Exxon Valdez Oil Spill
Restoration Project Final Report

Restoration of the Coghill Lake Sockeye Salmon Stock

Restoration Project 93024
Final Report

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Study History: Restoration Project 93024 was initiated in 1993 in response to declining sockeye salmon production at Coghill Lake in northwest Prince William Sound. An Alaska Department of Fish and Game technical report described the conditions at Coghill Lake prior to initiation of this restoration project (Edmundson, J.A., G.B. Kyle, and T.M. Willette. 1992. Limnological and fisheries assessment of Coghill Lake relative to sockeye salmon (*Oncorhynchus nerka*) production and lake fertilization. FRED Report no. 118, Alaska Dept. of Fish and Game, Division of Fisheries Rehabilitation, Enhancement and Development, Juneau, Alaska, 42p.). The U.S. Forest Service prepared an environmental assessment for the Coghill Lake fertilization project (U.S. Forest Service. 1993. Environmental assessment for fertilization of Coghill Lake, Prince William Sound. U.S. Forest Service, Glacier Ranger District, Girdwood, Alaska, 37p).

Abstract: The project goal was to restore the natural productivity of Coghill Lake and the resident sockeye salmon (*Oncorhynchus nerka*) population through lake fertilization. The Coghill Lake sockeye salmon stock had supported an important commercial fishery in western Prince William Sound, but production declines led to fishery restrictions. In 1982, 1.2 million sockeye salmon returned to Coghill Lake, but by 1993 the escapement was only 9,232 fish. In its initial year (1993), the nutrient enrichment program apparently caused elevated concentrations of phosphorus and chlorophyll *a* compared with the pre-fertilization period, but had no apparent effect on zooplankton density, biomass or species composition, compared with the pre-fertilization period. The nutrient enrichment program caused no apparent effect on the growth, condition, diet composition, or food consumption rate of sockeye fry. A more powerful analysis of the effects of the fertilization program on zooplankton and sockeye fry will be possible when data from several years of nutrient enrichment are available for comparison to the pre-enrichment period. The causes of an apparent 80% mortality of sockeye salmon fry between September and October 1993 require further study. The smolt that outmigrated from Coghill Lake in 1993 were unaffected by the fertilization program, because they outmigrated before fertilization began in June.

Key Words: *Exxon Valdez* oil spill, lake fertilization, limnology, *Oncorhynchus nerka*, sockeye salmon.

Project Data: Seven data sets were produced for this restoration project:

Description of data	*Format*	*Custodian*
1. water chemistry and phytoplankton density	Excel	Stan Carlson, Soldotna
2. zooplankton biomass and species composition	Excel	Stan Carlson, Soldotna
3. sockeye fry length weight	R:Base	Mark Willette, Cordova
4. sockeye fry stomach contents	R:Base	Mark Willette, Cordova
5. acoustic estimates of sockeye fry population	R:Base	Mark Willette, Cordova
6. sockeye smolt abundance	R:Base	Mark Willette, Cordova
7. sockeye smolt length and weight	R:Base	Mark Willette, Cordova

Availability - Copies of the data are available electronically by contacting Stan Carlson, ADF&G, 34828 Kalifornsky Beach Road, Suite B, Soldotna, AK 99669 or Mark Willette, ADF&G, P.O. Box 669, Cordova, AK 99574 per the table above. Please include a diskette for each data set.

Citation:
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Introduction:

The goal of this project is to restore the natural productivity of Coghill Lake and the resident sockeye salmon (*Oncorhynchus nerka*) population through lake fertilization (LeBrassseur et al. 1978; Stockner and Hyatt 1984; Koenings and Burkett 1987; Kyle et al. 1991). Coghill Lake is located 130 km northwest of Cordova at an elevation of 18 m. The outlet of the lake empties into the eastern side of Port Wells, Prince William Sound. Coghill Lake has a surface area of 12.7 km^2, a mean depth of 46.3 m, and a total volume of 587 x 10^6 m^3 (Pellisier and Somerville 1984). This project was conducted cooperatively by the Alaska Department of Fish and Game (ADFG) and the U.S. Forest Service (USFS).

The Coghill Lake sockeye salmon stock has historically supported an important commercial fishery in western Prince William Sound (PWS), but returns have declined considerably in recent years. In 1982, 1.2 million sockeye salmon returned to Coghill Lake, but by 1993 only 9,232 fish escaped into the lake. Edmundson et al. (1992) postulated that the decline in sockeye production was caused by excessive planktivory by large sockeye fry populations in the early 1980s. The poor salmon returns to Coghill Lake in recent years have led to time and area restrictions to fisheries in western PWS causing hardship for fishermen in the area.

Sockeye salmon rear in lakes for one to three years, typically leaving the lake environment after achieving a threshold weight of at least 2 g (Burgner 1991; Koenings and Burkett 1987). During the lake rearing lifestage, sockeye salmon fry feed largely on zooplankton. Copepods (*Cyclops spp., Diaptomus spp., Eurytemora spp.*) and cladocerans (*Daphnia spp., Bosmina spp., Holopedium spp.*) commonly comprise the major portion of the diet (Burgner 1958, Merrell 1964, Rogers 1968, Hoag 1972, Carlson 1974).

The production of sockeye salmon populations is closely linked to the productivity of rearing lakes. The availability of nutrients (nitrogen and phosphorus) to resident phytoplankton populations often determines the rate of photosynthesis (Vollenweider 1976; Schindler 1978; Smith 1979). Growth rate of sockeye salmon was positively correlated with the rate of photosynthesis in Bare Lake, Alaska (Nelson 1958). An index of areal rates of photosynthesis was positively correlated with sockeye salmon smolt production over a wide size range of oligotrophic lakes in Alaska (Koenings and Burkett 1987). The mechanism that causes these correlations likely involves food chain linkages between increased nutrient loading (Hanson and Leggett 1982), primary production (Hrbacek 1969; Melack 1976; McConnell et al. 1977; Liang et al. 1981) , secondary production (Dermott et al. 1979) and increased fish yield.

Limnological studies indicate that fry food resources in Coghill Lake cannot support large numbers of juvenile sockeye salmon. Mean annual zooplankton biomass in Coghill Lake has averaged (1986-1991) 79 mg m^{-3} (Edmundson et al. 1992). Mean annual zooplankton biomass for twenty-two other sockeye nursery lakes in Alaska averaged (1981-1992) 596 mg m^{-3} (Edmundson et al. 1992). Low fry food abundance in Coghill Lake may contribute to low fry growth, small fry size prior to winter, and poor overwinter survival. The overwinter survival of sockeye fry in Coghill Lake averaged about 12% compared with 65% for other Alaskan lakes (Edmundson et al. 1992). Over-winter mortality is typically size-dependent (Shuter et al. 1980, Port and Evans 1989). The size of age-1 sockeye smolts emigrating from Coghill Lake has ranged from 1.0 to 1.9 g (Edmundson et al. 1992); below the typical threshold size (2.0 g) for smolt outmigration from nursery lakes (Koenings and Burkett 1987). The small size of smolts outmigrating from Coghill Lake likely leads to reduced smolt-to-adult survival (Koenings et al. 1991).

In a typical dimictic lake, nutrients are replenished to the upper layer each year during spring and fall turnover (Hutchinson 1957, Likens 1985). However, Coghill Lake is meromictic, e.g. a saltwater (~26 ppt) bottom layer (monimolimnion) begins at about 30 m depth extending to the bottom. The saltwater layer in Coghill Lake likely traps organic matter that sinks into it. Thus, nutrients remineralized in the monimolimnion are not returned to the trophogenic zone (surface layer) by seasonal turnover. Coghill Lake also receives glacial silt from several tributary streams. Relatively high turbidity levels in late summer reduce the euphotic zone depth and likely limit primary and secondary production (Edmundson et al. 1992).

Lake fertilization techniques typically involve increasing the overall abundance of nutrients while maintaining the nitrogen to phosphorus ratio at about 18:1 (Kyle et al. 1995). The goal is to produce a sustained increase in primary and secondary production without negatively affecting the plankton community structure (Kyle et al. 1995). A low N:P ratio (near 5:1) tends to favor nitrogen-fixing blue-green algae; whereas, higher ratios favor green algae and diatoms which exhibit faster growth rates (Stockner 1977). Vollenwieder (1976) developed a technique for estimating the critical annual phosphorus loading rate. Nitrogen loading rates are then set to achieve the desired N:P ratio.

Two other meromictic lakes in Alaska have been treated with nutrients with apparent positive results. Nutrient enrichment at Redoubt Lake was followed by increases in primary and secondary production, increased smolt size, and higher adult returns (Kyle et al. 1995). Similarly, primary production and zooplankton biomass increased after nutrient enrichment at Hugh-Smith Lake (Peltz and Koenings 1989).

Objectives:

This project will achieve the following objectives. More than one year of study will be required to achieve objectives 3 through 5.

1. Apply fertilizer to Coghill Lake and elevate the productivity of the lake ecosystem.

2. Monitor the residence time of nutrient-enriched water in Coghill Lake.

3. Determine the effect of fertilization on primary and secondary production.

4. Determine the effect of fertilization on the food consumption, growth, condition, and survival of sockeye salmon fry.

5. Determine the effect of fertilization on the overwinter survival, age, size, and condition of smolts emigrating from the lake.

Methods:

Objective 1:

The critical loading rate for phosphorus was estimated using methods developed by Vollenweider (1976). A pharmaceutical-grade liquid fertilizer was applied to Coghill Lake by releasing it from a low-flying aircraft. Application consisted of six to nine passes of five-minute duration several times each week. The fertilizer was applied over an area of 3.9 km^2 to encompass the majority of the sockeye salmon rearing area of the lake (Figure 1). People reserving the cabin at Coghill Lake were notified of the fertilization schedule. Notices were also posted in the cabin. Fertilizer was applied no closer than a mile and a half from the cabin and lagoon where most recreational activity takes place.

Objective 2:

The residence time of nutrient-enriched water in Coghill Lake was monitored to determine the most effective spatial and temporal distribution of fertilization effort. Current speed was measured in the Coghill River during low, medium, and high flow periods using a flowmeter. Water depth and current speed was measured at 5 m intervals along a transect drawn perpendicular to the stream length. The cross-sectional area of each segment and the current speed were used to estimate the discharge within each segment. The discharge estimates for all segments along the transect were summed to estimate the total stream discharge. Regression analysis was used to develop an empirical model relating stream level to stream discharge and stream discharge to lake water residence time. The empirical model was used to construct a time series of stream discharge throughout the fertilization period. The mean lake residence time in days was calculated for the upper 30 meters of the lake assuming that the surface freshwater layer does not mix with the underlying saltwater layer.

