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Redacted for privacy

Abstract approved: ______________________
Charles E. Warren

The production (tissue elaboration) of juvenile coho salmon (Oncorhyncus kisutch) was monitored in 12 laboratory streams having six treatment levels of fine sediments and in six laboratory streams having six different substrate particle sizes. Fish production decreased with increases in sedimentation and with decreases in substrate size. Lower fish production in streams with high sediment levels was apparently caused by lower levels of food organisms. Lower fish production in the substrate experiments was related to water velocity and food supply. Substrate Score, based on a visual technique for evaluating stream substrate quality, was found to be highly correlated with geometric mean particle size of the substrate and with fish production. Substrate Score may be useful for assessing substrate quality of salmonid rearing

and spawning areas. The results of the sedimentation experiments suggest that protection against fine sediments should be considered for juvenile habitat as well as for spawning areas. The results of the substrate experiments indicate that the use of cobble sized gravel in artificial rearing channels may optimize juvenile fish production.

Effects of Fine Sediments and Substrate Size on Growth of Juvenile Coho Salmon in Laboratory Streams

by

Michael Robert Crouse

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Professor of Fisheries in charge of major

Redacted for privacy

Head of Department of Fisheries and Wildlife

Redacted for privacy

Dean of Graduate School

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Typed by Bonnie Collins and Kim Ledford for Michael Robert Crouse

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EFFECTS OF FINE SEDIMENTS AND SUBSTRATE SIZE ON GROWTH OF JUVENILE COHO SALMON IN LABORATORY STREAMS

INTRODUCTION

Relationships between the character of stream substrates and biological communities have long interested aquatic biologists. Percival and Whitehead (1929) and Sprules (1947) studied relationships between substrate size and the density and diversity of benthic fauna. In recent years, much of the research on stream substrates has been concentrated on the detrimental effects of fine sediments in stream gravels on salmonid fish resources. Sedimentation of stream gravels can affect salmon and trout populations by decreasing embryo survival (Cooper 1965), by reducing the capacity of streams to produce food organisms (Phillips 1971), and by reducing habitat for juvenile and adult fish (Bjornn et al. 1974). The major interest in controlling stream sedimentation has been to protect salmonid spawning areas (Iwamoto et al. 1978). But for some salmonids such as coho salmon and trout whose juveniles rear in small streams the productivity of rearing areas may need to be protected from sedimentation. Although increased siltation generally reduces invertebrate density and diversity (Cordone and Kelley 1961; Hynes 1970), the effects of sediment on salmonid production (i.e. tissue elaboration) have not been clearly demonstrated. Fine sediments may also reduce protective cover for juveniles, especially in winter (Bjornn et al. 1974), but this has not been investigated for many salmonid species.

Knowledge of relationships between stream substrate character and salmonid and insect production is also of importance when artificial rearing channels are used as an alternative to hatchery rearing of young salmonids. Mundie (1974) encouraged exploring the feasibility of combining the desirable features of natural salmonid rearing streams with the productive capacities of hatcheries to reduce production costs and create a more "natural" setting for juvenile rearing. Williams et al. (1977) evaluated optimizing the use of benthic invertebrates in salmonid rearing channels by observing the cropping potential of benthos as fish food and the response of invertebrates to waste food stuff and fish feces. The channels were recolonized rapidly after disturbance and limited quantities of waste foodstuffs and fish feces enhanced benthic invertebrate numbers. Williams and Mundie (1978) examined the responses of benthic invertebrates to different substrate types within the size range that could practically be used in artificial rearing channels. Uniform sized gravel of 24 mm in diameter supported significantly greater invertebrate numbers and biomass than gravel 11.5 mm or 40.8 mm in diameter. To determine the proper mixture of gravels for use in rearing channels, Williams (1980) allowed stream invertebrates to colonize baskets of gravel having the same mean particle size but greatly different particle size distributions. No significant differences in invertebrate biomasses, numbers or taxa were observed between any of the gravel mixtures.

In this research, I evaluated the effects of fine sediments and substrate particle size on the capacity of stream systems to support juvenile salmonid production or total tissue elaboration. Capacity is an abstract concept that encompasses all possible performances of a system in all possible environments (Warren and Liss 1977). As such, capacity can never be directly or fully evaluated. But partial evaluations can be achieved by determining values of a system performance (e.g., production of a fish population) over a range of environmental conditions (e.g., fine sediment level and substrate size). Such an evaluation was attempted in this research by measuring fish production in laboratory streams with a wide range of fine sediment levels and substrate sizes.

Warren (1975) and Siem et al. (1977) used similar laboratory streams to assess the effects of kraft mill effluents on the capacity of stream systems to support salmonid production. While cautioning against extrapolating laboratory stream results to natural stream systems, Warren and Davis (1971) state that laboratory experiments can define the threshold of detrimental effects of a pollutant and reduce the scope of experiments required in natural stream systems. In the experiments reported here, some of the habitat variables associated with stream substrate quality were studied.

MATERIALS AND METHODS

Experimental Streams

The 18 laboratory streams used in this research were located in two greenhouses at the Oak Creek Laboratory of Biology, Oregon State University, Corvallis, Oregon. Each stream was contained in a wooden trough 3.3 m long, 0.66 m wide, and 0.25 m deep and was divided into two halves by a median partition open at each end (Figure 1). Area available to the fish and for insect colonization was 1.55 m^2, which excludes the space occupied by the paddle wheel. Stainless steel paddle wheels driven by electric motors at 12 rpm maintained constant water velocities in the streams. Exchange water from a small spring-fed stream flowed through each laboratory stream at a rate of 2 liters/min. Shade cloths were placed over the greenhouse roofs during the summer months to reduce ambient light. This prevented excessive periphyton growth in the streams and reduced daytime temperatures in the building and the streams. A refrigeration unit was also used when necessary during the summer months to maintain the streams at temperatures suitable for salmonid survival and growth. Water temperature ranged from 0.0°C in February to 20°C in August.

Stream Substrate Compostion and Sedimentation Levels

The mineral substrates used to form two riffles and two pools in each stream were from river deposits. For the sedimentation experiments, gravel of a composition believed to be good for invertebrate colonization and production was placed in 12 streams (Tables 1 and 2). In October 1977 fine sediments (less than 2.00 mm in size) were added to different streams in six different amounts ranging from 0 to 100 percent riffle embeddedness (the extent to which fine sediments covered the cobble).

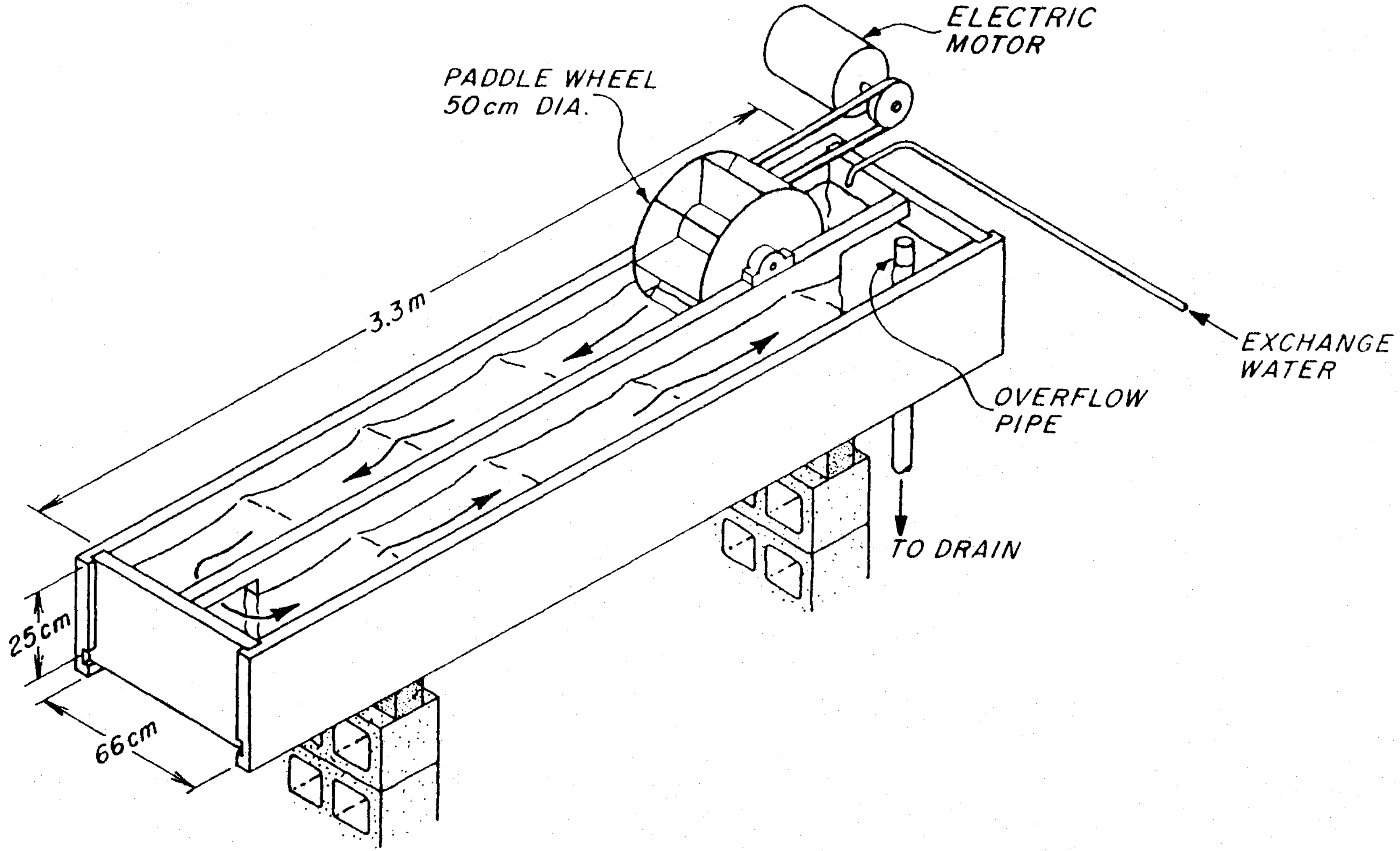

Figure 1. Illustration of one laboratory stream channel.

Table 1

Approximate size range of mineral substrates used in sediment and substrate experiment.

Classification (Wentworth 1922; in Cummins 1966)	Appr. diameter used (mm)
Cobble (64 - 256 mm)	50 - 127
Pebble (4 - 64 mm)	7 - 40
Granule (2 - 4 mm)	2 - 6
*Silt to coarse Sand (0.0625 - 2.0 mm)	0.004 - 2.00

* Referred to in text as fine sediment

Table 2

Sedimentation experiment: Addition of fine sediment in the twelve laboratory streams

Stream	Substrate composition by vol. (m^3)		Fine sediment (m^3)	Percent cobble embeddedness
6, 10	Cobble = 0.135	Pebble = 0.035	0	0
5, 9	"	"	0.015	20
4, 8	"	"	0.030	40
2, 7	"	"	0.045	60
1, 12	"	"	0.060	80
3, 11	"	"	0.075	100

The substrate experiments were conducted concurrently in six streams located in a separate building. In October 1977, gravel substrates ranging from 2 mm to 127 mm were placed in different proportions in the streams (see Table 3). The procedures thereafter were identical to those used in the sedimentation experiments, except that no fine sediments were added.

