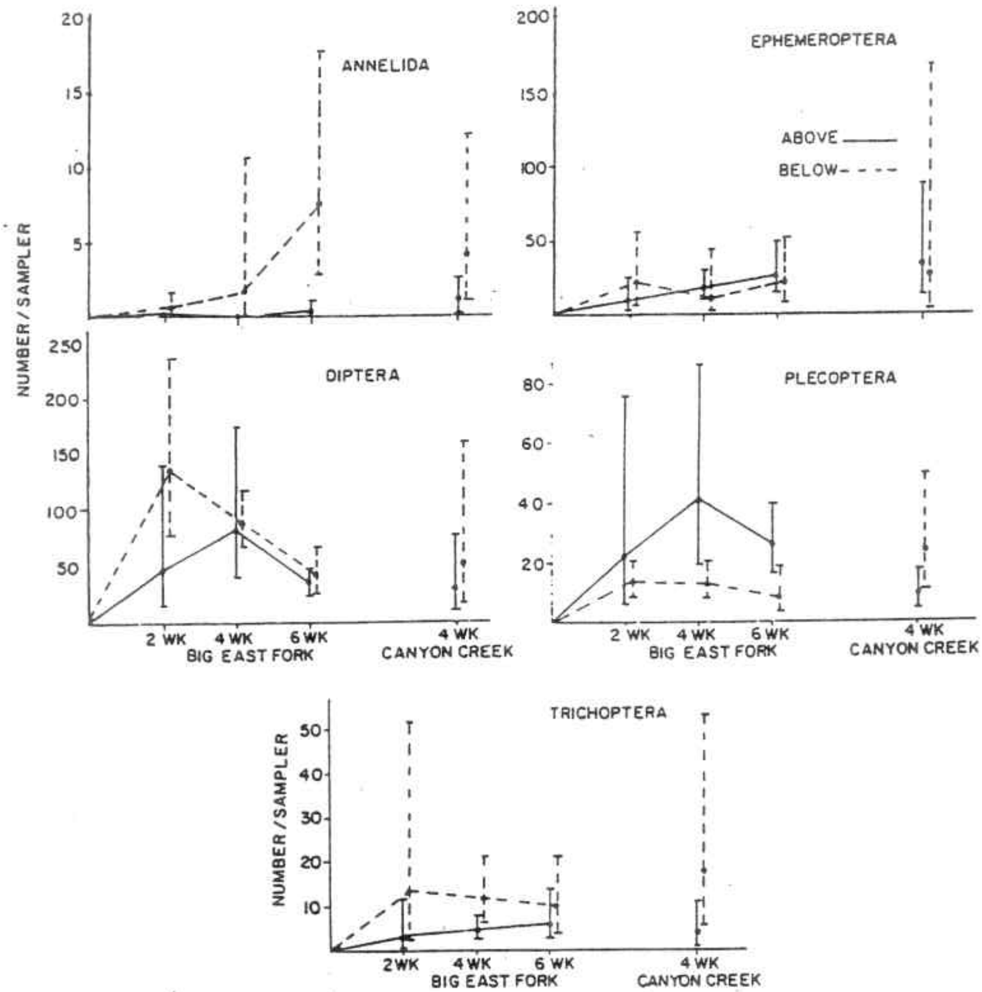

FIGURE 3.—Back-transformed mean numbers and 95% confidence limits for annelids, dipterans, ephemeropterans, plecopterans, and trichopterans per artificial-substrate sampler above and below dredges in Canyon Creek basin, California. Means are for seven samplers. WK = week.

found in artificial-substrate samplers. The Shannon–Weiner index increased from about 2.9 to 3.8 during the 2–6-week colonization period, both in kick samples (Table 2) and in artificial-substrate samplers in Big East Fork (Figure 1). Percentage composition of grazers in kick samples (Table 2) was similar to their composition in samplers (Figure 2), whereas percentages were lower for gatherers and higher for predators in kick samples. The composition of filterers and shredders in kick samples was variable (Table 2).

All invertebrate taxa captured in drift samples were common in kick and artificial-substrate samples. Taxa in drift and kick samples, but not in artificial-substrate samplers, were *Stenelmis* sp. and Carabidae. Density of drift organisms was highest at 2200 hours. The most common taxa were Chironomini, *Eukiefferiella* sp., *Baetis* sp., and *Zapada columbiana*. Gatherers were the most abundant functional group in drift samples; they were most numerous below dredges in both streams at 2200 hours.