Objective 3:

The effect of lake fertilization on primary and secondary production was assessed by comparing limnological data collected pre- and post-fertilization. Five years of limnological data collected monthly at Coghill Lake prior to 1993 was available for the comparison (Appendix I). From 1986 to 1992 (except 1987) stations A and B were sampled at time periods approximately corresponding to the sampling schedule that took place at these stations during 1993. The schedule was not entirely consistent among years before 1993. For example, September samples were collected at both stations in 1986, '88, '90, and '92, but not '89 or '91. However, since each season was sampled each year, seasonal mean data are fairly comparable among years.

Two statistical analyses were conducted to (*i*) evaluate within-1993 spatial differences in nutrient status, and (*ii*) compare the nutrient status of pre-fertilization years (1986-92) with 1993. Dependent variables in the analyses were limited to turbidity (NTU), total phosphorus (TP in $\mu g\ L^{-1}$), turbidity corrected TP (NTP in $\mu g\ L^{-1}$), and chlorophyll *a* (chl*a* in $\mu g\ L^{-1}$). NTU is included because it can alter total phosphorus concentrations. NTP is defined as .823+.585(TP) when NTU > 5 (Koenings et al. 1987). Station was considered a random effect or block and year as the treatment in the analysis of variance. The station×year interaction term can therefore be used as the error term (with the assumption of no significant interaction). Residuals from each univariate analysis were tested for normality using the Shapiro-Wilk W statistic. To statistically evaluate spatial differences within 1993, time period was used as a blocking factor or random effect and station as the treatment in the analysis of variance. Pillai's Trace statistic was used to test the hypothesis of no overall spatial differences.

Limnological sampling was conducted as in past years to insure valid pre- and post-fertilization comparisons. Sampling was conducted twice each month from June through October at two stations (A & B) that have been sampled in past years (Figure 1). An additional station (D) was added within the fertilizer application zone. The samples collected within each month were used as replicates in the pre- and post-fertilization comparison. Temperature and dissolved oxygen concentrations were measured from the surface to a depth of 40 m using a YSI model-57 meter. Measurements of light penetration (footcandles) were measured at 1 m increments from the surface to a depth equivalent to 1% of the subsurface light using a Protomatic submarine photometer. The euphotic zone depth (Schindler 1978) was calculated as the y-intercept derived by regressing depth against the logarithm of the percent subsurface light. Secchi disk transparency was determined as the averaged reading (depth) taken by lowering a standard 20 cm disk until it disappears and then raising the disk until it reappears. Water samples were collected from the 1 m stratum, chemocline, and monimolimnion using a non-metallic opaque Van Dorn sampler. Eight liters of water were collected from each depth, stored (<24 hr) in pre-cleaned polyethylene carboys, transported to Cordova for processing, and then shipped to the ADFG Limnology Laboratory in Soldotna for analysis.

Water samples were analyzed for the following parameters as described by Koenings et al. (1987). Conductivity (μmhos/cm) was measured with a YSI model-32 conductance meter. Alkalinity levels (mg/L) were determined by acid titration (0.02 N H_2SO_4) to pH 4.5 using a Corning model-399A specific ion meter. Calcium and magnesium (mg/L) were determined from separate EDTA (0.01 N) titrations after Golterman (1969), turbidity (NTU) was measured with a HF model-DRT100 turbidimeter, and color (Pt units) was determined with a spectrophotometer. Total iron (μg/L) was analyzed by reduction of ferric iron with hydroxylamine during hydrochloric acid digestion after Strickland and Parsons (1972).

All nutrient samples were analyzed by methods detailed by Koenings et al. (1987). Filterable reactive phosphorus (FRP) was analyzed by the molybdate-blue/ascorbic-acid method of Murphy and Riley (1962), as modified by Eisenreich et al. (1975). Total phosphorus was determined using the FRP procedure, after persulfate digestion. Nitrate and nitrite (NO_3 + NO_2) was determined as nitrite, following Stainton et al. (1977) after cadmium reduction of nitrate. Total Kjeldahl nitrogen (TKN) was determined as total ammonia following sulfuric acid block digestion (Crowther et al. 1980). Total nitrogen was calculated as the sum of TKN and NO_3 + NO_2. Reactive silicon was determined using the method of ascorbic acid reduction to molybdenum-blue (Stainton et al. 1977). Estimation of the yearly phosphorus loading in Coghill Lake was calculated after Vollenweider (1976).

Algal standing crop was estimated by chlorophyll *a* analysis, after the fluorometric procedure of Strickland and Parsons (1972). The low-strength acid addition recommended by Riemann (1978) was used to estimate phaeophytin. Water samples (1-2 L) were filtered through 4.25-cm GF/F filters to which 1-2 mls of a saturated $MgCO_3$ solution is added just prior to the completion of filtration. The filters were stored frozen in individual plexislides for later analysis. Samples of unfiltered lake water were preserved with Lugol's acetate solution for later identification of phytoplankton species.

In 1993, replicate vertical zooplankton tows were taken from 25 m depth at four stations using a 0.5 m diameter, 153-µ mesh, conical net. Prior to 1993, zooplankton samples were collected at two stations using a 0.2 m diameter, 153-µ mesh, conical net. In each year, the net was pulled at a constant 1 m s^{-1}, and all organisms were preserved in a 10% neutralized formalin solution. Cladocerans and copepods were identified using keys developed by Brooks (1957), Pennak (1978), Wilson (1959), and Yeatman (1959). Copepodite stages were identified and enumerated. Enumeration consisted of counting animals in triplicate 1 ml subsamples taken with a Hansen-Stempel pipette in a 1 ml Sedgewick-Rafter cell. Body length was measured to the nearest 0.01 mm for 30 randomly selected individuals from each taxonomic group in each sample (Koenings et al. 1987). Body weight was estimated from an empirical regression between body length and dry weight for each major taxonomic group. Zooplankton biomass was estimated for each species by the product of average body weight and abundance (Koenings et al. 1987).

Analysis of variance was used to test for differences in zooplankton density and biomass among years. A split-plot design was used with season and year as classification variables and station as the replicate. Separate analyses were conducted for each major taxonomic group. The analysis was limited to two stations which had been sampled each year since 1988. A separate analysis was conducted to test for differences in zooplankton density and biomass among sampling dates in 1993. A randomized complete-block design was used for this analysis with station as the replicate. Separate analyses were conducted for each major zooplankton taxonomic group. This analysis was limited to four stations which had been sampled each sampling date during the 1993 season.

Objective 4:

The effect of the fertilization program on the sockeye fry condition, growth, diet composition, and stomach fullness was assessed by testing for changes in these variables over time as the fertilization proceeded. A more powerful analysis of the effects of the fertilization program on sockeye fry will be possible when data from several years of nutrient enrichment are available for comparison to the pre-enrichment period. In addition, food consumption rate was estimated from diel feeding periodicity studies conducted each month and gastric evacuation rate (Brett and Higgs 1970). Samples of fry were collected in July, August, September, October and November using beach seines and tow nets. Each fish was placed on ice immediately after collection and frozen as soon as possible thereafter. Later in the laboratory, wet (W_w) and dry (W_d) weight of eviscerated fry was measured to a precision of 0.1 mg. Total stomach weight (including lining) was measured to a precision of 0.1 mg and each stomach was preserved in 10% buffered formaldehyde for later stomach contents analysis. The head of each fry was removed and preserved in 100% ethanol for later otolith microstructure analysis.

The vertical distribution of the fish, water temperature profiles, and continuous temperature measurements were used to estimate the temperature exposure history of sockeye fry in Coghill Lake. These data were used to estimate temperature-specific gastric evacuation rates and temperature-specific growth at maximum ration. Mean temperature at 1 m and 10 m (from continuous electronic recorders) was used to estimate the temperature of the habitat occupied by fry while feeding at night. Mean temperature at 20 m and 30 m (from continuous electronic recorders) was used to estimate the temperature of the habitat occupied by fry during daylight hours. Results from hydroacoustic surveys during each month at Coghill Lake indicated that the majority of the fry were in the 0-10 m layer at night. However, hydroacoustic data is not available for daylight hours at Coghill Lake. Narver (1970) found that sockeye fry consistently descended to approximately 20-30 m during the day; although, patterns of diel vertical migration vary considerably among populations of sockeye salmon (Burgner 1991). Sockeye fry at Coghill Lake are prevented from descending substantially below 30 m due to the presence of an anoxic saltwater layer.

The effect of the fertilization program on fry condition was evaluated by testing for changes in condition among months. The relationship between eviscerated dry body weight (W_d) and fork length (L) is described by

$$W_d = a\ L^b \tag{1}$$

where a is the condition factor and b is the slope of the linear-transformed model (Ricker 1975). A separate slopes analysis of covariance model was used to compare length-adjusted weights between months (ln-ln transformed data); least squares means were computed along with type I error probabilities. Individual fish were used as the sample unit in the analysis. Percent water content of fry was also calculated by

$$\%Water = \frac{W_w - W_d}{W_w} \tag{2}$$

where W_w is the eviscerated wet weight of fry. A one-way analysis of variance model was used to test for differences in percent water content among months. Individual fish were used as the sample unit in the analysis.