Autochthonous and Allochthonous Materials

Water depths of about 5 cm in the riffles and 20 cm in the pools were maintained by standpipes. Water velocities were measured at 0.3 m intervals in all streams (Table 4). Water quality determinations were made on one occasion (Appendix I). Periphyton communities developed primarily from algal cells that entered with the exchange water. Deciduous leaves collected in and along the banks of Oak Creek, a nearby natural stream, were added to the laboratory streams to supplement autotrophic food sources for macroinvertebrates.

Macroinvertebrate Colonization

Macroinvertebrate communities developed in the laboratory streams primarily from seedings with benthic fauna collected from riffles and pools in Oak Creek. Macroinvertebrates were collected with a kick net (570 micron mesh opening) and a Mundie (1971) sampler (53 and 570 micron mesh opening) and stocked in the streams five times between October 1977 and February 1978. Insect eggs laid in the stream by adults or entering via the exchange water may also have contributed to macroinvertebrate colonization.

Fish

On 18 March 1978, eight coho salmon juveniles, each about 50 mm in length and about 1.5 g in weight, were stocked in each stream. The fish

Table 3

Substrate experiment: Substrate composition in the six laboratory streams

		Substrate Composition (m^3)		
Stream	Substrate	Cobble	Pebble	Granule
13	100% G	-	-	0.170
14*	80% C + 20% P	0.135	0.035	-
15	50% P + 50% G	-	0.085	0.085
16	100% P	-	0.170	-
17	50% C + 50% G	0.085	-	0.085
18	100% C	0.170	-	-

*Note: Substrate composition of Stream 14 is the same as the control streams (6, 10) in Sedimentation Experiments.

Table 4

Average water velocities in the laboratory streams

Sedimentation experiment

Percent cobble Embeddedness	Stream	Water velocity m/sec.
0	6	0.19
	10	0.21
20	5	0.20
	9	0.19
40	4	0.21
	8	0.20
60	2	0.20
	7	0.20
80	1	0.20
	12	0.19
100	3	0.20
	11	0.21

Substrate experiment

Percent substrate type	Stream	Average water velocity m/sec.
100 granule	13	0.27
80 C + 20 P	14	0.18
50 P + 50 G	15	0.32
100 P	16	0.32
50 C + 50 G	17	0.22
100 C	18	0.17

were recaptured and weighed to the nearest thousandth of a gram by means of a top loading analytical balance every 28 days thereafter to 28 June (spring experiment) when fish growth rates in all streams were approaching zero. On 18 July, two fish, each about 63 mm in length and 2.6 g in weight, were stocked in each stream and reweighed every 14 days thereafter to 13 September (summer experiment).

The streams were checked daily for dead fish which, when discovered, were weighed immediately. These weights were used in the production calculations. When a fish was too decomposed to weigh accurately or was discovered to be missing during regular sampling, it was assumed to have lived for half the sampling interval and to have had the same growth rate as the remaining fish. Any injured fish was replaced with another of equal weight, but emaciated fish were not replaced. At the end of the spring experiment, the number of fish supported by the streams ranged from five to eight. The number of fish during the summer experiment was maintained at two per stream. Calculation of fish production so as to take into account loss of fish was made using the technique of Davis and Warren (1965). When all fish lived the entire sampling interval, production was calculated using the following formulas:

Production (P) = mean relative growth rate (GR) x mean biomass (B)

or: $$P = \frac{\text{total tissue elaborated (TTE)}}{\text{stream area (A)} \times \text{\# of days (T)}}$$

$$TTE = \text{Final weight of fish (WF)} - \text{Initial weight of fish (WO)}$$

$$B = \frac{WF + WO}{2 \times A}$$

$$GR = \frac{(WF/A) - (WO/A)}{B \times T}$$

If fish were lost during the sampling interval production was calculated as follows:

Adjusted (ad) $P = \text{ad GR} \times \text{ad B}$

or $P = \dfrac{\text{ad TTE}}{A \times T}$

Adjusted TTE = (WF/# of fish) - WO/# of fish) x average # of fish that lived during the sampling interval (assumes missing fish lived half the interval)

Adjusted WF = WO + ad TTE

Adjusted B $= \dfrac{\text{WO} + \text{ad WF}}{2 \times A}$

Adjusted GR $= \dfrac{(\text{ad WF}/A) - (\text{WO}/A)}{\text{ad B}/T}$

Fish production was measued in laboratory streams having a wide range of particle size treatments in order to empirically evaluate the cumulative effects of fine sediments and substrate size on stream productivity. Production is defined as the total tissue elaborated by a population per unit area per unit time, regardless of the fate of the tissue (Ivlev 1966). A theoretical relationship between growth rate, biomass, and producton in a resource-limited environmental system is presented in Figure 2 (Warren 1971). When the population biomass is low, the relative growth rate is high because resources are relatively abundant. But as the population bomass increases, resources become depleted and relative growth rate decreases. Thus production increases to a maximum and then declines to zero with increasing biomass and decreasing growth rate. A production curve defines the capacity of the environmental system to produce a particular population, under a particular set of conditons.

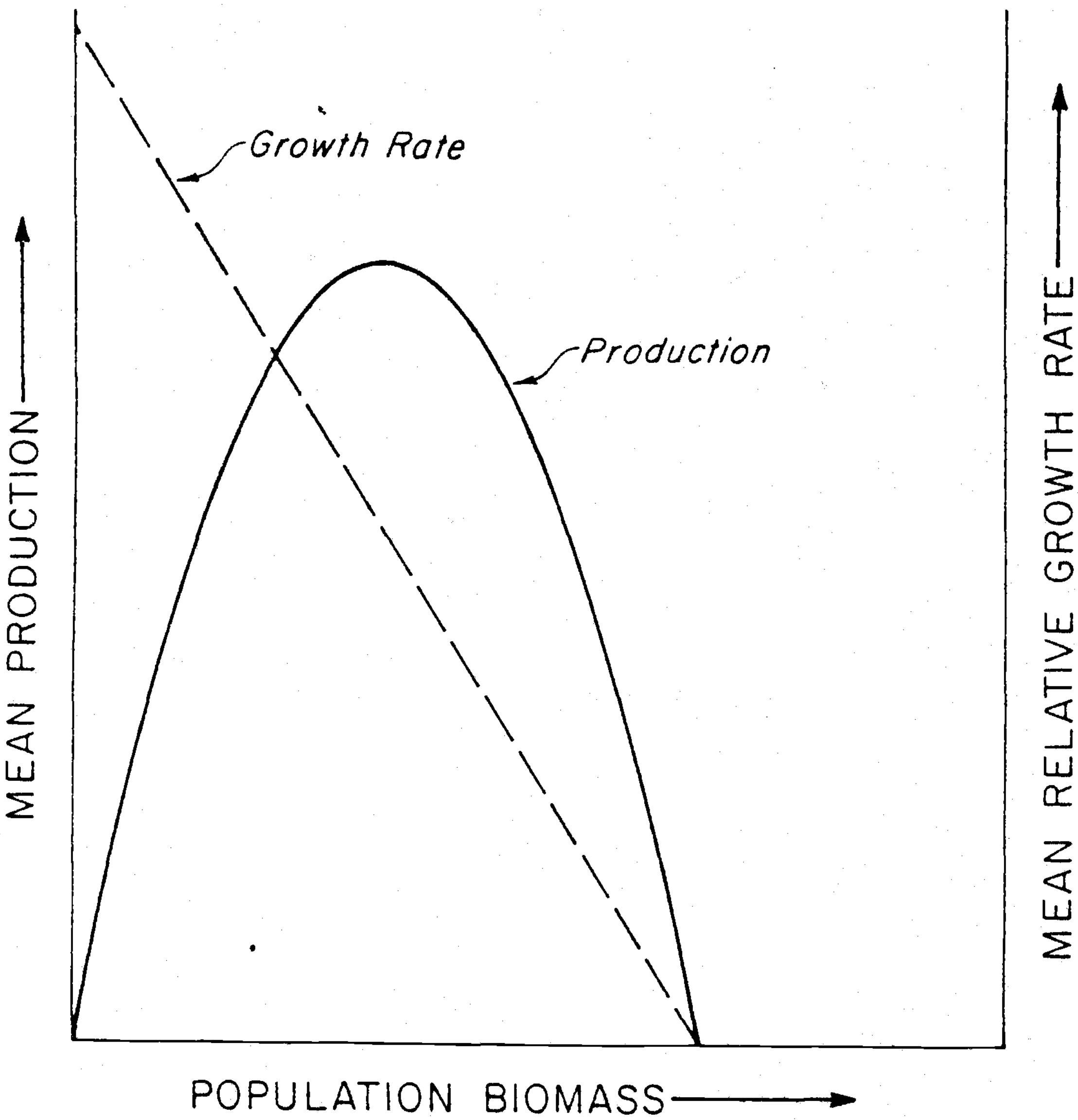

Figure 2. Theoretical relationship between growth rate and biomass and between production and biomass in a resource limited system (after Warren 1971).

Figure 3 illustrates how different levels of sedimentation might affect the capacity of streams systems to produce fish. With different levels of sedimentation, different production curves could be conceived to exist, lower and narrower curves defining lower levels of productivity resulting from excessive sedimentation.

Macroinvertebrate Sampling

Invertebrate standing crop in each stream was determined by sampling some 0.11 m^2 area every 28 days from February 27 to October 5. An elutreator (Stuart 1975) was used to separate benthic organisms from sediments and detritus. The abundance of drifting invertebrates was determined by collecting in a 300 micron mesh plankton net organisms leaving the streams via the stand pipe. A plastic sleeve placed around the standpipe permitted sampling at mid-water depth. Organisms less than 1 mm in length were subsampled. The invertebrates were preserved in formalin until needed for taxonomic identification, generally to genus. Body lengths of the most dominant organisms were converted to freeze dry weights using regression formulas established for each taxa.

Particle Size Distribution and Substrate Score

The amounts of fine sediment and the substrate particle sizes in the streams were measured in two ways. In the first, substrate samples removed during macroinvertebrates sampling were oven dried and mechanically sieved to determine particle size distribution (Cummins 1966). Figure 4 shows the cumulative percent distribution by weight of particles according to size, determined as the mean of eight core samples for each sediment treatment level. Certain statistics that have been used in research on the effects of sediment on embryos (e.g., geometric mean particle size and percent of fine sediments) can be determined from this graph (Platts *et* al. 1979; Shirazi et al. 1979).