Discharge in Canyon Creek ranged from 4.06 m^3/s (August 20) to 0.84 m^3/s (October 22); in Big East Fork it ranged from 0.22 m^3/s (September 1) to 0.08 m^3/s (October 9). Conductivity was higher in Big East Fork than in Canyon Creek and never exceeded 75 $\mu S/cm$. Turbidity was higher in Big East Fork below dredges than at all other sites and exceeded 15 NTU (nephelometric turbidity units)

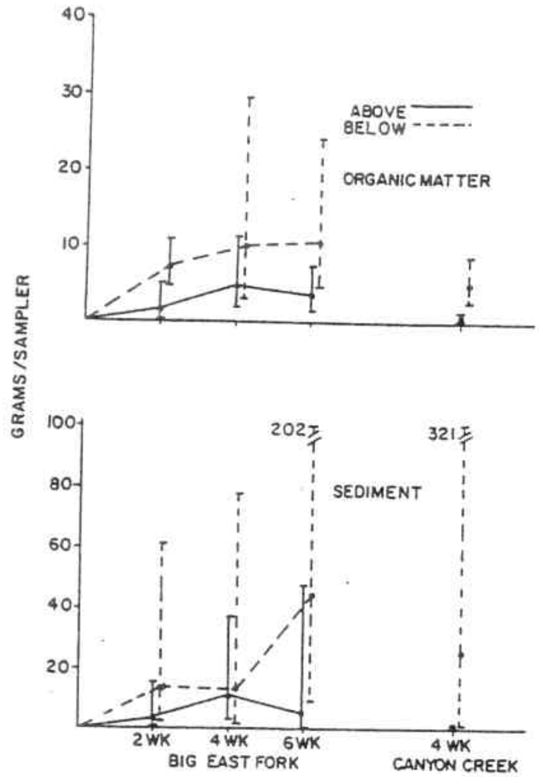

FIGURE 4.—Mean weights and 95% confidence limits for sediment and organic matter in artificial-substrate samplers above and below dredges in Canyon Creek basin, California. Means are for seven samplers. WK = week.

near the dredge outfall. Diel variation in water temperature was 2°C in Big East Fork and 0.6° in Canyon Creek.

The amount of sedimentation and particle sorting by size fractions were functions of mining operation and distance from dredges. Daily sedimentation rates, extrapolated from the sediment traps, were as follows: Big East Fork above dredges, 29 g/m^2 at 100 m and 23 g/m^2 at 50 m; Big East Fork below dredges, 1,711 g/m^2 at 40 m and 698 g/m^2 at 113 m; Canyon Creek above Big East Fork, 13 g/m^2; Canyon Creek below Big East Fork, 12 g/m^2. Dredge operations excavated below the gravel armor layer to a fine sand and silt layer that produced much of the transported sediment. Dredge holes were 2 m deep and 2–3 m wide, and the substrate in the dredge hole was bedrock and large cobbles.

Discussion

The operation of suction dredges in Big East Fork Creek resulted in a dredge hole-and-tailings ("pocket-and-pile") stream morphology. The streambeds in Canyon Creek and Big East Fork were altered only seasonally by the dredging. Dredge tailings generally were displaced by high flows, and dredge holes and tailings were not visible by the following summer. We observed salmon and steelhead spawning in areas of Canyon Creek that had been dredged the previous year. Prokopovich and Nitzberg (1982) found that gravels resulting from dredging provided good spawning habitat in the American River, California, and

TABLE 1.—Significance of multiple-regression analysis for major taxa collected in artificial-substrate samplers from Canyon Creek basin, California, in relation to water depth and velocity, organic matter, and sediment.

Taxa	Transformation[a]	Multiple R	Multiple R^2	Overall significance
Annelida	3	0.8044	0.6470	0.001
Corynoneura sp.	2	0.5371	0.2885	0.001
Eukiefferiella sp.	2	0.6471	0.4187	0.001
Baetis sp.	2	0.7198	0.5181	0.001
Serratella sp.	2	0.4100	0.1681	0.048
Cinygmula sp.	2	0.4918	0.2419	0.006
Epeorus sp.	2	0.4125	0.1701	0.046
Rhithrogena sp.	2	0.6498	0.4222	0.001
Paraleptophlebia sp.	2	0.4477	0.2004	0.020
Ameletus sp.	All			NS
Mesocapnia sp.	1	0.4810	0.2314	0.008
Zapada sp.	2	0.5841	0.3412	0.001
Calineuria californica	2	0.4711	0.2219	0.011
Perlodidae	2	0.4713	0.2221	0.011
Hydropsychidae	2	0.6126	0.3753	0.001
Lepidostoma sp.	2	0.4731	0.2239	0.011
Rhyacophila sp.	2	0.4816	0.2319	0.008

[a] Transformations used: 1 = no transformation; 2 = log(y + 1); 3 = square root (y + 1).