Growth rate was estimated for each monthly time period in terms of fork length and eviscerated dry body weight. Age frequencies were used to determine if multiple cohorts of fish were present in the lake. Otolith microstructure analysis was used to estimate fish age from otolith increment counts. Otolith increments are formed daily in juvenile sockeye salmon (Marshall and Parker 1982, Wilson and Larkin 1980). Thin sections of the otoliths were prepared using methods developed by Volk et. al. (1984). A computer image analysis system was used to examine the otoliths. The number of otolith increments produced since outmigration was visually counted, and the outmigration check was visually identified. Samples from monthly net sets were pooled and we assumed that a simple random sample of sockeye fry was obtained. The growth rate for each monthly time period was estimated as

$$\hat{G}_i = \frac{\overline{W}_{j+1} - \overline{W}_j}{t_{j+1} - t_j} \tag{3}$$

where $\hat{G}_i$ is the estimated growth rate for the i^{th} time period, $\overline{W}_{j+1}$-$\overline{W}_j$ is the difference in mean fork length or eviscerated dry weight between successive sample dates j and j+1, and t_{j+1}-t_j is the number of days between the sample dates. The growth rate variance was estimated as

$$v(\hat{G}_i) = (t_{j+1} - t_j)^{-2} S^2 \left(\frac{1}{n_{j+1}} + \frac{1}{n_j}\right) \tag{4}$$

where S^2 is the mean squared error (a pooled variance) from a 1-way analysis of variance comparing fry weight between (monthly) sample dates and n is the number of fry in the sample. Confidence intervals (α=0.05) were then used to test whether growth rates differed from zero between monthly periods; positive lower and upper confidence limits indicated significant growth for that period. The approximate 95% confidence interval is

$$\hat{G}_i \pm 2\sqrt{v(\hat{G}_i)}\,. \tag{5}$$

We also evaluated whether changes in the growth rate occurred between periods. The estimated change in growth rate between two periods (k) is defined as

$$\Delta\hat{G}_k = \hat{G}_{i+1} - \hat{G}_i \tag{6}$$

and the estimated variance is given as

$$v(\Delta\hat{G}_k) = v(\hat{G}_{i+1}) + v(\hat{G}_i) \ . \quad (7)$$

Confidence intervals (α=0.05) were then used to test for changes in growth rate. If the interval estimate overlapped zero, no significant change in growth rate occurred. Positive confidence limits indicated a significant increase and negative confidence limits indicated a significant decrease in the growth rate. The approximate 95% confidence interval is

$$\Delta\hat{G}_k \pm 2\sqrt{v(\Delta\hat{G}_k)} \ . \quad (8)$$

The growth of sockeye fry in Coghill Lake was also compared to temperature-specific growth of sockeye fry in the laboratory at maximum ration. The mean temperature weighted by the estimated amount of time spent in surface (0-10 m) and deep layers (20-30 m) was used as a measure of temperature exposure history of sockeye fry in Coghill Lake. It was asssumed that fry inhabited the 20-30 m layer during the day and the 0-10 m layer at night. Temperature-specific growth at maximum ration was calculated from data provided by Shelbourn et al. (1970).

Stomach contents analysis was used to assess changes in total stomach contents weight and prey composition between months. Stomach samples (n=10) were collected at night from at least ten sites throughout the lake in July, August, September, and October. Stomach contents weight was calculated by subtracting estimated stomach lining weight from whole stomach weight. Stomach lining weight was estimated from a regression relating stomach lining weight to eviscerated wet weight of fry. Prey items in the stomach were identified to the lowest possible taxonomic level. Prey length was measured to the nearest 0.01 mm. Prey body weight was estimated from an empirical regression between zooplankter body-length and dry weight (Koenings et al. 1987).

Analysis of variance was used to test for differences in diet composition, stomach fullness, and mean prey length between months. An unbalanced two-stage nested design was used to test for differences in diet composition between months with net sets nested within months. Diet composition was expressed as the proportion of total stomach contents weight in each prey category. Only three prey items (*Cyclops spp.*, *Chydorinae spp.*, and *Bosmina spp.*) which comprised the majority of stomach contents were included in the analysis. An unbalanced two-stage nested design was used to test for differences in stomach fullness between months with net sets nested within months. Stomach fullness was described by total stomach contents wet weight as a proportion of eviscerated fish wet weight. An unbalanced three-stage nested design was used to test for differences in mean prey length between months with net sets nested within months and fry specimens nested within net sets.

Food consumption rate was estimated from diel feeding periodicity studies at Coghill Lake and gastric evacuation rates obtained from laboratory studies. Brett and Higgs (1970) estimated the gastric evacuation rate of juvenile sockeye salmon (30-40 g) between 3 and 23° C. Gastric evacuation rate is described by a negative exponential function, i.e.

$$V_t = V_0 \, e^{-bt} \tag{9}$$

where V_t is the stomach weight (g) at time t, V_o is the stomach weight (g) at time 0, and b is the instantaneous gastric evacuation rate (Fange and Grove 1979). Samples of at least ten sockeye salmon fry were collected at four hour intervals throughout a 24 hour period using a tow net.

Analysis of variance was used to test for differences in stomach fullness between samples collected every four hours. A two-stage nested design was used with net set nested within sampling period. Food consumption rate (I) during each four hour period (i) was estimated by:

$$I = \sum_{i=1,6} V_i \, (1 - e^{-bt}) \tag{10}$$

where V_i is the mean stomach contents weight at the beginning of the four hour interval, and b is the temperature-specific gastric evacuation rate (Brett and Higgs 1970). In cases where there was no significant difference in stomach fullness among sampling periods, mean stomach fullness for the entire diel study was used in equation 10 . The vertical distribution of the fish and water temperature data were used to estimate the temperature of the habitat occupied by the fry during each four hour time period. The food consumption rates during each of the four hour periods were summed to estimate daily ration.

In 1993, hydroacoustic surveys were conducted in July, August, September and October to estimate the total abundance of fish in Coghill Lake. A 120 kHz dual-beam echosounder was used for these surveys. A detailed description of the methods is presented in Appendix III. The species composition of tow-net catches was used to estimate the proportion of total fish abundance (obtained from hydroacoustic data) comprised of sockeye salmon.

Objective 5:

The effect of the fertilization program on the overwinter survival of sockeye fry was evaluated by comparing pre- and post-fertilization survivals. The ratio of fall fry to spring smolt population size was used to estimate overwinter survival. Techniques described by Seber (1982) were used to estimate the variance of the survival estimate. Fall fry and spring smolt population estimates are available for the 1987, 1988, 1989, and 1992 brood years at Coghill Lake. Hydroacoustic data was collected along 10 transects oriented perpendicular to the longitudinal axis of the lake in November, 1988, October, 1989, September, 1990 and October, 1991. In October 1993, hydroacoustic data was collected along 17 transects. A 420 kHz Biosonics model 105 echo sounder was used in 1988. In each of the other years, a 70 kHz Simrad EY-M scientific echo sounder was used. In all years, the data was analyzed using echo counting techniques (Thorne 1988). Acoustic surveys were conducted during the darkest period of night when juvenile sockeye salmon are distributed in the upper to middle part of the water column (Narver 1970; McDonald 1973; Eggers 1978; Simpson et al. 1981; Nunnallee 1983; Burczynski and Johnson 1986; Levy 1987). A 7.5-m long mid-water trawl with a 2 x 2 m opening was used in conjunction with the hydroacoustic surveys to determine species composition, size, and age of fish targets. Fish were frozen and later measured to the nearest millimeter and weighed to the nearest 0.1 g in the laboratory. A scale smear was taken from each fish over 60 mm FL, affixed to a glass slide, and aged using a microfiche projector. The species composition of tow-net catches was used to estimate the proportion of total fish abundance (obtained from hydroacoustic data) comprised of sockeye salmon.

The effect of the fertilization program on outmigrant smolts was evaluated by testing for pre- and post-fertilization differences in smolt condition as well as the length and weight of age 1 smolts. Sockeye salmon smolts emigrating from Coghill Lake were enumerated using incline-plane traps (Kyle 1983). The traps were operated from May 5 to June 3 in 1989, May 5 to May 29 in 1990, May 6 to July 22 in 1991, and May 3 to June 14 in 1993. Trap efficiencies were determined by mark and recapture analysis (Rawson 1984). Methods described by Rawson (1984) were used to calculate unbiased yearly estimates of smolt abundance, variances, and 95% confidence limits. No trap efficiency data was collected in 1990. The smolt population in 1990 was estimated from trap efficiencies measured in 1991 when the trap configuration was similar to 1990. A sample of 40 smolts was collected each day to estimate age composition. The fish were anaesthetized with MS-222. Several scales were taken from each fish, affixed to a glass slide and aged later in the laboratory using a microfiche projector. Each fish was measured to the nearest millimeter and weighed to the nearest .01 g. Analysis of covariance was used to test for differences in smolt condition among years. Data was available from 1989, 1990, 1991, and 1993. The dependent variable in the model was ln of smolt wet weight. The year of smolt outmigration was an independent class variable in the model with ln length as a covariate. Individual smolt were used as the sample unit in the analysis. Analysis of variance was also used to test for differences in length and weight of age 1 smolts, respectively, among years. The independent variables in the model were year with sampling time periods nested within years. Individual smolt were used as the sample unit in the analysis.

Results:

Objective 1:

The critical loading rate needed for full phytoplankton productivity was estimated to be 650 mg m^2 yr^2 (Edmundson et al. 1992). The recent five-year average loading of phosphorus into Coghill Lake is 312 mg m^2 yr^2 (Edmundson et al. 1992). Therefore, an additional 273 mg m^2 yr^2 of phosphorus was needed to achieve full phytoplankton productivity. In addition, 2,273 mg m^2 yr^2 of nitrogen was needed to maintain an 18:1 atomic ratio of nitrogen to phosphorus. Achievement of this loading rate required application of sixty-five thousand kilograms of liquid fertilizer (20-5-0) containing 20% nitrogen and 5% phosphorus and seventy-two hundred kilograms of nitrogen fertilizer (32-0-0) comprised of equal portions of ammonium, nitrate-nitrite, and organic nitrogen (Table 1).

Objective 2:

Regression analysis indicated a significant relationship between stream discharge and river water height in Coghill River (Figure 2). The discharge of Coghill River peaked in the middle of May then generally declined throughout the remainder of the summer (Figure 3). The mean stream discharge for Coghill River was 7,406,612 m^3 day^{-1} in 1993. The mean residence time of the surface freshwater layer of Coghill Lake (upper 30 m) was estimated to be 51.4 days during May through August, 1993.

Objective 3:

Nutrient enrichment apparently lead to increased phosphorus and chl*a* concentrations in Coghill Lake in 1993. Pillai's Trace statistic indicated significant differences in nutrient concentration among years (P=0.024). NTU and TP levels were significantly higher in 1993 than during the pre-fertilization period (Table 2). However, when the correction for turbidity was applied, the difference in phosphorus (NTP) levels between 1993 and the pre-fertilization period was only marginally significant (P=0.083). Chl*a* concentration was significantly higher (P=0.002) in 1993 compared to the pre-fertilization period and exceeded previous years by a factor of three (Table 2).