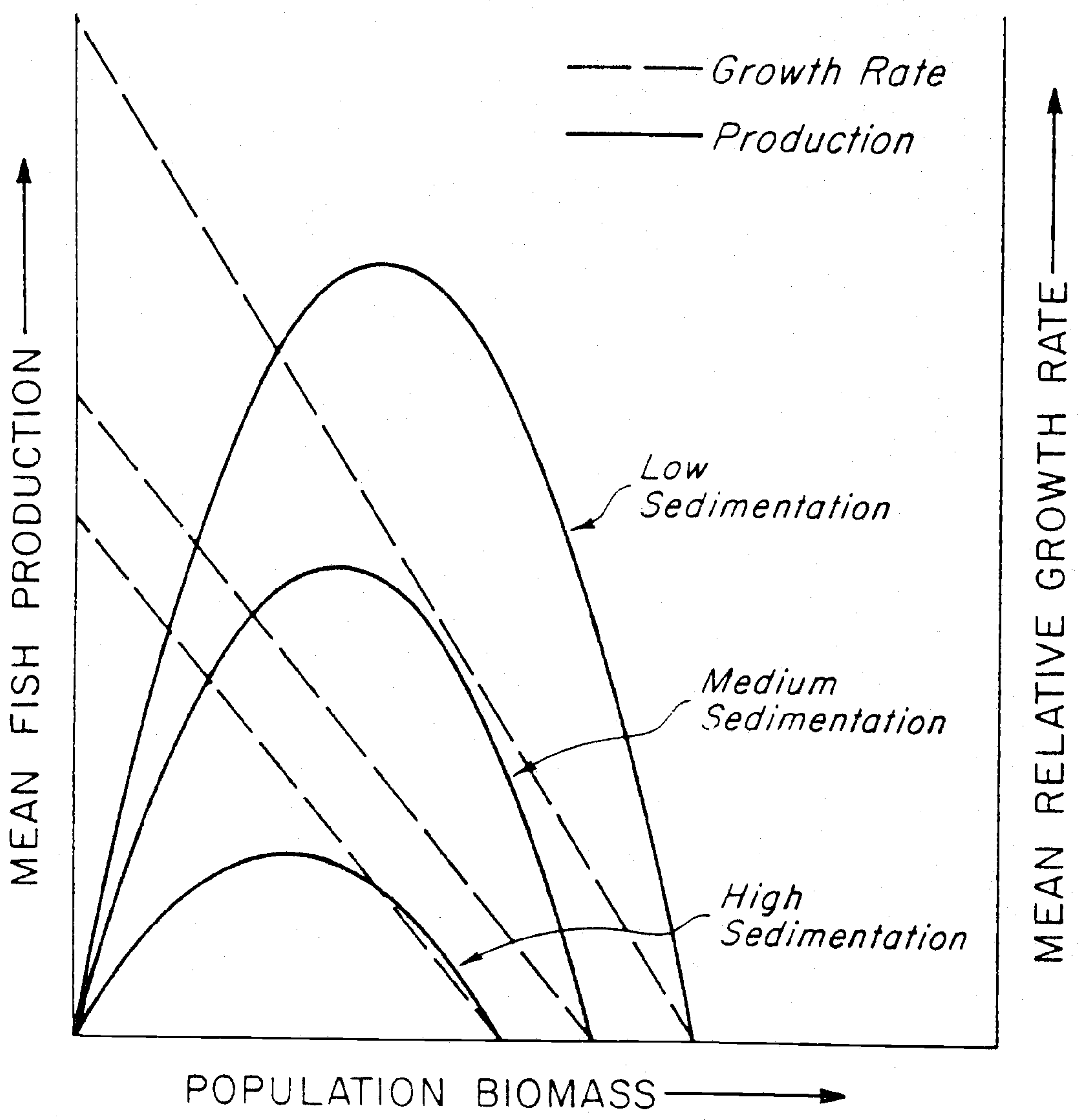

Figure 3. Hypothetical effects of sedimentation on relations between population biomass, relative growth rate and production.

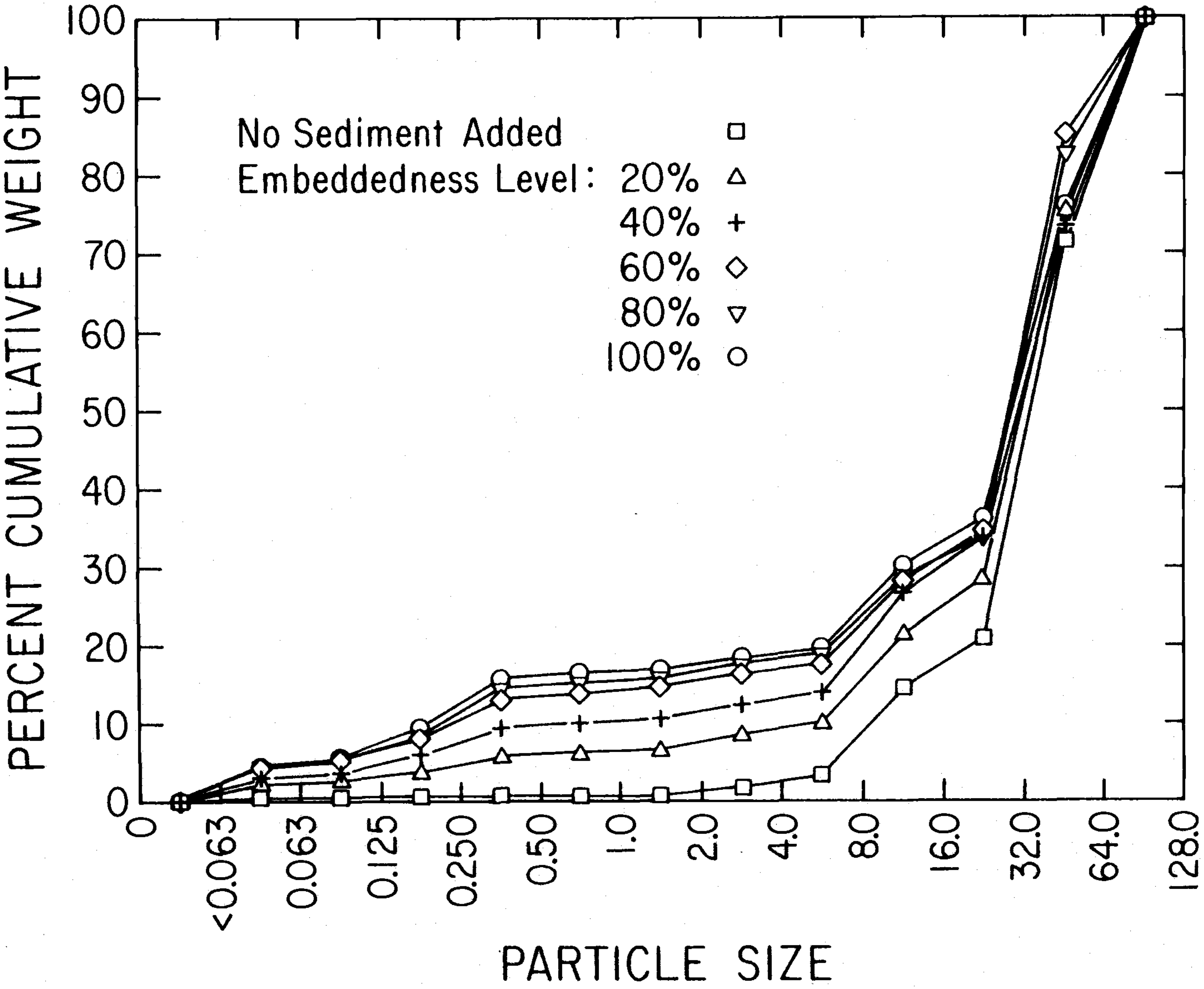

Figure 4. The cumulative weight of sediment size versus particle size millimeters.

In the second method, the substrate characteristics in each stream were evaluated at 0.3 m intervals by a visual technique known as Substrate Score (Sandine 1974). The Substrate Score is a summation of four ranks, three concerning the size of substrate particles, the fourth the level of embeddedness. The most predominant particle (i.e. covering the most surface area) is assigned a rank from Table 5 based on its size; the second most predominant size of substrate particle is assigned a rank according to the same scale. The third rank corresponds to the size of the material surrounding the most predominant substrate particles. The fourth rank is an evaluation to which the predominant substrate particles are embedded in the material ranked in the third evaluation. These number are summed to obtain a single value, the Substrate Score (see Appendix II). Low values indicate poor habitat for benthic invertebrates. A high correlation was obtained between the average geometric mean particle size and the average Substrate Scores for the four sampled sections from each stream (Fig. 5).

Table 5

Particle size classification and corresponding rank used to derive the Substrate Score.

Particle type or size

1 = organic cover (over 50% bottom surface)
2 = < 1-2 mm (1/16")
3 = 2-5 mm (1/16-1/4")
4 = 5-25 mm (1/4-1")
5 = 25-50 mm (1-2 1/2")
6 = 50-100 mm (2 1/2 - 5")
7 = 100-250 mm (5-10") cobble
8 = > 250 mm (>10") boulder

Embeddedness* classification and corresponding rank.

1 - completely or nearly completely embedded.
2 - 3/4 embedded
3 - 1/2 embedded
4 - 1/4 embedded
5 - unembedded

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*Extent to which predominant-sized particles are covered by finer sediments.