TABLE 2.—Diversity indices and percent functional group composition for kick samples from Canyon Creek basin, California. e' = equitability index; H' = Shannon–Weiner diversity index.

Sample time	e'	H'	Percent				
			Predators	Shredders	Grazers	Gatherers	Filterers
Big East Fork above dredging (site 1)							
Week 2	0.67	2.86	25	8	3	64	0
Week 4	0.89	3.54	44	16	0	39	2
Week 6	0.68	3.55	23	13	6	57	2
Big East Fork below dredging (site 2)							
Week 2	0.80	3.11	26	0	2	57	15
Week 4	0.68	3.43	23	29	1	45	2
Week 6	0.78	3.83	13	18	2	62	7
Canyon Creek above dredging (site 3)							
Week 4	0.74	4.16	19	11	4	63	3
Canyon Creek below dredging (site 4)							
Week 4	1.00	3.01	45	0	0	52	3

Thomas (1985) observed that dredging improved gravel permeability within the dredged area.

The effects of the two dredges on aquatic insects varied with taxa and were site-specific. Dredging dislodged insects, and we observed young coho salmon and steelhead feeding on them. The stream bottom underwent major but localized changes. Dredge holes were excavated to a depth of 2 m, and substrate was altered to bedrock and large cobbles—probably a poor habitat for colonization. However, the effects of dredging (at the operating level during the study) on insects and habitat were minor compared with those of bed-load movement due to large streamflows during storms and from snowmelt.

The effects of dredging on benthic organisms must be viewed with regard to sampler colonization dynamics. The samplers below the dredges were selectively colonized at an accelerated rate, compared with samplers above dredges. Samplers placed in the silted stream reach below the dredges provided silt-free habitat suitable for colonization by aquatic invertebrates. As dredging continued, the samplers were filled with silt and the numbers of invertebrates declined. The samplers appeared to accurately sample the benthic community, because abundance and composition of insects were comparable for samplers and for kick and drift samples.

The effects of dredging on Canyon and Big East Fork creeks were not severe enough to cause differences in mean numbers of invertebrates or in diversity indices. Mean diversity indices for all sample sites were well within the range of 2.6–4.0 recorded for "healthy" streams by Wilhm (1970). Thomas (1985) found that, although the mean number of invertebrates in the dredged area of Gold Creek, Montana, was significantly lower than in the control area, there was no significant difference in numbers downstream from dredging. Bjornn et al. (1977) found that in moderately silted Knapp Creek, Idaho, the insect community was not affected but particular species were adversely affected; however, in Elk Creek, Idaho, benthic insect diversity was adversely affected when cobble embeddedness exceeded 66%.

Functional feeding groups responded differently to dredging. The number of predators in samplers increased with time below the dredges, and the predator *Calineuria californica* showed a significant positive relation to depth and sediment. Harvey (1986) found increased numbers of *Calineuria* sp. below dredging sites and suggested that the siltation from dredging may reduce hiding places and render prey more accessible to such predators.

In the present study grazers increased in number with time and were most abundant above the dredges. Because grazers feed on periphyton, the difference in their abundance may mean that silt limited periphyton production or covered periphyton in samplers below the dredges. The greater abundance of gatherers below than above the dredges may have resulted from the greater availability of organic matter below the dredges, along with a tolerance (or preference, as in annelids) of gatherers for silty substrates. The gatherer *Baetis* sp. showed a significant positive relation to sediment. However, Harvey (1986) found no changes in abundance of *Baetis* sp. below dredging and suggested that the deposited substrate was no more suitable than the cobble substrate present before dredging.

Filterers quickly colonized the new habitat provided by samplers. They decreased below the dredging sites as siltation increased and filled the samplers. Harvey (1986) found that the numbers of *Hydropsyche* sp. were reduced below dredge operations, and noted a reduction of clean cobble habitat. Gammon (1970) observed that high sediment load clogged nets constructed by *Cheumatopsyche* sp., which inhibited their feeding.