Pillai's Trace statistic indicated no significant nutrient differences among stations (P=0.520) in 1993. The highest algal biomass levels were in the fertilized zone, although the difference was only marginally significant (P=0.098). Seasonal mean chl*a* at the three stations sampled was 1.92, 1.19, and 2.02 in 1993.

Analysis of variance indicated that mean annual zooplankton densities were significantly different among years for *Cyclops spp.* (P=0.001) and *Daphnia spp.* (P=0.027; Table 3). Densities of *Bosmina spp.* were not significantly different (P=0.620) among years. Mean annual biomass was also significantly different among years for *Cyclops spp.* (P=0.006), but not for *Bosmina spp.* (P=0.380) and *Daphnia spp.* (P=0.089). The season and year-by-season interaction terms in the model were significant for *Cyclops spp.* density (P=0.001) and biomass (P=0.002; Figure 4), and *Daphnia spp.* density (P=0.001) and biomass (P=0.001). Results from multiple comparison tests are summarized in Appendix I.
In 1993, *Cyclops spp.* density (P=0.001) and biomass (P=0.001) were significantly different among sampling dates (Figure 5). In 1993, *Bosmina spp.* density (P=0.023) was significantly different among sampling dates (Figure 6), but biomass was not (P=0.331).

Objective 4:

Temperatures in the 1-10 m layer of Coghill Lake generally declined from late July to mid October (Figure 7). Temperatures in the 20-30 m layer generally increased during this same time period (Figure 7). The estimated temperature exposure history of sockeye fry varied little during this period; declining from a high of 6.6° C in late July to 6.0° C in mid October.

Significant differences (P=0.001) in sockeye fry condition (length-adjusted weight) occurred among months in Coghill Lake. Pairwise comparisons indicated that mean length-adjusted dry weights in August and October were significantly different from each other and all other months (Figure 8). Length-adjusted dry weights were not significantly different between July, September, and November. Variations in percent water content of fry were inversely related to fry condition (Figure 8). Significant differences (P=0.001) in water content of fry occurred among months. Pairwise comparisons indicated significant differences (P<0.050) between all months compared.

Growth rate in terms of fork length and eviscerated dry body weight was low in the July to August period, peaked in the August to September period, then declined through October (Table 4). Pairwise comparisons indicated that growth in terms of fork length and dry weight were significantly different between the July to August and August to September periods and between the August to September and October to November periods (Tables 5 and 6). Growth rate was positively related to changes in condition between months and inversely related to changes in percent water content between months (Figure 9). Growth rates of sockeye fry in Coghill Lake were substantially below expected temperature-specific growth at maximum ration in all months (Table 7).

The diet of sockeye fry in Coghill Lake shifted from predominantly *Chydorinae spp.* in July to predominately *Cyclops spp.* in August (Figure 10). Significant differences in the proportion of the diet comprised of *Cyclops spp.* (P=0.001), *Chydorinae spp.* (P=0.001), and *Bosmina spp.* (P=0.008) occurred among months. Pairwise comparisons indicated that the proportion of the diet comprised of *Cyclops spp.* and *Chydorinae spp.* was significantly different (P<0.001) between July and all other months combined for both prey species. Mean length of all prey species (combined) also increased significantly (P=0.004) from July through November (Figure 11). Mean stomach fullness differed significantly (P=0.001) among months (Figure 11). Pairwise comparisons indicated that stomach fullness was not different between July and August (P=0.405) and between September and October (P=0.242).

Significant differences in stomach fullness by time of day were not detected in diel feeding periodicity studies conducted in July, September, and October. However, stomach fullness was significantly different (P=0.003) among time periods in August (Table 8). Stomach fullness for September and October combined was estimated for subsequent calculation of food consumption rates, because the mean fullness was not different between these two months. Estimated food consumption was greatest in August and subsequently declined through October (Table 9 and Figure 11).

The estimated population of sockeye fry in Coghill Lake increased substantially from July to September, 1993 (Table 10; Appendix III). A population estimate was not developed for August due to problems with the data that could not be readily overcome. The fry population estimate declined by 80% from September to October (Table 10). The proportion of total fish abundance comprised of sockeye salmon fry in tow-net catches ranged from 71 to 98% (Appendix II). The fry were generally found in the 0-10 m layer at night during each of the months surveys were conducted (Appendix III).

Objective 5:

The estimated fall fry population size at Coghill Lake has exhibited roughly order of magnitude changes since 1988 (Table 11). The proportion of total fish abundance comprised of sockeye salmon fry in tow-net catches ranged from 62 to 100% among years (Appendix II). The fry population enumerated in 1993 was the first potentially affected by the fertilization program.

The estimated smolt population size at Coghill Lake has also exhibited roughly order of magnitude changes since 1988 (Table 12). Trap efficiencies ranged from 0.083 to 0.664 between 1989 and 1993 (Appendix II). However, the configuration of the traps varied considerably among years (Appendix II). There is no potential effect of the fertilization program on any of these smolt populations, because the fertilization was not initiated until after the smolt migration ended in 1993. The proportion of age 1 smolts at Coghill Lake has ranged from 63 to 99% (Table 12).

Overwinter survival estimates ranged from 8.0 to 29.7% for the 1987-1989 year classes (Table 13). The estimate for 1989 year class was calculated using only age 1 smolt abundance, because the smolt weir was not operated in 1992 when this year class outmigrated at age 2. None of these year classes was potentially affected by the fertilization program.

Significant differences ($P=0.002$) in the condition of smolts outmigrating from Coghill Lake occurred among years (Table 14). Smolt condition was not significantly ($P=0.315$) different between 1991 and 1993 (Appendix II). Significant differences ($P=0.001$) in smolt length and weight also occurred among years. Both length and weight of smolts was not significantly different between 1990 and 1991, and between 1990 and 1993, respectively (Appendix II). The condition, mean length, and mean weight of smolts was low in 1989.

Discussion:

The nutrient enrichment program at Coghill Lake apparently caused elevated concentrations of phosphorus (NTP) and chl*a* in 1993 compared with the pre-fertilization period. Analysis of the effects of the fertilization on nutrient concentrations and primary production is complicated by the presence of inorganic particulate phosphorus (IPP) or 'rock phosphate' derived from glacial silt particles. Approximately, 65% of the TP in glacial lakes is comprised of IPP (Edmundson and Koenings 1985). Turbidity-corrected phosphorus (NTP) is used to adjust for this effect on TP estimates in glacial lakes (Koenings et al. 1987). NTP includes dissolved and particulate forms of both organic and inorganic phosphorus, including the phosphorus in phytoplankton cells (Welch 1980). TP concentrations in Coghill Lake were significantly greater (P=0.008) in 1993 compared with the pre-fertilization period (Table 2); although, turbidity (NTU) was also greater in 1993. After correcting for the presence of IPP, phosphorus (NTP) concentrations were 12% greater in 1993 compared with the pre-fertilization period (P=0.083). The greatest apparent response was seen in chl*a* concentrations which increased by a factor of three in 1993 compared with the pre-fertilization period (P=0.002). Elevated chl*a* concentrations in Coghill Lake may also be caused by increased light penetration due to decreased inputs of glacial silt (Edmundson et al. 1992). However, this likely was not the cause of higher chl*a* in 1993 as turbidity levels were greater in 1993 compared with the pre-fertilization period (Table 2).

The nutrient enrichment program caused no apparent effect on zooplankton density, biomass or species composition in 1993. The density and biomass of *Cyclops spp.* in 1993 was the second highest measured since 1988 (Table 3). However, the density and biomass of *Cyclops spp.* was statistically greater in 1993 only compared with 1989 and 1990 (Appendix I). *Bosmina spp.* is typically the first zooplankton species to respond to nutrient enrichment (Koenings and Kyle 1995). There were no significant differences in the biomass or density of *Bosmina spp.* among years (Table 3). Edmundson et al. (1992) postulated that lower sockeye production at Coghill Lake in recent years is due to overgrazing of zooplankton by large sockeye salmon fry populations in the early 1980's. Zooplankton populations that have been overgrazed exhibit reduced density (Kyle et al. 1988), mean body size (Kyle et al. 1988, Soranno et al. 1993), and fecundity (Koenings and Kyle 1995). Zooplankton exposed to excessive planktivory may also alter diel vertical migratory behavior to reduce predation risk (Dini et al. 1993). Such restructured populations may become predator resistent and recovery may be delayed (Koenings and Kyle 1995).

It cannot be determined if the nutrient enrichment program caused changes in sockeye fry condition, growth, diet composition, or food consumption rate. Data on these parameters is only available from the post-fertilization period (1993) at this time. Comparison of these parameters among years will enable a more powerful analysis of the effect of the fertilization program in future years.

Changes in fry growth, condition, water content, stomach fullness, and feeding behavior indicate that feeding and growth conditions were relatively poor during July-August, favorable during August-October, and poor during October-November. Changes in fry condition (expressed in terms of dry wt.) between sampling periods were positively correlated with fry growth (expressed in terms of dry wt.) and inversely correlated with changes in percent water content of fry between sampling periods (Figure 9). Poor feeding and growth conditions during July-August may be related to diet composition. Fry diets in August were comprised primarily of *Chydorinae spp.* (Figure 10), and average prey length was about 0.4 mm (Figure 11). Kyle et al. 1988 concluded that 0.4 mm is the threshold size for feeding by juvenile sockeye salmon. Sockeye salmon fry typically select larger prey, and higher growth is expected when feeding on larger prey (Parsons and LeBrasseur 1973, Eggers 1978, Kyle et al.

1988). Growth rate during the July-August period may have also been underestimated. Length-frequency distributions indicated that sockeye fry were recruiting to Coghill Lake until September (Appendix II). Growth was estimated from changes in mean dry weight of fry from samples collected each month. Such population growth estimates may be negatively biased if smaller individuals are recruiting to the population (Ricker 1975). Relatively favorable growth conditions during the August-October period may be related to relatively high biomass of *Cyclops spp.* (Figure 5) and greater prey size (Figure 11). Feeding and growth conditions apparently declined after October (Tables 4 and 8, Figure 9). This decline in fry growth and stomach fullness may be related to a decline in water temperature (Figure 7) and the biomass of *Cyclops spp.* (Figure 5). However, average prey length continued to increase slightly after September (Figure 11). Lower water temperature may cause reduced growth (Brett et al. 1969, Shelbourn et al. 1973) and feeding rate (Brett and Groves 1979) in sockeye salmon fry.