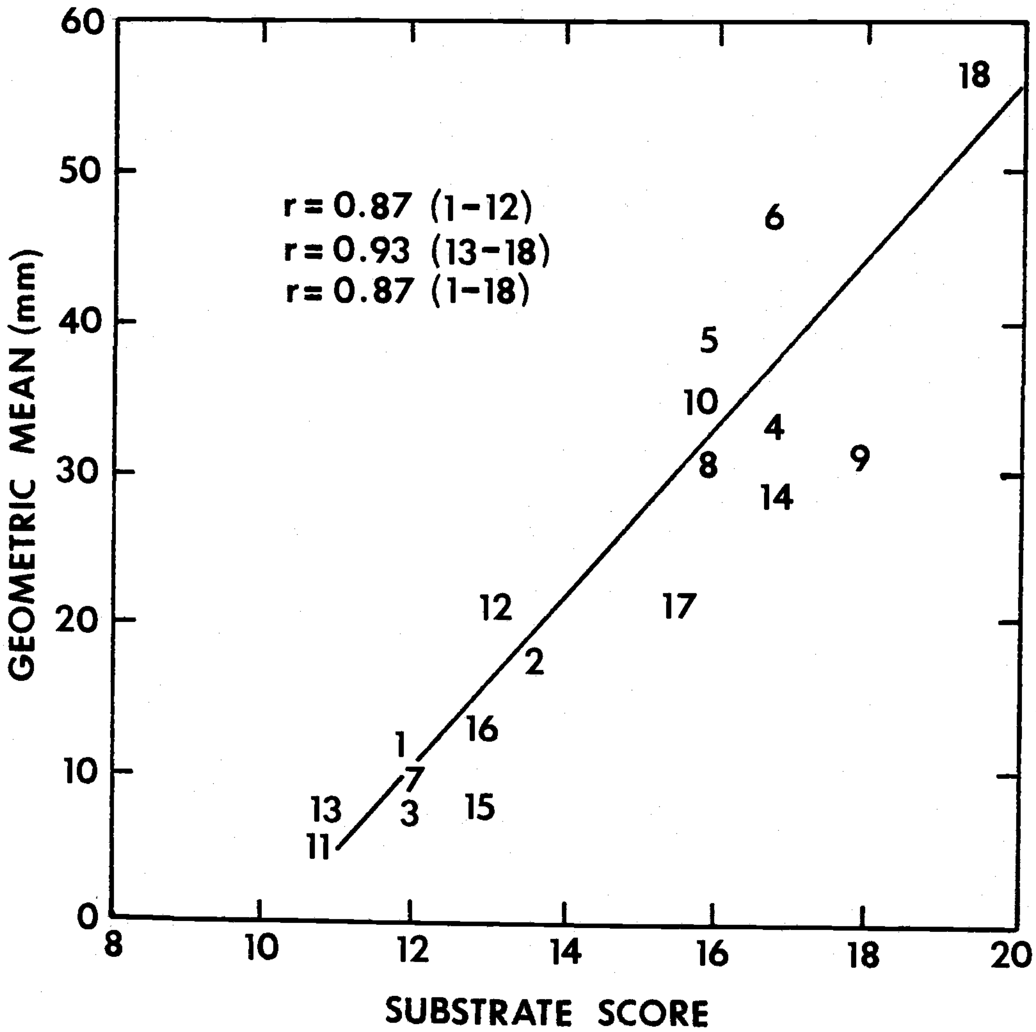

Figure 5. The average geometric mean particle size of four samples from each stream compared to the average Substrate Score of the sampled areas. Streams are numbered 1-12 for the sedimentation experiments and 13-18 for the substrae experiments.

RESULTS AND INTERPRETATION

Sedimentation Effects on Salmonid Production and Biomass

In the spring experiment, the differences in the descending limbs of production curves for three levels of sedimentation suggest that increased sediment reduced the capacity of the laboratory streams to support fish production (Figure 6). The data from twelve streams have been summarized and plotted in the three groups by averaging replicates and treatment levels as follows: 1) 0 and 20 percent; 2) 40 and 60 percent; and 3) 80 and 100 percent embeddedness. Because of the high initial stocking biomass, the ascending limbs and maximum of each production curve (dashed line) were not defined. High levels of sediment greatly decreased the productivity of the streams and it appears from Figure 6 that intermediate levels resulted in higher productivity than low levels. The low sediment curve as drawn does not, however, reflect the importance of the extremely high production value (130 mg/m^2/day) for the third period. Cumulative production values of replicates and treatments summed for the entire experiment were 9.14, 8.03, and 4.24 g/m^2 for the low, intermediate, and high sediment levels.

A similar trend of reduced fish production with increasing sediment level was observed in the summer experiment (Figure 7). Again, only the decending limbs of the production curves are defined, even though the stocking biomasses were much less than those for the spring experiment. As in the spring experiment, production was lower at high sediment levels. Means and standard errors of the production and biomass values used in Figures 6 and 7 are shown in Table 6. These calculations indicate considerable variability in the productivity of some of the replicate streams, especially during the summer experiment. Some of the variability may be explained by the influence of uncontrolled environmental factors, such as light. The laboratory streams were

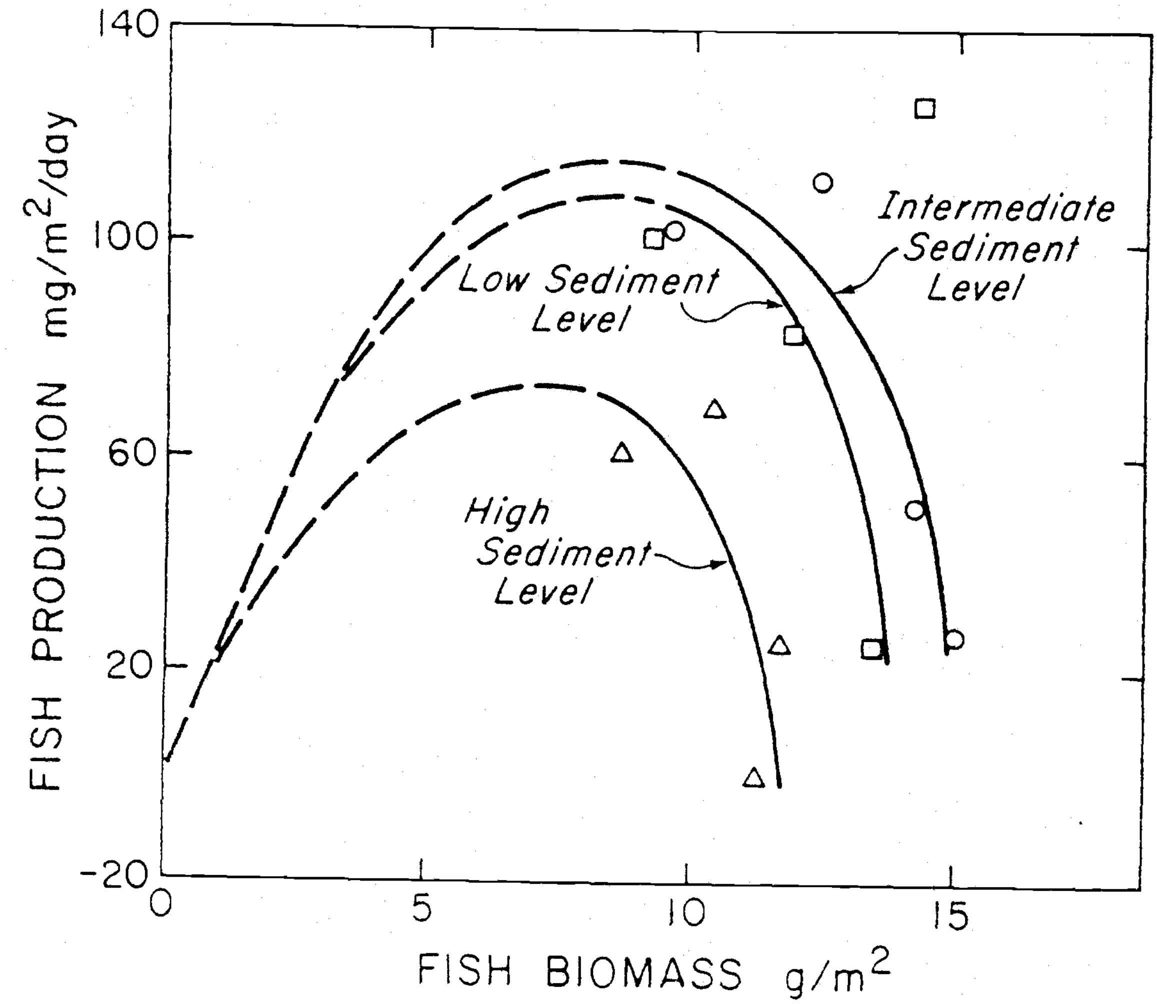

Figure 6. Production in relation to biomass of juvenile coho salmon for the spring sedimentation experiment. The data from twelve streams have been summarized and plotted in three groups by averaging replicates and treatment levels as follows: 1) 0 and 20 percent; 2) 40 and 60 percent; and 3) 80 and 100 percent embeddedness. Curves were fitted by inspection.

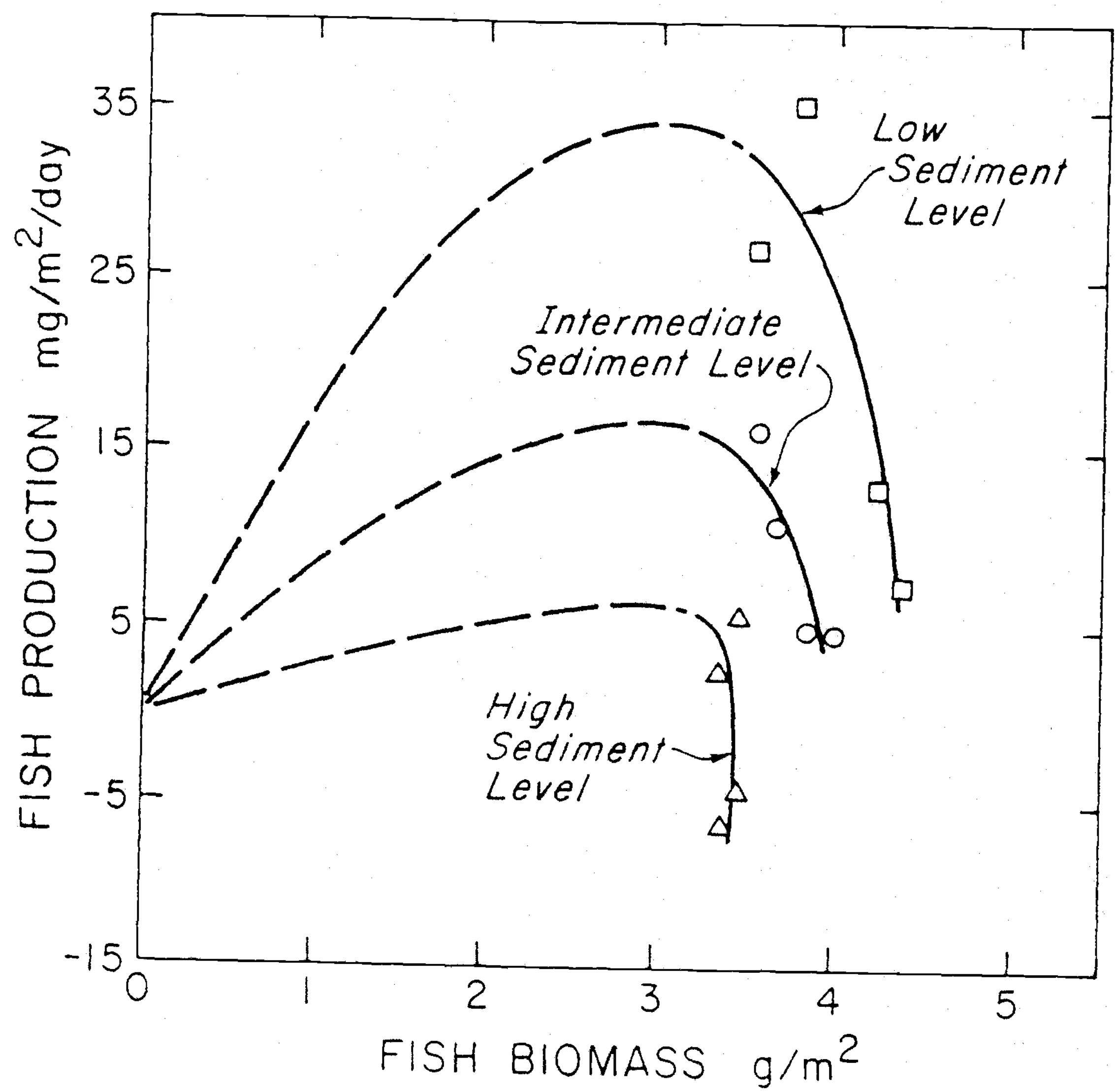

Figure 7. Production in relation to biomass of juvenile coho salmon for the summer sedimentation experiment. The data from twelve streams have been summarized and plotted in three groups by averaging replicates and treatment levels as follows: 1) 0 and 20 percent; 2) 40 and 60 percent; and 3) 80 and 100 percent embeddedness. Curves were fitted by inspection.