Shredders were most abundant above the dredges. *Zapada cinctipes* and *Z. columbiana* were common shredders in samplers, and their abundance was inversely related to sediment. Leaf matter that developed periphyton and provided shelter for shredders was probably covered with silt below the dredging sites. Cummins (1974) found a nutritional dependence by shredders on the microbial flora that developed on organic matter rather than on the substrate itself.

For some invertebrate groups, ecological differences between creeks appeared to be more important than sediment input from suction-dredge mining. Grazers were more abundant in Canyon Creek, probably because of increased sunlight (proportionately less canopy) and thus increased periphyton. Shredders were proportionately more numerous in Big East Fork, probably because of greater canopy coverage, which resulted in the deposition of more leaf matter.

Because high water prevented removal of samplers 1 month after the dredge season, the recolonization of dredged areas by invertebrates could not be evaluated. Griffith and Andrews (1981) observed that benthic invertebrates recolonized dredged plots after 38 d. Thomas (1985) found that the mean number of aquatic insects, except for trichopterans, was not significantly different between dredged and undredged areas after 1 month. Harvey (1986) observed that downstream impacts for ephemeropterans (*Tricorythodes* sp.) and plecopterans (Chloroperlidae) were still present 2 weeks after dredging ceased. Meehan (1971), who investigated the effects of gravel cleaning on bottom organisms, reported that benthic populations returned to pretreatment levels in 3 months.

Suction-dredge mining had little influence on benthic invertebrate functional groups collected in the drift except for gatherers, which were significantly more abundant below the dredging in Big East Fork. Griffith and Andrews (1981) observed the entrainment and later drift of invertebrates associated with suction-dredge mining. Gammon (1970) observed that increasing sediment concentration elevated drift rates, whereas Bjornn et al. (1977) found no relation between sedimentation and drift rates. Pearson and Franklin (1968) postulated that turbidity reduced light penetration in the water column and triggered behavioral drift.

Turbidity plumes created by dredging in Big East Fork were visible in Canyon Creek, 123 m downstream. Peak turbidity measured during dredging was only 15 NTU and probably had no significant effect on insects or fish. Griffith and Andrews (1981) also found low turbidities below dredging sites in two Idaho streams. There has been concern that high turbidity adversely affects feeding of fish. Sigler et al. (1984) found that salmonids subjected to continuous turbidities of 25 NTU grew more slowly than controls. Harvey (1986) recorded turbidities as high as 50 NTU caused by suction dredging, but he observed no deleterious effects on salmonid feeding. Brusven and Rose (1981) found no effect of suspended sediment on feeding by torrent sculpins *Cottus rhotheus*.

Peak daily sedimentation rate in Big East Fork below the dredges (1,711 g/m^2) was comparable to estimates derived by Harvey et al. (1982) for the North Fork of American River, California (2,070 g/m^2) and by Thomas (1985) for Gold Creek, Montana (1,720 g/m^2). Downstream in Canyon Creek, daily sedimentation rates had returned to control levels (12 g/m^2). In Big East Fork, 21% by weight of sediment trapped 40 m below the dredge, and 38% trapped 113 m below it, were less than 0.1 mm in diameter. Griffith and Andrews (1981) found that fine sediment less than 0.5 mm in diameter constituted up to 18% by weight of sediment from dredging.

Suspended sediment in Big East Fork did not return to background levels 113 m downstream from the dredge. Thomas (1985) noted that most sediment was deposited within 20 m of the dredge; however, suspended sediment levels did not return to background levels 30 m downstream. Harvey et al. (1982) observed sediment deposition to 60 m downstream. The sediment in Big East Fork was displaced farther downstream because of the steeper gradient and the high proportion of fines released in the overburden. Harvey et al. (1982) suggested that downstream sediment deposition was determined by size and number of dredges, stream size, and proportion of fines in the substrate. Sediment concentrations measured in our samplers indicated relative differences between sites, but we did not quantitatively measure deposition rates in samplers.

California regulations for dredge aperture size and season appeared adequate to protect fish and habitat at the level of dredging we observed during the study in the Canyon Creek basin. However, dredge activity was low during the study because of high streamflow. During low-flow years, increased activity could disturb spring chinook salmon and summer steelhead that hold in the basin, possibly causing mortality. Further studies on dredging in small streams should be conducted to determine (1) the extent and effects of bank undercutting, bank sluicing, and removal of instream woody debris and riparian vegetation on aquatic organisms and their habitat; (2) the influence of dredging on downstream sedimentation in regulated rivers such as the Trinity River; (3) the cumulative effects of dredging, especially during low-flow years; and (4) the long-term effect on species composition of aquatic insects in heavily dredged areas.

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