Mean stomach fullness and daily ration were greatest during August (Tables 8 & 9). August was also the only month during which significant (P=0.003) diel changes in stomach fullness were detected (Table 8). Diel feeding periodicity may be expected when feeding rate exceeds gastric evacuation rate at relatively high prey densities (Swenson and Smith 1973, Pandian and Vivekanandan 1985). However, diel feeding periodicity may also be related to patterns of diel vertical migration. Zooplankton abundance is typically greater in the upper layer of sockeye salmon nursery lakes and fry typically feed in the upper layer (Burgner 1991). Patterns of diel vertical migration (and feeding) may also be related to bioenergetic efficiency (Brett 1971, Biette and Geen 1980) or predator avoidance (Clark and Levy 1988).

The causes of an apparent 80% fry mortality between September and October are not clear. The estimated fry population in Coghill Lake declined from 2,966,131 in September to only 609,587 in October (Table 10). It is possible that there is a considerable bias in the October acoustic population estimate. Such a bias may be related to the vertical distribution of the fish. Thermal stratification may affect the vertical distribution of sockeye salmon fry and their prey. However, the water column at Coghill Lake was less stratified in October than in September (Figure 7). LeBrasseur et al. (1978) found that sockeye fry avoid temperatures less than 4° and greater than 17° C. These temperature extremes did not occur in the upper 30 m of the water column at Coghill Lake during the summer, 1993 (Figure 7). The sockeye salmon fry in Coghill Lake were primarily distributed in the upper 2-5 m of the water column during all surveys in 1993 (Appendix III). The acoustic survey technique employed at Coghill Lake did not insonify the upper 2 meters of the water column. It was assumed that the fish density in the 0-2 m layer was equal to the density in the 2-5 m layer. The validity of this assumption is not known and should be tested. We recommend that the vertical distribution of sockeye fry in Coghill Lake be investigated through paired side-looking sonar and tow net sampling stratified by depth.

The observed apparent mortality between September and October may be related to exhaustion of metabolic reserves. Overwinter mortality is typically size dependent (Shuter et al. 1980, Post and Evans 1989). Smaller fish are expected to have a higher overwinter mortality, because their energy reserves are relatively low and their metabolic rate is relatively high (Paloheimo and Dickie 1966, Brett et al. 1969, Brett and Glass 1973). The magnitude of energy reserves at the onset of winter and winter temperatures largely determine the length of time elapsed before starvation and death occurs (Shuter et al. 1980). Examination of the length-frequency distributions of fry in Coghill Lake (Appendix II) indicates that approximately 8% of the fry collected in September were less than 40 mm FL; whereas, none of the fry collected in October were less than 40 mm FL. These differences may be caused by size-dependent mortality, growth, or sampling error (Post and Evans 1989). Nevertheless, even 100% mortality in this group of small fish cannot account for the observed apparent mortality rate. Assuming the acoustic population estimates are generally correct, significant mortality must have also occurred among fish greater than 40 mm FL. This seems unlikely because the condition and water content of fry sampled in October was the greatest measured in 1993 (Figure 8). However, it is possible that mean condition, water content, and body weight (growth) in October was also biased by size-dependent mortality.

Edmundson et al. (1992) estimated an average overwinter mortality of sockeye fry in Coghill Lake of 88% (1987 & 1988 brood years). These estimates were derived from fall fry hydroacoustic surveys and spring smolt population estimates. The magnitude of the apparent fry mortality that occurred between September and October, 1993 is similar to the overwinter mortality estimated by Edmundson et al. (1992). Perhaps the timing of the mortality is the important issue. Further studies are needed to determine if significant mortality actually occurs in autumn among sockeye fry in Coghill Lake.

The smolt that outmigrated from Coghill Lake in 1993 were not affected by the fertilization program, because they moved out of the lake before the fertilization began in June 1993. No hydroacoustic population estimate is available from the fall of 1992 as this project was not funded at that time. As a result, no estimate of overwinter survival is available for the fish that outmigrated from the lake in 1993.

Smolt population estimates may be biased if the efficiency of smolt traps is size dependent. The vertical distribution of fish is often size dependent with larger fish tending to distribute deeper in the water column. In the present study, a size-dependent bias in trap efficiency is likely not related to vertical distribution, because the inclined plane traps operated at Coghill Lake sampled the entire water column. However, larger smolts may be capable of avoiding the inclined plane traps at Coghill Lake. Current speed in Coghill River ranged from 0.6 to 1.0 m sec^{-1} during normal discharge and increased to 2.0 m sec^{-1} during high discharge. Puckett and Dill (1984) found that the burst swimming speed of juvenile coho salmon was about 9 body lengths per second. Assuming that juvenile sockeye salmon exhibit a similar burst swimming speed, a 60 mm age-1 smolt could burst swim at 0.5 m sec^{-1}. Considering that current speeds near the bottom are typically much lower due to friction, it appears likely that a size-dependent bias in trap efficiency is possible. We recommend that time-lapse video techniques be used to investigate trap avoidance (Irvine et al. 1991).

The configuration of smolt traps may affect the catchability of traps for sockeye salmon fry. Trap configurations at Coghill Lake have varied considerably among years (Appendix II). Comparison of smolt population estimates among years may not be valid due to these differences in trap configuration. The angle of the trap wings relative to the current and the distance between the wings are likely important characteristics affecting catchability. We recommend that trap configurations be strictly maintained from year to year and that more than one trap array be deployed to evaluate effects of trap configuration and location.

The poor condition, weight, and length of smolt that outmigrated from Coghill Lake in 1989 was likely related to the large escapement into the lake in 1987. Approximately, 187,263 adult sockeye spawned in the Coghill Lake system in 1987 (Edmundson et al. 1992). This level of escapement exceeds the escapement goal (40,000) for this system. Density-dependent growth has caused reduced smolt size in other Alaskan sockeye populations (Kyle et al. 1988, Koenings and Kyle 1995).

Conclusions:

1. The nutrient enrichment program apparently caused elevated concentrations of phosphorus and chlorophyll *a* in 1993 compared with the pre-fertilization period.

2. The nutrient enrichment program caused no apparent effect on zooplankton density, biomass or species composition in 1993 compared with the pre-fertilization period.

3. The nutrient enrichment program caused no apparent effect on the growth, condition, diet composition, or food consumption rate of sockeye fry in Coghill Lake. A more powerful analysis of the effects of the fertilization program on sockeye fry will be possible when data from several years are available for comparison.

4. The causes of an apparent 80% mortality of fry between September and October, 1993 are not clear. Further study is needed to determine if significant fry mortality actually occurs in autumn at Coghill Lake.

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Table 1: Schedule for application of fertilizer to Coghill Lake in 1993. The 20-5-0 liquid fertilizer contains 20% nitrogen and 5% phosphorus. The 32-0-0 liquid fertilizer contains equal portions of ammonium, nitrate-nitrite, and organic nitrogen.

	Amount of Fertilizer Applied (kg)	
Week Beginning	20-5-0	32-0-0
June 29	3,000	-
July 6	3,000	-
July 13	4,400	-
July 20	3,400	-
July 27	3,400	-
Aug. 3	2,000	-
Aug. 10	-	3,000
Aug. 17	-	3,000
Aug. 24	-	3,000
Aug. 31	-	3,000
Sept. 7	-	2,400

Table 2: Results from analysis of variance tests for pre- and post-fertilization differences in limnological parameters at Coghill Lake.

Variable	Group	Mean	P-value
NTU	1993	7.06	
	1986-92	4.44	0.005*
TP	1993	10.14	
	1986-92	8.04	0.008*
NTP	1993	7.91	
	1986-93	7.07	0.083
Chl*a*	1993	1.55	
	1986-92	0.53	0.002*

Table 3: Mean annual density (no. m^{-2}) and biomass (mg m^{-2}) of major taxonomic groups of zooplankton in Coghill Lake, 1988-1993.

Species	1988	1989	1990	1991	1992	1993
Density						
Cyclops	90,280	19,610	6,588	37,836	-	44,600
Bosmina	177	267	146	26	-	68
Daphnia	372	155	0	18	-	0
Biomass						
Cyclops	170	33	17	54	-	87
Bosmina	0.30	0.80	0.26	0	-	0
Daphnia	0.92	.36	0	0	-	0

Table 4: Mean growth of sockeye fry at Coghill Lake, 1993 in terms of fork length (fl, mm day^{-1}) and eviscerated dry weight (dw, mg day^{-1}) with associated standard errors.

Index	Sampling Period	Mean Growth (fl)	Standard Error	Mean Growth (dw)	Standard Error
1	Jul. - Aug.	0.040	0.022	-0.070	0.182
2	Aug. - Sep.	0.105	0.016	1.117	0.133
3	Sep. - Oct.	0.079	0.033	0.636	0.274
4	Oct. - Nov.	0.043	0.021	0.440	0.173

Table 5: Pairwise comparisons of mean growth (in terms of fork length) differences between sampling periods for Coghill Lake sockeye fry, 1993. Comparisons significant at the 0.05 level are indicated with an asterisk.

Pairwise Comparison	Mean Difference	Lower 95% CF	Upper 95% CF	Significance
1-2	0.065	0.012	0.118	*
2-3	-0.026	-0.098	0.045	
2-4	-0.063	-0.114	-0.011	*
3-4	-0.036	-0.112	0.040	

Table 6: Pairwise comparisons of mean growth (in terms of dry weight) differences between sampling periods for Coghill Lake sockeye fry, 1993. Comparisons significant at the 0.05 level are indicated with an asterisk.

Pairwise Comparison	Mean Difference	Lower 95% CF	Upper 95% CF	Significance
1-2	1.247	0.804	1.690	*
2-3	-0.541	-1.138	0.056	
2-4	-0.737	-1.165	-0.309	*
3-4	-0.196	-0.830	0.438	

Table 7: Comparison of temperature-specific growth (% BW day^{-1}) of sockeye salmon fry in Coghill Lake (1993) to growth of sockeye fry fed an excess ration in the laboratory.