Table 6. Production and biomass of juvenile coho salmon in 1.55 m^2 laboratory streams as a function of streambed sedimentation. Values are means ± standard error of four streams, averaging replicates and treatment levels as follows: 1) 0 and 20%; 2) 40 and 60%; and 3) 80 and 100% embeddedness. Values followed by the same letter are not significantly different (Duncan's Multiple Range test, $P < 0.05$).

% Embedd.	Starting Biomass g/m^2	Sampling Interval 1 Production mg/m^2/day	1 Biomass g/m^2	2 Production mg/m^2/day	2 Biomass g/m^2	3 Production mg/m^2/day	3 Biomass g/m^2	4 Production mg/m^2/day	4 Biomass g/m^2	Cumulative Production g/m^2
Spring Experiment: eight fish per stream; 28 days sampling interval										
0+20	7.97 ±0.05	101.42 ± 15.16	9.36 ±0.22	83.45 ±14.00	12.03 ± 0.51	127.44 ± 22.27	14.54 ± 0.57	23.70 ±13.76	13.64 ± 0.82	9.14 ±1.07 a
40+60	8.10 ±0.09	101.62 ± 9.39	9.50 ±0.21	111.97 ± 6.50	12.45 ± 0.32	50.03 ± 9.95	14.31 ± 0.51	25.78 ±12.88	15.14 ± 0.59	8.03 ±0.34 a
80+100	7.90 ±0.10	60.16 ± 10.10	8.84 ±0.13	69.02 ±11.92	10.53 ± 0.28	23.79 ± 6.09	11.83 ± 0.36	-0.03 ±12.31	11.44 ± 0.66	4.24 ±0.42 b
Summer Experiment; two fish per stream, 14-day sampling interval										
0+20	3.29 ±0.03	26.41 ± 1.40	3.48 ±0.04	34.67 ± 5.65	3.90 ± 0.24	12.89 ± 5.22	4.22 ± 0.09	7.30 ±12.80	4.37 ± 0.06	1.15 ±0.23 a
40+60	3.37 ±0.07	15.52 ± 6.23	3.67 ±0.16	10.50 ± 8.28	3.66 ± 0.24	3.36 ± 6.59	3.98 ± 0.42	4.34 ±12.73	4.03 ± 0.41	0.48 ±0.31 b
80+100	3.41 ±0.09	3.03 ± 4.90	3.43 ±0.49	5.23 ± 4.03	3.49 ± 0.05	-4.96 ± 7.53	3.49 ± 0.09	-4.80 ± 1.68	3.42 ± 0.14	-0.03 ±0.21 b

aligned with one set of replicates on the south side of the greenhouse and the other set on the north side. In the summer experiment, the production values of replicate streams on the south side were about 40 percent more than those for the streams on the north. Light measurements made on two occasions during the summer experiment showed that light intensities at those particular times were on the average 50 percent more on the south side of the greenhouse, suggesting that higher light levels may have resulted in greater productivity of streams on the south side. Similar influences of light intensity have been noted during other laboratory stream experiments carried out in this building (Siem, person. comm. 1981). In spite of the variability between replicate streams, the cumulative production values were significantly different between the high and low sediment streams in both the spring and summer experiments (Duncan's Multiple Range Test, $P<0.05$). Cumulative production values in both the spring and summer experiments were positively correlated with average Substrate Score (Figures 8 and 9).

Substrate Size Effects on Salmonid Production

Fish production in the substrate experiments was also positively correlated with Substrate Score (Figures 10 and 11). Greatest production occurred in streams with cobble (50 percent cobble/50 percent pebble, 100 percent cobble, and 80 percent cobble/20 percent pebble, respectively; see Table 3 and Appendix III). Fish production during the summer experiment was low and even negative in some streams, the fish losing weight in the streams with smaller substrate material. Unusually high aggression was observed among the fish in the streams without cobble. Once, after two fish that had jumped out of the 100 percent pebble stream were replaced, the resident fry repeatedly attacked the

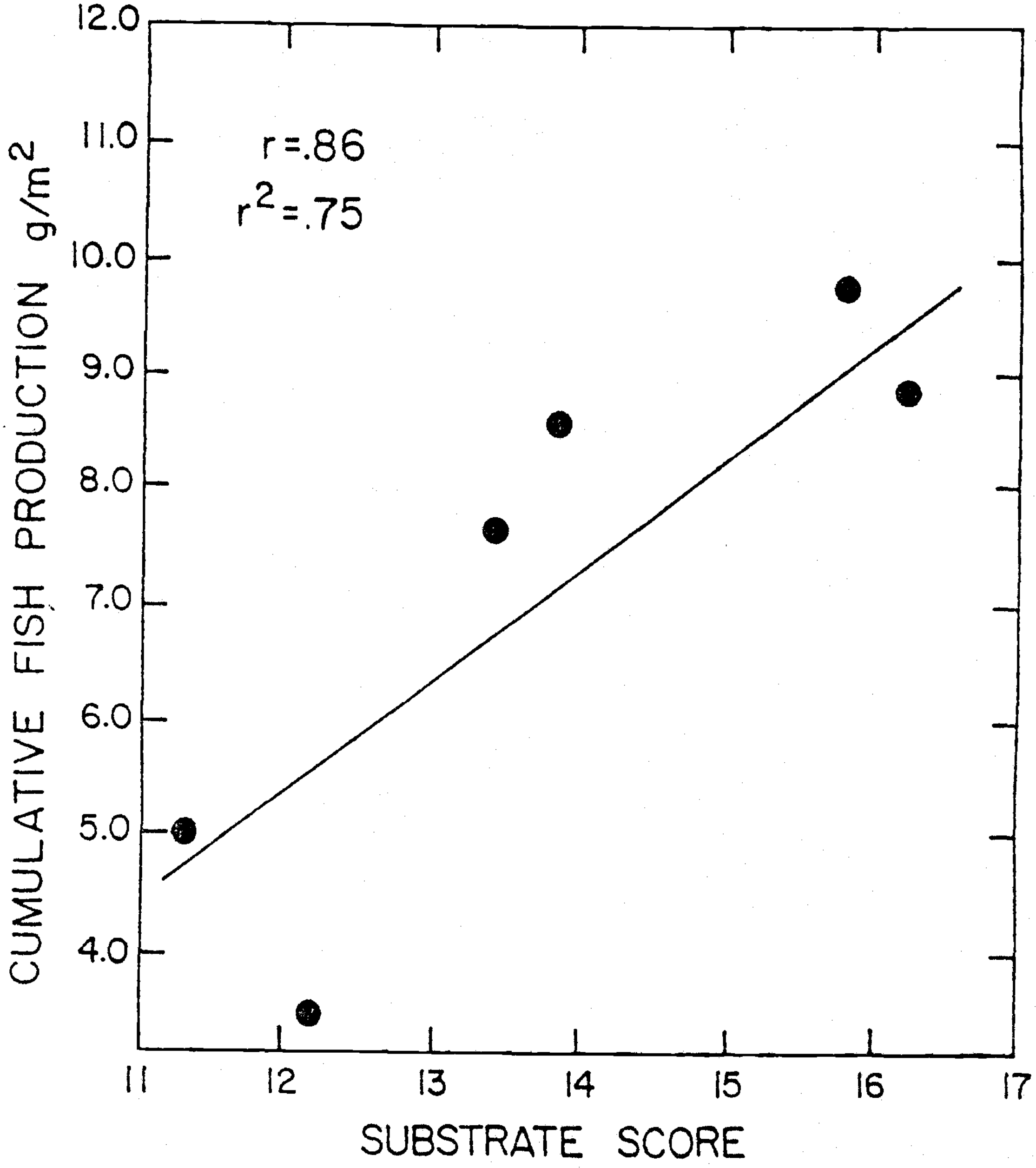

Figure 8. Total production of juvenile coho salmon summed for the entire spring sedimentation experiment in relation to average Substrate Score. Points are means of two replicates for six different treatment levels.