Sampling Period	Temp. (C)	Actual Growth	Predicted Growth	Difference
Jul.-Aug.	6.6	-0.07	3.08	-3.78
Aug.-Sep.	6.5	1.12	3.03	-1.91
Sep.-Oct.	6.0	0.64	2.73	-2.10
Oct.-Nov.[1]	-	-	-	-

[1] Temperature data not available.

Table 8: Stomach fullness (% body weight) of Coghill Lake sockeye fry by time of day and mean stomach fullness for each sampling period overall. Level of statistical significance (P) for tests of differences by time of day.

	Time of Day								
Month	0000-0400	0040-0080	0080-1200	1200-1600	1600-2000	2000-2400	Overall Mean	n	P
Jul. 27	1.51	-	1.25	2.70	-	1.24	1.85	85	0.142
Aug. 25	1.85	1.58	1.84	0.80	3.72	3.45	2.19	190	0.003
Sep. 21	1.32	0.97	0.93	1.79	0.87	0.95	1.16	208	0.120
Oct. 11	-	2.02	0.84	-	1.85	1.44	1.55	69	0.804
Nov.	0.32	-	-	-	-	0.68	0.56	104	0.201

Table 9: Estimated food consumption rate (% body weight) by time of day and daily ration (% body weight) of sockeye salmon fry in Coghill Lake, 1993.

Month	Time of Day 0000-0400	0040-0080	0080-1200	1200-1600	1600-2000	2000-2400	Total Daily Ration
Jul. 27	1.05	0.38	0.38	0.38	0.38	1.05	3.64
Aug. 25	0.75	0.35	0.41	0.18	0.82	1.40	3.90
Sep. 21	0.44	0.40	0.36	0.36	0.40	0.44	2.39
Oct. 11	0.40	0.38	0.36	0.36	0.38	0.40	2.27
Nov. 15	0.16	0.16	0.16	0.16	0.16	0.16	0.96

Table 10: Summary of hydroacoustic estimates of sockeye fry population in Coghill Lake, 1993.

Month	Point Estimate	Lower 95% CI	Upper 95% CI
July	1,665,446	1,079,187	2,251,705
Aug.	-	-	-
Sept.	2,966,131	2,618,709	3,313,553
Oct.	609,587	437,901	781,273

Table 11: Summary of fall fry sockeye population estimates for Coghill Lake, 1988-1993.

Year	No. Transects	Point Estimate	Lower 95% CI	Upper 95% CI
1988	6	3,269,000	10,583	6,527,417
1989	9	280,514	184,657	376,371
1990	10	1,550,154	789,644	2,310,664
1991	10	442,367	317,794	566,940
1993	17	609,587	437,901	781,273

Table 12: Summary of smolt outmigration estimates for Coghill Lake, 1989-1993.

Year	Point Estimate	Lower 95% CI	Upper 95% CI	Age 1	Age 2
1989	374,376	357,395	391,357	369,822	4,554
1990	18,632	14,734	22,530	11,853	6,779
1991	163,708	109,390	218,026	124,024	39,684
1993	289,611	233,246	345,976	274,977	14,634

Table 13: Summary of fall fry and smolt (by age group) population estimates, and fry-to-smolt survival estimates for Coghill Lake (brood years 1987-1992).

Brood Year	Fall Fry	Smolt Production age-1	Smolt Production age-2	Fry-Smolt Survival (%)
1987	3,269,000	369,800	6,780	11.5
1988	173,650	11,850	39,680	29.7
1989	1,550,150	124,020	-	8.0[a]
1990	442,370	-	14,630	-
1991	-	274,980	-	-

[a] Based on age-1 smolt only

Table 14: Condition (length-adjusted weight) and mean length and weight of age 1 smolts outmigrating from Coghill Lake in 1989, 1990, 1991, and 1993.

Year	Condition	SE	Weight	SE	Length	SE
1989	0.39	0.004	1.06	0.058	51.8	0.786
1990	0.51	0.006	1.77	0.118	60.2	1.595
1991	0.55	0.003	1.63	0.058	57.5	0.785
1993	0.55	0.003	1.97	0.053	61.6	0.713

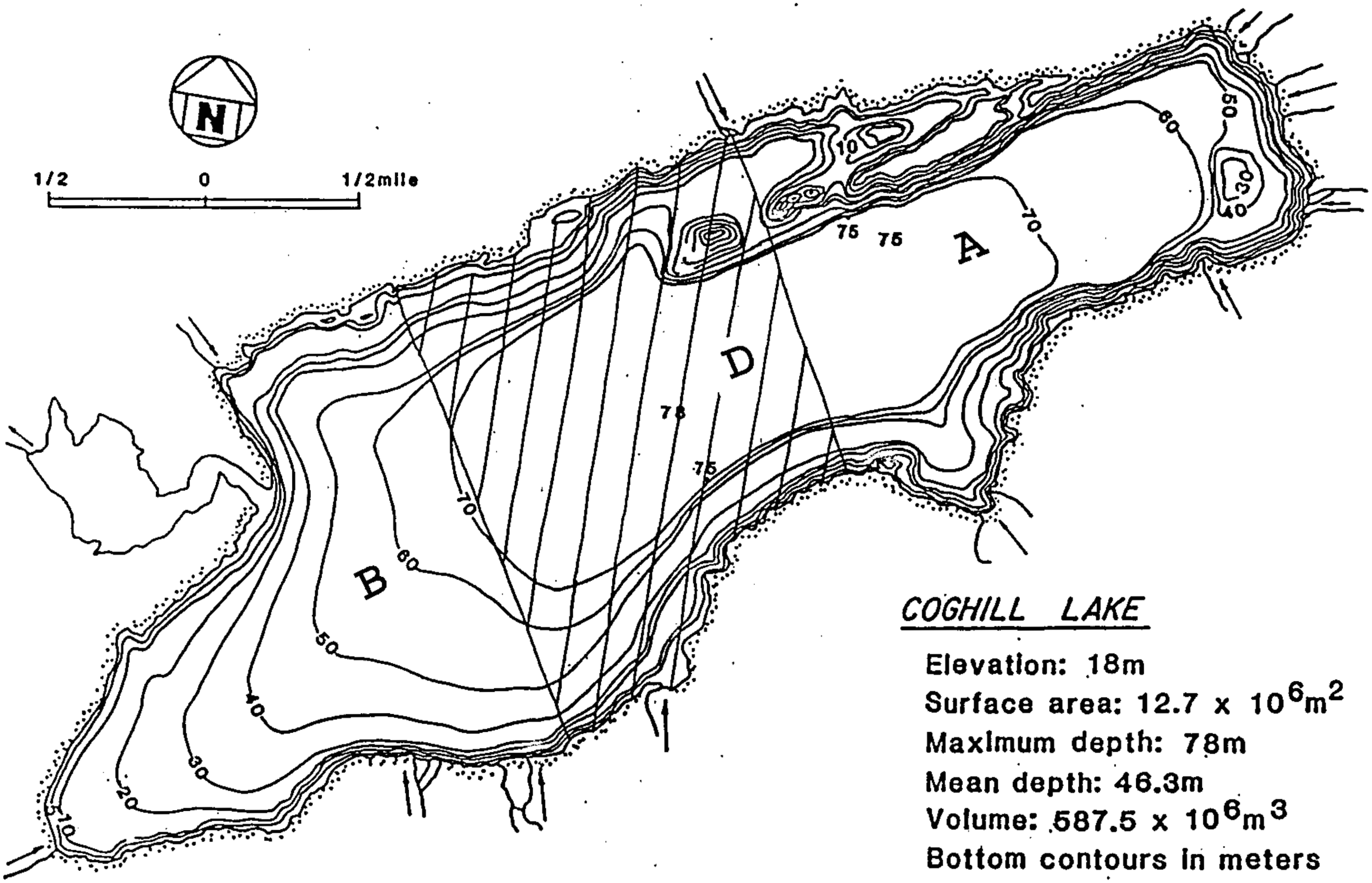


Figure 1: Map of Coghill lake indicating the fertilizer application zone and limnology sampling stations.

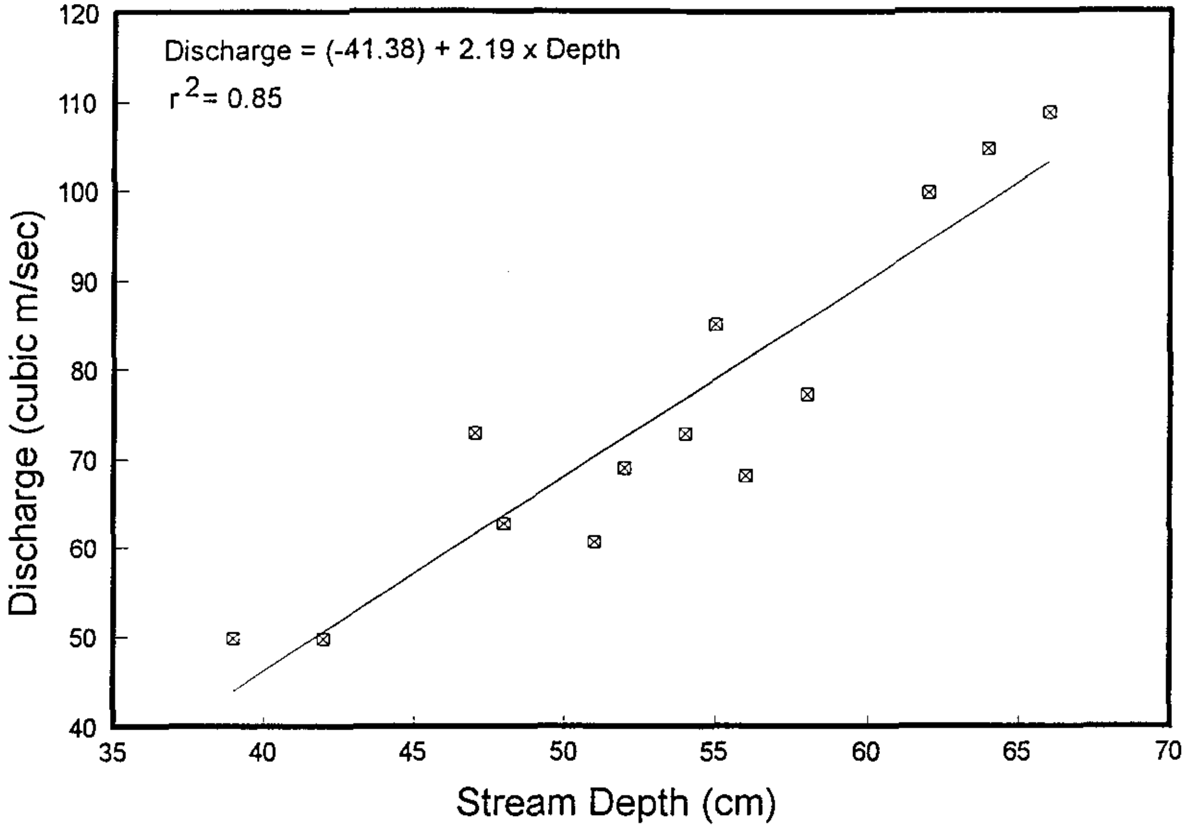


Figure 2: Relationship between stream discharge and stream depth in Coghill River, 1993.

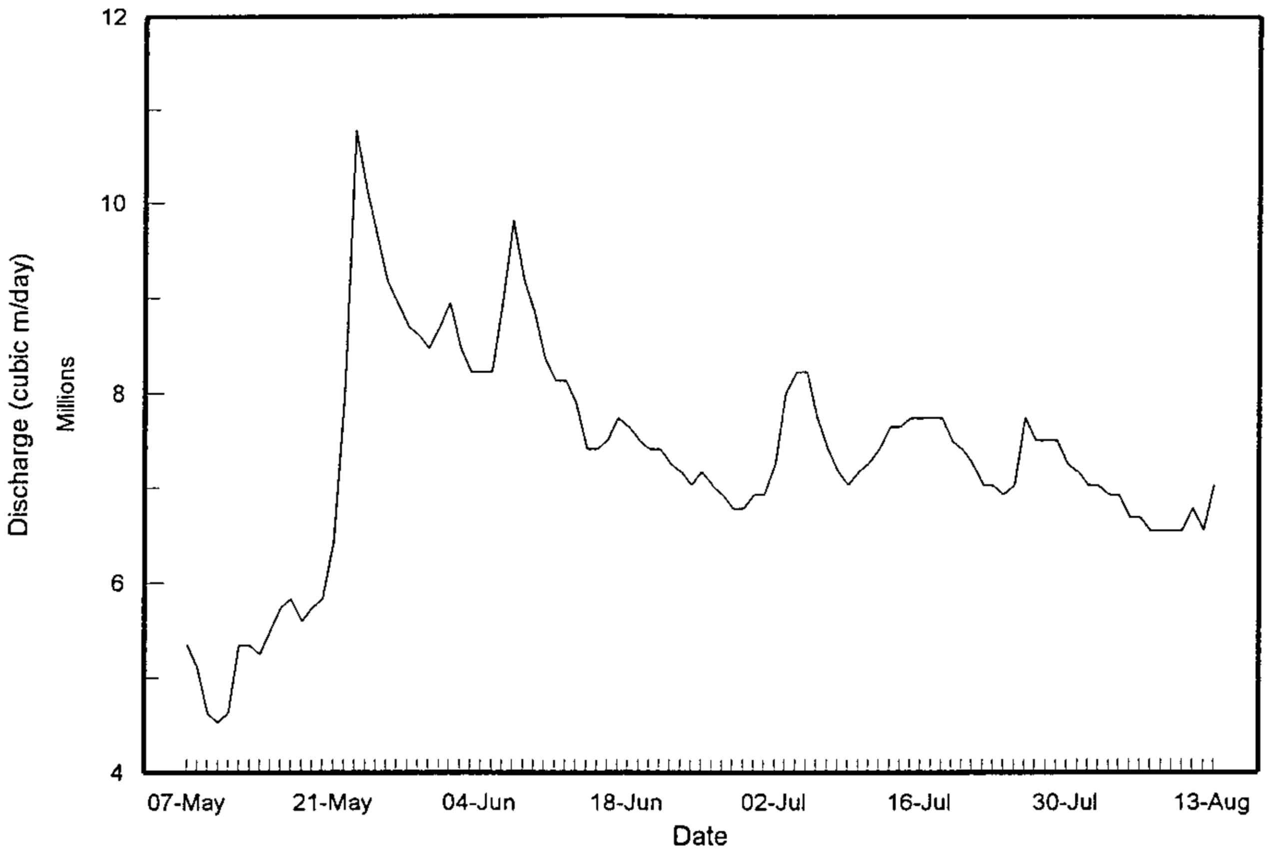


Figure 3: Time series of discharge for Coghill River from May to August, 1993.

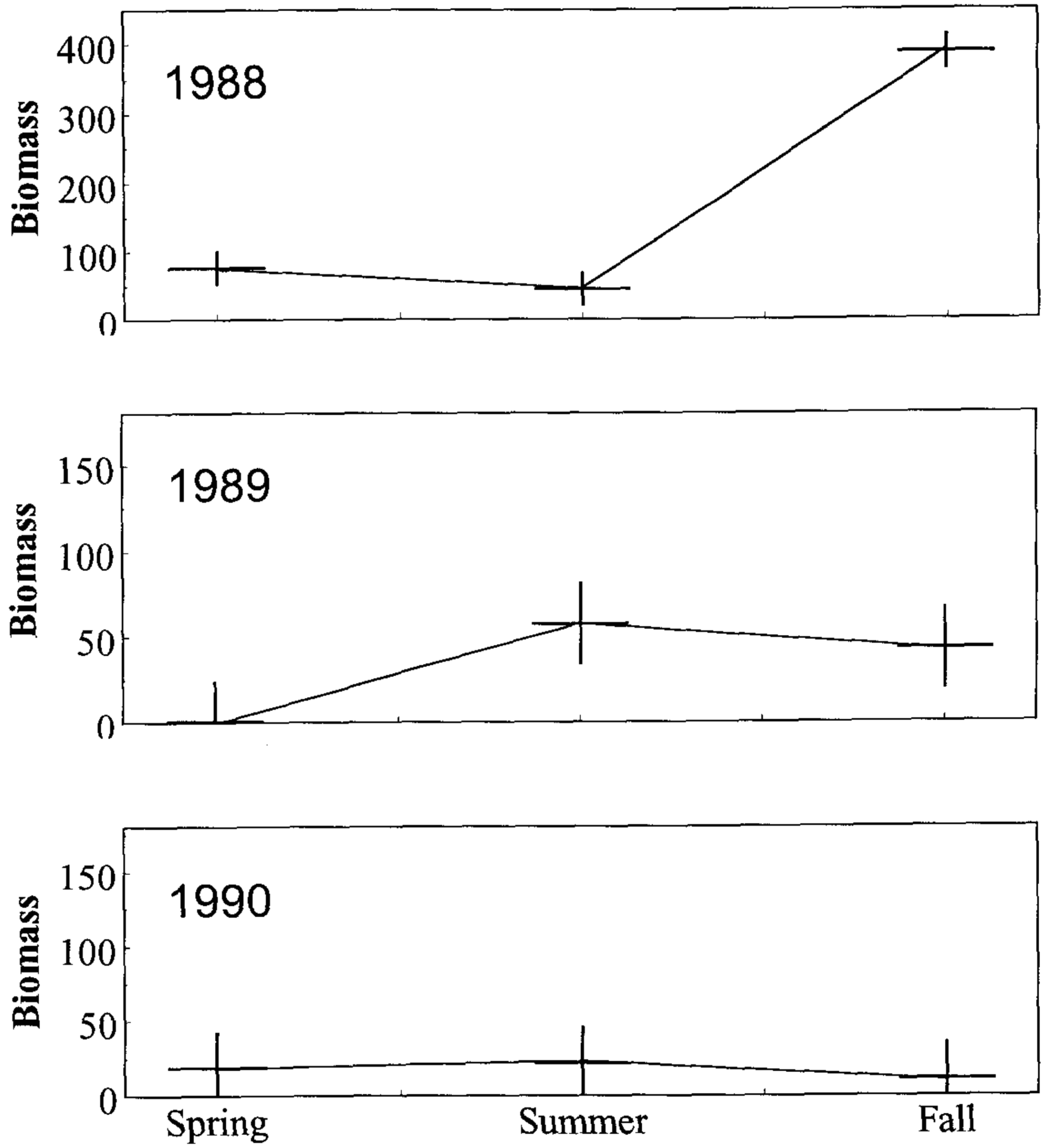


Figure 4: Seasonal mean biomass (mg/sq. m) of *Cyclops spp.* in Coghill Lake, 1988-1993. Vertical bars indicate the standard error of the mean.