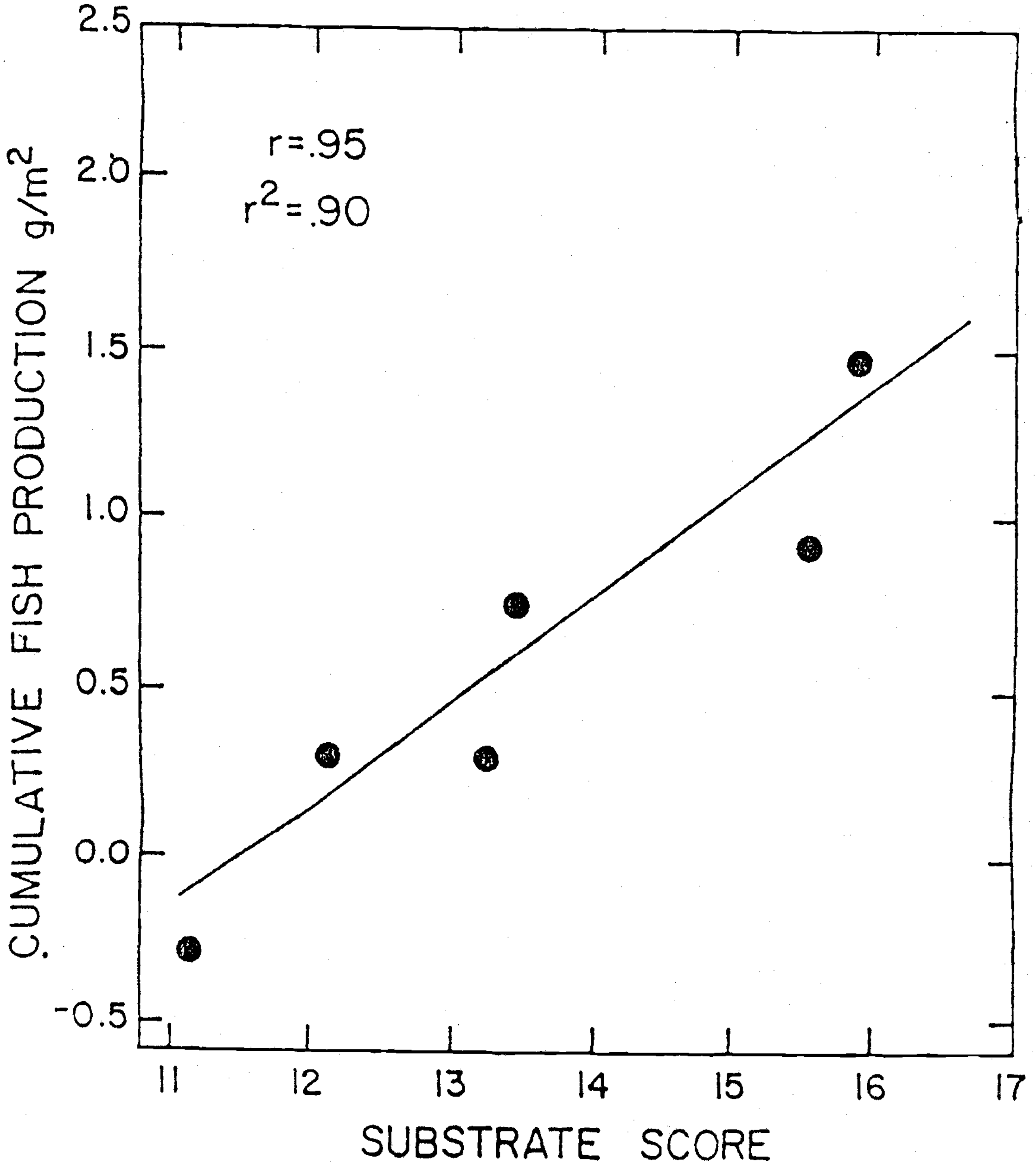

Figure 9. Total production of juvenile coho salmon summed for the entire summer sedimentation experiment in relation to average Substrate Score. Points are means of two replicates for six different treatment levels.

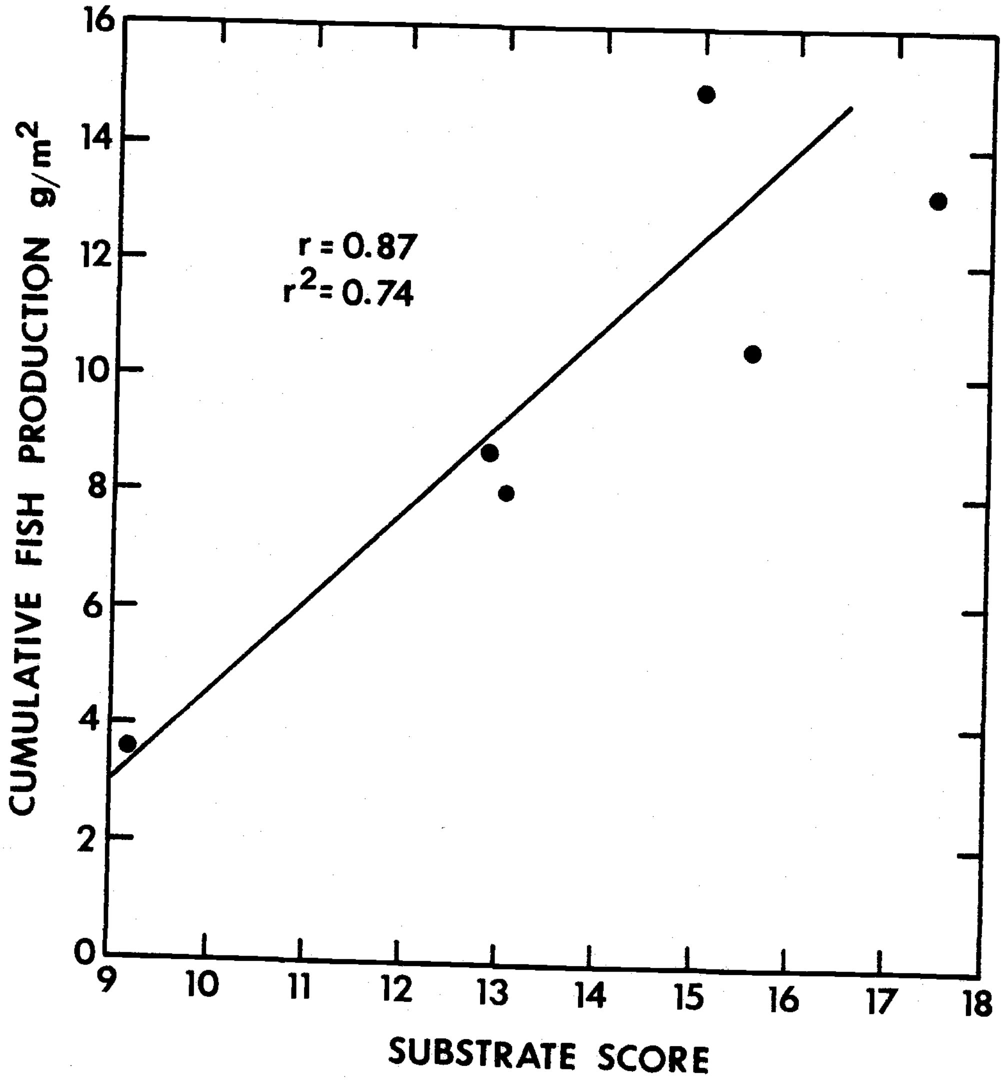

Figure 10. Total production of juvenile coho salmon, summed for the entire spring substrate experiment, in relation to average Substrate Score. Points represent six different substrate sizes.

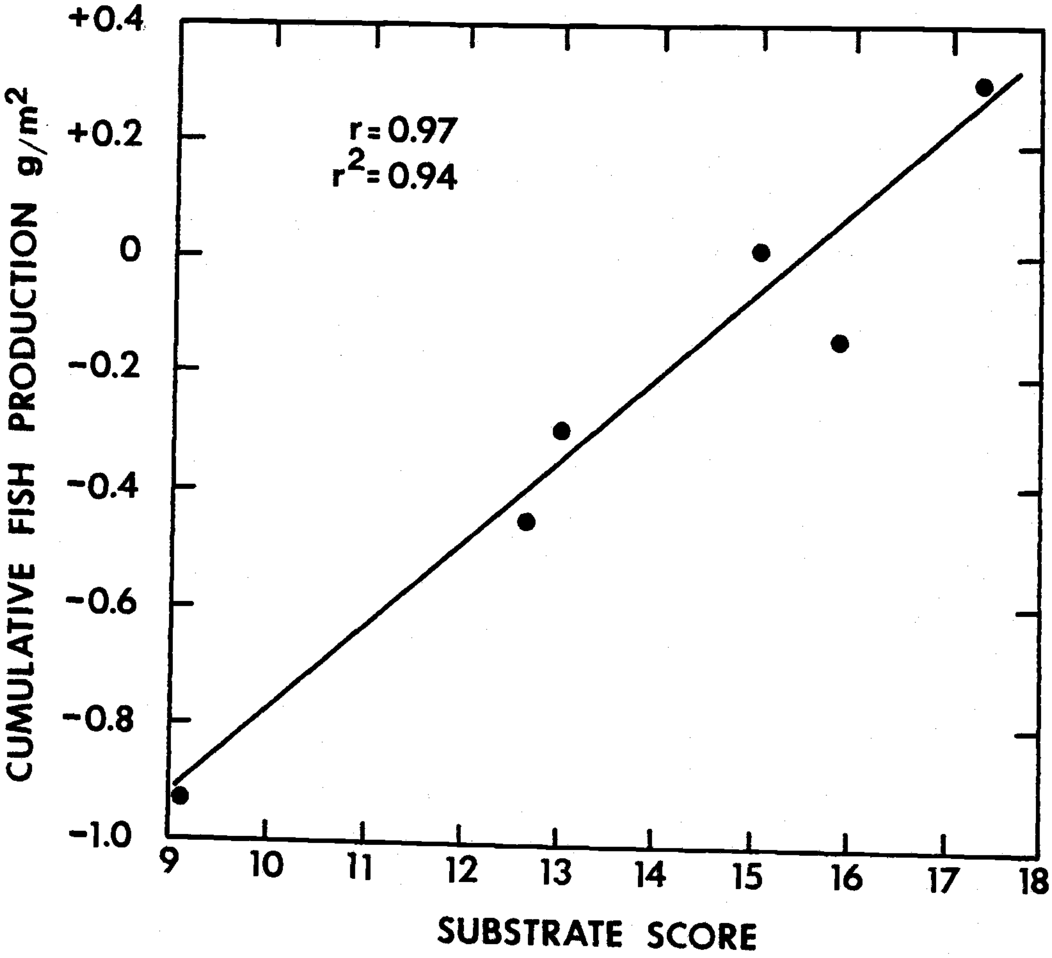

Figure 11. Total production of juvenile coho salmon, summed for the entire summer substrate experiment, in relation to average Substrate Score. Points represent six different substrate sizes.

new recruits. Both recruits were found dead on the floor the next morning. The aggressive behavior may be related to the absence of cobble that provides visual seperation between fish and to higher water velocities in these streams (Table 4). Hartman (1965) and Ruggles (1966) reported similar agonistic behavior of coho fry reared in swift streams.

Macroinvertebrate Species Composition and Densities

Species composition and numbers of macroinvertebrates in the benthic community varied with sampling date and stream substrate type (Tables 7 and 8). In general, the most abundant organisms collected in the benthic samples were in the orders Copepoda, Cladocera, Oligochaeta, Nematoda, and Ostracoda. Except for the oligochaetes, these organisms were less than 1.00 mm in length and contributed little to the total biomasses of the samples. The most common insects in the benthic samples were the ephemeropterans *Baetis*, *Ameletus*, *Cinygmula*, and *Paraleptophlebia*; plecopterans *Nemoura*, *Isoperla*, and *Alloperla*; and dipterans Chironomidae and Cerataponidae.

Benthic invertebrate species diversity, as measured by the Shannon-Weaver and equitability indices (Weber 1973), was not significantly related to substrate size or fine sediment level (Table 8). These results are at variance with those of Chutter (1969), Herbert et al. (1961), and Cederholm and Lestelle (1974) who found that species diversity decreased with decreasing substrate size and increasing sedimentation. The method of invertebrate seeding and environmental conditions in the laboratory streams may have resulted in more uniform and restricted species composition.

Table 7 - Species composition and relative abundance[1] of macroinvertebrates in benthic and drift samples.

Taxa	Abundance in Benthos	Abundance in Drift
Amphiboda*	P	A
Collembola*	P	A
Hydrozoa*	P	A
Planaridae*	P	P
Tardigrada*	P	P
Oxytrema	P	P
Acarina*	P	P
Nematoda*	C	A
Oligochaeta	E	A
Ostracoda*	C	P
Copepoda*	E	E
Cladocera*	E	E
Emphemeroptera		
Baetes	C	C
Ameletus	C	C
Cnygmula	C	C
Paraleptophlebia	C	C
Ephemerella	C	C
Epeorus	P	P
Plecoptera		
Leuctrina	C	P
Acroneuria	C	P
Isoperla	C	C
Isogenus	C	P
Alloperla	C	C
Hesperoperla	P	P
Pteronarcella	P	P
Capnia	P	P
Paraperlu	P	P
Nemoura	P	C

[1] A = absent, P = present, C = common, E = extremely abundant, * = less than 1.00 mm in length

Table 7 continued

Taxa	Abundance in Benthos	Abundance in Drift
Megaloptera		
Sialis	P	P
Coleoptera		
Heterlimnius	C	C
Odonata		
Gomphidae	P	P
Tricoptera		
Limnephillus	P	P
Wormaldia	A	P
Leptidostoma	P	P
Polycentropus	P	P
Glossosoma	P	P
Diptera		
Dixidae	A	P
Tipulidae	P	A
Ceratapogondiae	C	C
Chironomidae	E	E
Sarconphogidae	P	P
Simuliidae	A	P

Table 8: Macroinvertebrate data for the sedimentation and substrate experiments. Numbers and biomasses shown are totals of monthly benthic samples and weekly drift samples summed for each experiment per substrate area or volume of outflow, respectively. Shannon-Weaver (S.W.) and equitability (e) diversity indices were calculated based on two benthic samplings, one in the spring and one in the summer. For the sedimentation experiments the results are averages of replicate streams.

% Embeddedness	Average Sub. Score	Benthic #/m²	Benthic Biomass (g/m²)	Benthic Sp. Div. S.W.	Benthic Sp. Div. e.	Drift #/m³	Drift (>2.00 mm) #/m³
Sedimentation Experiments: Spring (Number of samples = 5 benthic, 17 drift)							
0	16.3	11245	140.70	1.3	0.3	214.3	0.7
20	15.8	7576	125.45	1.8	0.4	196.9	1.3
40	14.0	9683	164.19	1.9	0.4	29.2	1.0
60	13.4	607	157.62	1.7	0.4	37.3	1.0
80	11.8	3305	113.09	1.1	0.2	37.3	1.1
100	11.2	2763	120.98	1.3	0.3	31.1	0.8
Summer Experiment (Number of samples = 3 benthic, 13 drift)							
0	16.3	5195	90.17	2.3	0.6	47.1	1.5
20	15.8	3610	49.63	1.4	0.4	36.3	1.7
40	14.0	5092	56.79	2.2	0.5	23.0	1.1
60	13.4	3824	75.71	1.9	0.5	12.7	0.8
80	11.8	1850	42.46	2.5	0.5	15.3	1.4
100	11.2	2780	48.11	1.5	0.5	12.0	1.1
Substrate Experiments: Spring (Number of samples = 5 benthic, 17 drift)							
Substrate							
100C	17.3	6869	195.79	1.6	0.3	218.5	1.6
80C + 20P	15.9	5447	233.76	1.6	0.3	145.6	0.5
50C + 50G	15.0	5816	277.45	0.8	0.2	383.9	0.8
100P	13.0	22412	148.89	0.6	0.1	16.5	0.6
50P + 50G	12.7	4879	79.82	1.8	0.3	21.3	0.9
100G	9.1	12139	55.99	1.3	0.2	24.3	2.0

Table 8 continued

% Embedd-edness	Average Sub. Score	Benthic #/m2	Benthic Biomass (9/m2)	Benthic Sp. Div. S.W.	e.	Drift #/m3	Drift (>2.00 mm) #/m3
Summer Experiment	(Number of samples = 3 benthic, 13 drift)						
100C	17.3	2112	122.42	1.7	0.3	19.0	0.2
80C + 20P	15.9	6465	77.96	2.2	0.5	7.7	0.4
50C + 50G	15.0	5183	53.86	1.0	0.2	25.8	0.7
100P	13.0	2720	37 69	1.7	0.4	6.6	0.6
50P + 50G	12.7	794	112.61	2.0	0.3	11.4	1.6
100G	9.1	5727	41.88	2.4	0.5	11.4	2.3

Benthic macroinvertebrate numbers decreased with increasing sedimentation (Table 8). The correlation coefficents between cummulative invertebrate numbers and average Substrate Scores were r=0.89 and 0.74 in the spring and summer respectively. There were no significant differences between benthic invertebrate biomasses at different levels of fine sediment, this indicating that increased sedimentation decreased the number of smaller organisms that contributed little to the biomass of the samples. Possible mechanisms to account for the reduction of benthic organisms with increased sedimentation are: filling of gravel interstices that reduces available living spaces for invertebrates; clogging of interstices that reduces the flow of oxygenated water; interferring with respiratory structures of insects; and reduction of substrate available for periphyton growth and detritial material accumulation. The abundance of cladacerans was significantly decreased in streams with high sediment levels, possibly because the fine particles interfered with their filter feeding.

In the drift samples, macroinvertebrates other than insects were very numerous, but the dominant taxa were not the same in the drift as in the benthos (Table 7). For example, oligochaetes were extremely abundant in the benthic samples but were almost entirely absent from the drift. Cladocerans and copepods were extremely abundant in the drift, particularly in the low sediment and cobble streams, The most abundant insects in the drift were chironomids, followed by ephemeropterans and plecopterans. The number of drifting organisms collected during the spring experiments was many times greater than during the summer, because many of the insects had emerged by summer and cladocerans were much less abundant. The reduced food supply and the metobolic costs associated with warmer water temperatures probably accounted for the greatly reduced fish production during the summer.

To understand the underlying causes of the lower fish production associated with sedimentation and some substrate mixtures, the abundances of prey organisms under different conditions were compared. Samples were not taken from the guts of the experimental fish, so as to avoid excessive stress. Coho fry of the size used in these experiments feed almost exclusively on drifting organisms (Mundie 1969) and select smaller organisms, generally less than 10 mm in length (Hughes 1980). In both the spring and summer experiments, total numbers of drifting organisms were significantly reduced in the high sediment streams (Table 8). But for the organisms 2.0 mm or greater in length, no relationship between numbers and level of sedimentation was apparent. The larger organisms were much less abundant in the drift than were the smaller organisms. These results suggest that greater fish production occurred in the low sediment streams because small prey such as cladacerans, chironomids, and smaller ephemeropterans and plecopterans were more abundant.

In the substrate experiments, no statistically significant relationship was found between total number of invertebrates in the drift and substrate size (Table 8). Biomasses, but not numbers, of invertebrates were generally greater in streams with cobble. The number of drifting organisms longer than 2.00 mm was greatest in the stream with high water velocities this perhaps indicating that these organisms were more frequently dislodged. Total fish production in the spring was positively correlated with drifting invertebrate numbers ($r=0.88$), but a similar relationship was not found in the summer experiment. Fish production may have been influenced by water velocity as well as food supply (Table 4). Higher metabolic costs for fish in swift streams probably contributed to the lower fish production in the streams without cobbles.

DISCUSSION

Based on the high correlation between Substrate Score and both fish production and geometric mean particle size (Figure 3), Substrate Score may be a valuable field tool in assessing substrate quality in salmonid spawning and rearing areas. This visual technique is much less laborious than core sampling and mechanical sieving, and so it is possible to evaluate the quality of a large area of substrate quite rapidly. Visual evaluation of substrate condition has been shown to be accurate and meaningful in assessing sediment conditions in salmonid streams (Shirazi et al. 1979). Nevertheless, field testing of the Substrate Score technique is recommended.

In assessing the effect of sedimentation on the capacity of streams to support fish, all life stages must be considered. Coho salmon production can be regulated by the abundance and quality of stream rearing habitat. Hunter (1959) and Chapman (1962) showed that smolt production from rearing streams was relatively constant while the numbers of spawners fluctuated significantly. In another case, stabilization of stream flow resulted in a twelve fold increase in embryo survival, but smolt numbers showed little variation because suitable fry rearing habitat had not correspondingly increased (McFadden 1969). McNeil and Ahnell (1964) found that salmonid embryo survival was drastically reduced when fine sediments (<0.833mm) in the spawning gravels exceed 20 percent by volume of the total substrate. In the sedimentation experiments, significant decreases in fish production occurred in the 80 percent and 100 percent embeddedness streams when fine sediments (2.00 mm or less) in these streams were 26 and 31 percent by volume of the total substrates. These results suggest that the stream rearing habitats of juvenile salmonids as well as spawning gravels require protection from excessive fine sediment.

The results of the substrate experiments indicate that the use of cobble sized gravel in artifical rearing channels may optimize juvenile fish production. This contradicts the results of Williams and Mundie (1978) who found that a substrate of uniform sized pebbles (24.5 mm in diameter) supported significantly greater invertebrate numbers and biomasses than smaller or larger substrate sizes. In the substrate experiments reported here, however, fish production may have been influenced as much by water velocity and cover as food supply. Fish production in the 100 percent pebble stream (mean diameter 24 mm) was significantly less than streams with cobble even though benthic invertebrates were as abundant. The greater aggression of the juveniles in streams without cobble and the higher metabolic costs associated with living in swift water may have combined to reduce fish production in these stream. Ruggles (1966) found that swift stream supported fewer coho smolts than streams of slower velocity even though food organisms were many times more abundant in the swift streams. He attributed the reduction of smolt numbers in the swift streams to greater aggression and more distinct territorial tendencies that forced emigration of smolts. Proper arrangement of cobble may create resting and feeding locations and decrease territorial aggressive interactions by providing visual seperation between fish. This would permit maximum numbers and biomasses of salmonids to occupy a given area.

The results of these experiments should be extrapolated to nature only with care. The laboratory streams differed in several important ways from the small natural streams used by coho fry. Macroinvertebrates in small streams depend heavily on allocthonous material such as leaf material for a food source while the energy source in the laboratory streams was primarily periphyton. The laboratory streams were partially closed systems for the import and export of nutrients and drifting macroinvertebrates. The high abundance of invertebrates such as cladocerans and copepods in the laboratory streams is not typical of small natural streams. The influence of other environmental factors, such as light, may mask the effects of fine sediments on the productivity of natural streams. Murphy et al. (1981) found that the detrimental effects of fine sediments on cutthroat trout production were not as great for streams with an open canopy compared to closed canopy streams with similar levels of fine sediments. In my laboratory experiments, greater fish production occurred during the summer sedimentation experiment in the set of replicate streams that received more light. When fish production for each set of replicates were analyzed seperately, however, both showed the same trend of decreased productivity with increasing level of fine sediments. The significance of the experiments reported here is the demonstration that fine sediments and substrate size can decrease the capacity of laboratory streams for fish production, which can also be said with some certainty for natural streams. This laboratory study may serve as a foundation in designing experiments involving more complex systems. Laboratory studies alone are not adequate to fully quantify the effects of habitat variables on natural populations, but perhaps general relationships between salmonid production and sedimentation and substrate size have been made clearer.

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APPENDICES

Appendix I: Water quality analysis of natural stream water used in laboratory streams. Samples were collected from the outlets of each laboratory stream on May 2, 1978. Data shown are means and standard deviations.

Stream	Cond. Umho	Tot. solids mg/L	Susp. solids mg/L	T. Vol. solid mg/L	Turbidity Jack. units
1-12 (Sediment Ex.)	215 ± 15	131 ± 3	5.0 ±1.8	2 ±1	<3 ±0
13-18 (Substrate Ex.)	215 ± 15	127 ± 5	3.0 ±1.4	2 ±1	<3 ±0

Stream	T.I. Carbon mg/L	PH	Alkalinity mg/L	HCO_3 Alk. mg/L	Kjel.Nit. mg/L
1-12 (Sediment Ex.)	15.6 ± 1.3	8.0 ±0.0	87 ± 1	<87 ± 1	0.06 ±.01
13-18 (Substrate Ex.)	16.3 ± 0.5	8.0 ±0.0	87 ± 1	<87 ± 1	0.06 ±.01

Stream	Ammonia mg/L	NO_2+NO_3 mg/L	Phos.(T.) mg/L	Phos.(D.) mg/L	Phos.(O.) mg/L
1-12 (Sediment Ex.)	0.005 ±0.0	0.015 ± 005	0.031 ±0.004	0.032 ±0.005	0.019 ±0.002
1-12 (Substrate Ex.)	0.005 ±0.0	0.010 ±0.0	0.032 ± 005	0.031 ±0.011	0.016 ±0.002

Appendix II: Substrate Scores of 18 laboratory streams. Substrate Scores were measured from photographs taken at 0.3 m intervals in each stream on January 15, 1978.

SUBSTRATE SCORE

STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	AVE
1	10	10	13	17	14	16	11	10	7	10	10	10	11	11	12	12	16	11.8
2	9	10	12	13	17	17	14	11	11	11	11	10	13	17	13	16	16	13.0
3	7	7	10	12	12	13	12	11	10	11	7	11	12	13	12	17	12	11.1
4	9	9	12	13	16	16	19	12	11	11	10	11	12	16	17	18	16	13.4
5	11	10	14	19	17	18	19	12	13	18	18	19	17	19	16	17	17	16.4
6	10	11	15	12	17	19	19	19	19	10	10	17	19	17	17	19	17	15.8
7	11	9	10	14	16	17	19	12	11	16	11	11	13	17	12	17	16	13.7
8	10	11	10	18	16	18	18	14	13	11	11	14	13	17	16	14	18	14.5
9	11	12	11	19	17	19	19	18	16	10	10	19	15	20	19	14	16	15.2
10	15	15	17	19	17	16	18	19	18	15	17	16	17	16	17	18	17	16.8
11	9	9	9	15	13	12	13	12	9	9	10	7	10	13	11	13	19	11.3
12	10	7	12	16	17	11	12	11	12	11	10	11	12	13	13	16	18	12.4
13	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12.0
14	12	10	17	17	17	16	18	17	16	15	16	16	17	18	16	16	15	15.9
15	12	12	12	12	13	13	13	13	13	13	13	13	13	13	13	13	13	12.7
16	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13.0
17	13	14	14	16	15	16	15	15	13	14	14	15	13	16	15	19	17	15.0
18	18	20	20	19	19	20	19	19	19	18	19	18	20	19	19	19	20	19.0

Appendix III

Mean biomass, mean relative growth rate, and production in wet weight of coho salmon in laboratory streams at 28 day intervals (Spring Experiments).

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
		March 9, 1978 (Initial Weight)		
0%	6		8.017	
	10		7.826	
20%	5		8.007	
	9		8.008	
40%	4		8.025	
	8		8.307	
60%	2		7.919	
	7		8.160	
80%	1		7.856	
	12		7.672	
100%	3		7.957	
	11		8.121	
100C	18		8.536	
80C+20P	14		8.410	
50C+50G	17		7.115	
100P	16		8.796	
50P+50G	15		8.927	
100G	13		8.241	
		April 6, 1978		
0%	6	67.675	8.931	7.577
	10	89.493	9.079	9.857
20%	5	138.973	9.883	14.061
	9	109.516	9.542	11.478
40%	4	89.462	9.232	9.690
	8	128.917	10.112	12.749
60%	2	99.020	9.256	10.698
	7	89.078	9.407	9.469
80%	1	30.562	8.696	8.269
	12	66.429	8.602	7.723
100%	3	67.670	8.871	7.628
	11	75.991	9.185	8.273
100 C	18	186.290	11.145	16.715
80C+20P	14	137.498	10.335	13.304
50C+50G	17	188.433	9.754	19.319

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
100P	16	128.733	10.598	12.146
50P+50G	15	105.207	10.401	10.115
100G	13	105.599	9.720	10.864
		May 4, 1978		
0%	6	79.977	11.382	7.026
	10	64.009	11.228	5.701
20%	5	124.055	13.496	9.192
	9	65.760	11.995	5.482
40%	4	128.802	12.243	10.520
	8	110.370	13.369	8.256
60%	2	97.120	11.953	8.125
	7	111.568	12.216	9.133
80%	1	89.654	9.936	9.023
	12	46.774	10.186	4.592
100%	3	89.608	11.039	8.117
	11	50.046	10.950	4.571
100 C	18	121.033	15.447	7.835
80C+20P	14	118.986	14.158	8.404
50C+50G	17	118.940	14.057	8.461
100P	16	217.821	15.450	14.098
50P+50G	15	128.226	13.669	9.381
100G	13	41.601	11.794	3.527
		May 31, 1978		
0%	6	177.146	14.982	11.824
	10	143.230	13.318	10.754
20%	5	118.029	15.925	7.411
	9	71.371	13.915	5.129
40%	4	63.710	14.938	4.265
	8	21.359	15.158	1.409
60%	2	63.318	14.199	4.459
	7	51.705	12.962	3.989
80%	1	9.217	11.321	0.814
	12	29.538	11.255	2.625
100%	3	37.143	12.814	2.899
	11	19.263	11.920	1.616
100 C	18	162.389	17.389	9.339
80C+20P	14	68.053	16.743	4.065
50C+50G	17	77.429	16.225	4.772

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
100P	16	-125.329	12.571	-9.970
50P+50G	15	41.222	14.518	2.839
100G	13	-37.868	11.180	-3.385
		June 28, 1978		
0%	6	-11.313	13.186	-0.853
	10	19.924	13.566	1.469
20%	5	54.531	15.855	3.433
	9	32.661	11.954	2.732
40%	4	8.433	15.948	0.529
	8	63.839	16.351	3.904
60%	2	11.728	14.324	0.819
	7	19.106	13.953	1.369
80%	1	- 4.147	10.805	-0.384
	12	-15.001	10.056	-1.492
100%	3	-16.912	13.097	-1.291
	11	35.924	11.818	3.040
100 C	18	5.645	19.660	0.287
80C+20P	14	44.194	18.280	2.418
50C+50G	17	149.201	17.029	8.761
100P	16	63.687	11.770	5.411
50P+50G	15	35.806	11.513	3.110
100G	13	14.147	7.350	1.925

Mean biomass, mean relative growth rate, and production in wet weight of coho salmon in laboratory streams at 14 day intervals (Summer Experiments).

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
		July 18, 1978(initial weight)		
0%	6		3.235	
	10		3.328	
20%	5		3.238	
	9		3.362	
40%	4		3.526	
	8		3.227	
60%	2		3.450	
	7		3.280	

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
80%	1		3.295	
	12		3.243	
100%	3		3.499	
	11		3.596	
100C	18		4.576	
80C+20P	14		4 640	
50C+50G	17		4.662	
100P	16		4.610	
50P+50G	15		6.964	
100G	13		4.649	
		August 1, 1978		
0%	6	24.009	3.404	7.054
	10	29.309	3.533	8.296
20%	5	28.295	3.436	8.235
	9	24.009	3.530	6.801
40%	4	14.240	3.625	3.928
	8	13.548	4.079	3.321
60%	2	32.212	3.675	8.765
	7	2.074	3.295	0.629
80%	1	2.535	3.313	0.765
	12	15.346	3.351	4.580
100%	3	2.857	3.519	0.812
	11	- 8.618	3.536	-2.437
100 C	18	1.336	4.585	0.291
80C+20P	14	7.143	4.690	1.523
50C+50G	17	23.088	4.824	4.786
100P	16	5.899	4.651	1.268
50P+50G	15	0.230	4.495	0.051
100G	13	15.069	4.755	3.169
		August 15, 1978		
0%	6	44.839	3.885	11.540
	10	18.664	3.869	4.824
20%	5	35.760	3.885	9.206
	9	39.401	3.974	9.915
40%	4	13.733	3.821	3.594
	8	2.304	3.432	0.671
60%	2	32.120	4.125	7.786
	7	- 6.175	3.266	-1.891

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
80%	1	9.493	3.397	2.794
	12	4.101	3.487	1.176
100%	3	12.903	3.630	3.555
	11	- 5.576	3.436	-1.623
100 C	18	23.594	4.760	4.957
80C+20P	14	-6.866	4.692	-1.463
50C+50G	17	-1.797	4.973	-0.361
100P	16	5.806	4.733	1.227
50P+50G	15	-12.350	4.410	-2.801
100G	13	-69.171	4.376	-15.807
		August 29, 1978		
0%	6	17.926	4.088	4.385
	10	10.461	4.073	2.569
20%	5	23.410	4.299	5.446
	9	- 0.230	4.426	-0.052
40%	4	- 1.567	3.906	-0.401
	8	21.889	3.602	6.078
60%	2	- 8.940	5.159	-1.733
	7	2.074	3.237	0.641
80%	1	11.244	3.543	3.174
	12	2.028	3 530	0.574
100%	3	- 9.539	3.653	-2.611
	11	-23.594	3.232	-7.300
100 C	18	1.014	4.932	0.206
80C+20P	14	1.244	4.653	0.267
50C+50G	17	-5.714	4.921	-1.161
100P	16	-7.465	4.721	-1.581
50P+50G	15	-14.608	4.221	-3.461
100G	13	0 922	3.914	0.236
		September 13, 1978		
0%	6	39.613	4.511	8.782
	10	13.978	4.251	3.289
20%	5	-19 828	4.314	-4.596
	9	- 4.559	4.390	-1.038
40%	4	-11.527	3.809	-3.026
	8	41.548	4.066	10.217
60%	2	0.000	5.097	0.000
	7	-12.645	3.157	-4.006

Treatment	Stream	Production mg/m2/day	Biomass (g/m2)	Growth rate (mg/g/day)
80%	1	- 6.151	3.575	-1.720
	12	- 4.688	3.509	-1.336
100%	3	- 0.215	3.585	-0.060
	11	- 8.129	3.006	-2.704
100 C	18	- 4.172	4.908	-0.850
80C+20P	14	-11.226	4.577	-2.453
50C+50G	17	-13.462	4.780	-2.817
100P	16	-24.215	4.487	-5.396
50P+50G	15	- 5.161	4.080	-1.265
100G	13	-11.656	3.833	-3.041