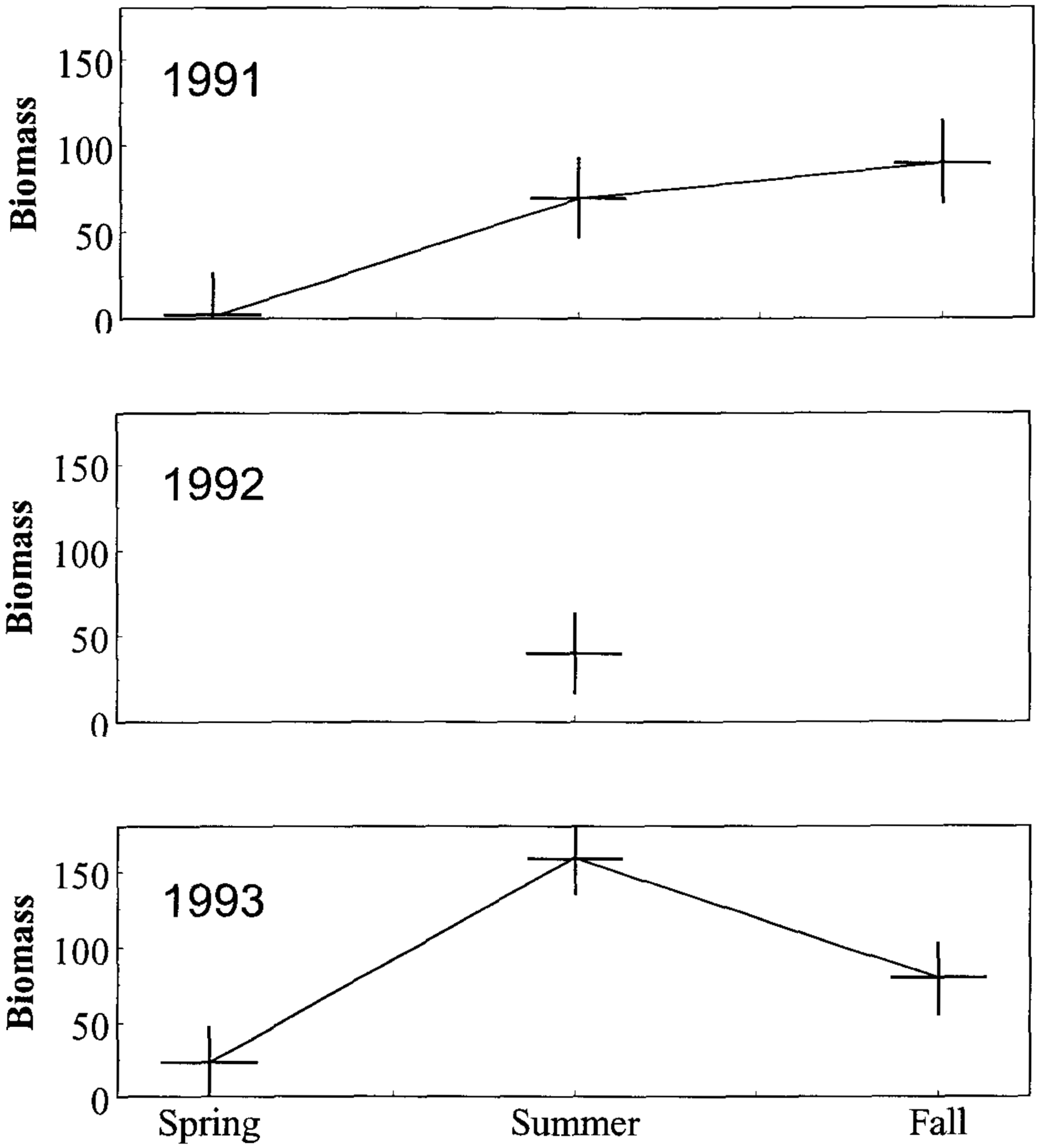


Figure 4: Seasonal mean biomass (mg/sq. m) of *Cyclops spp.* in Coghill Lake, 1988-1993. Vertical bars indicate the standard error of the mean.

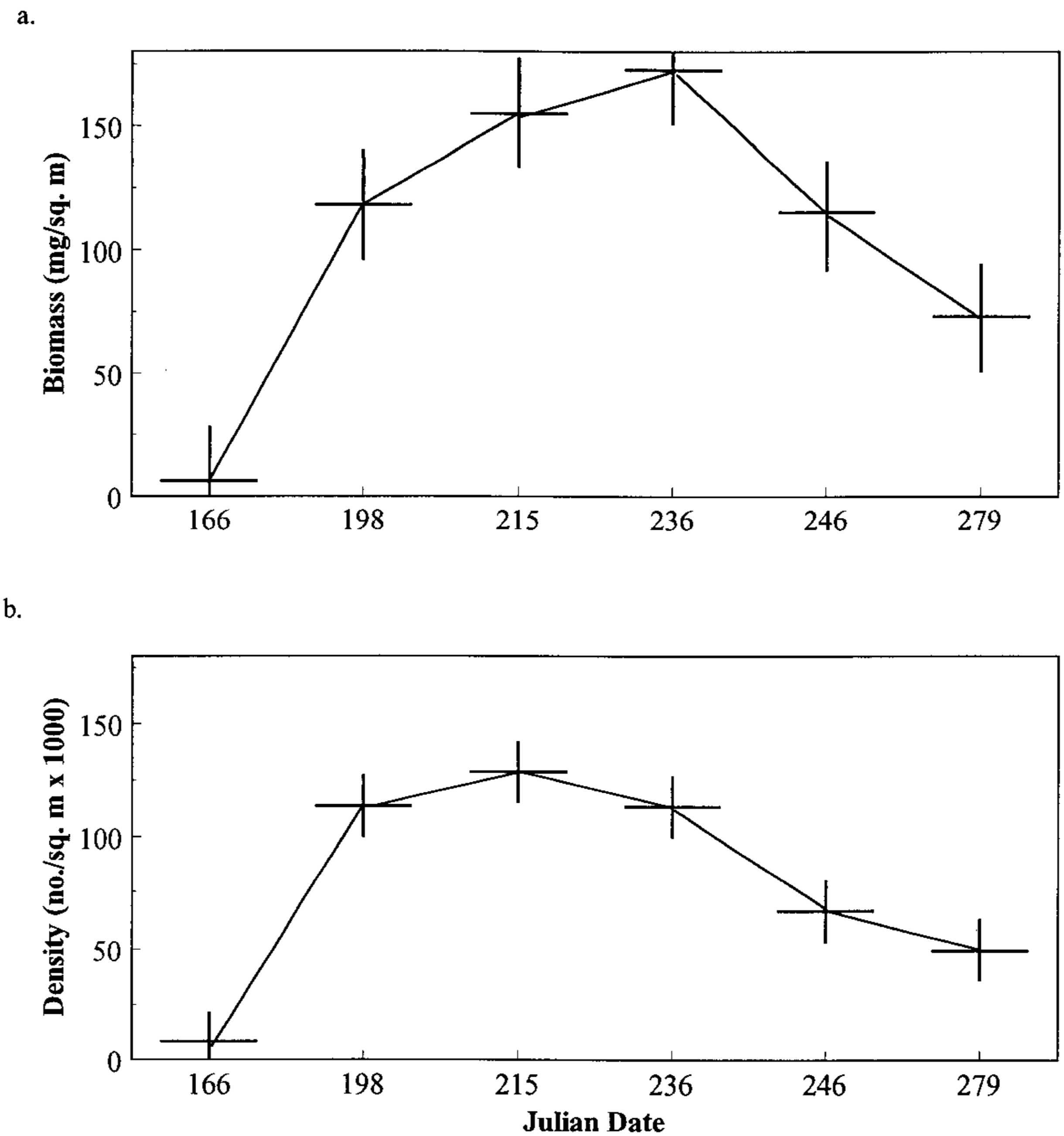
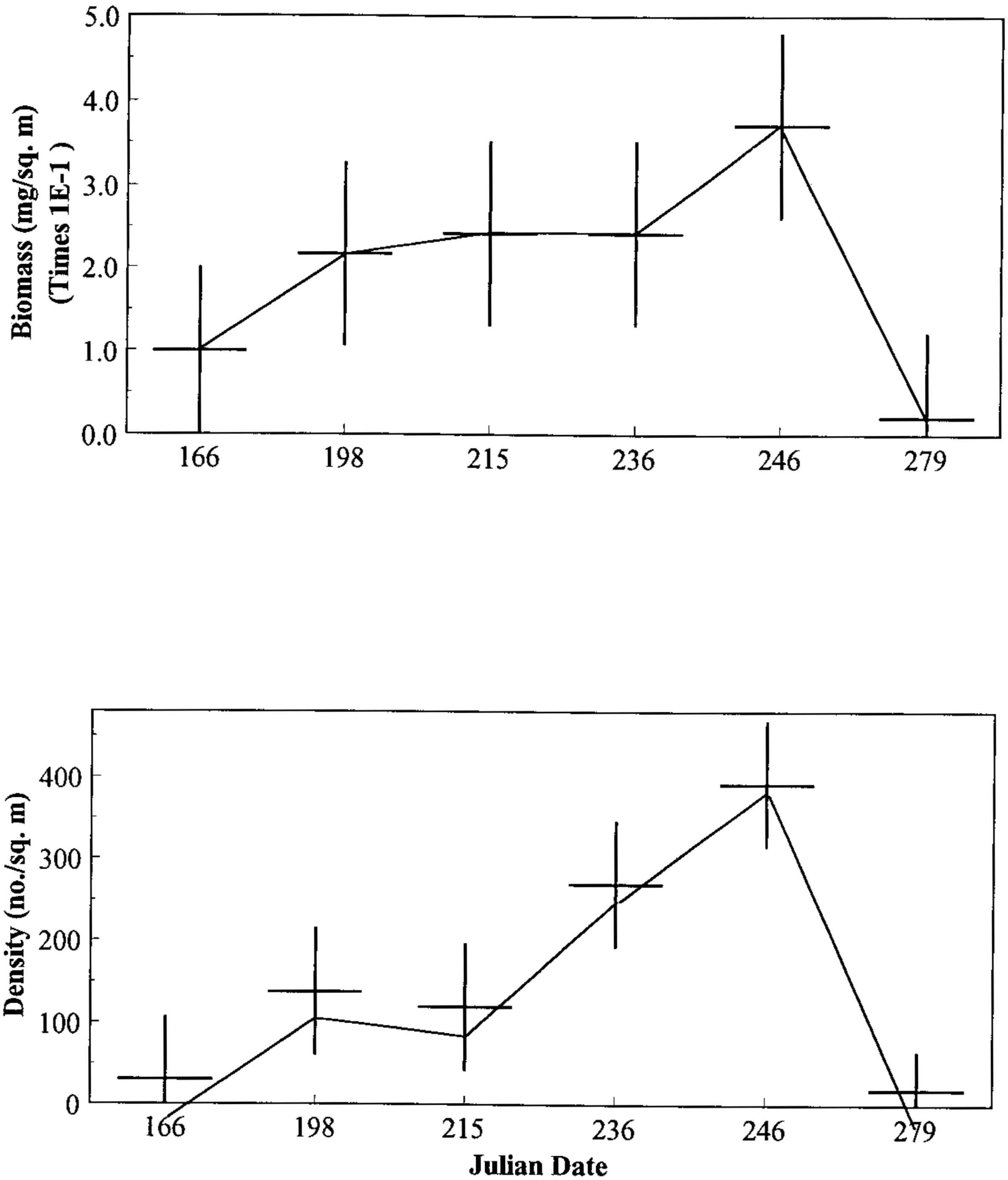


Figure 5: Mean (a) biomass and (b) density of *Cyclops spp.* in Coghill Lake, 1993. Vertical bars indicate the standard error of the mean.

a.



b.

Figure 6: Mean (a) biomass and (b) density of *Bosmina spp.* in Coghill Lake, 1993. Vertical bars indicate the standard error of the mean.

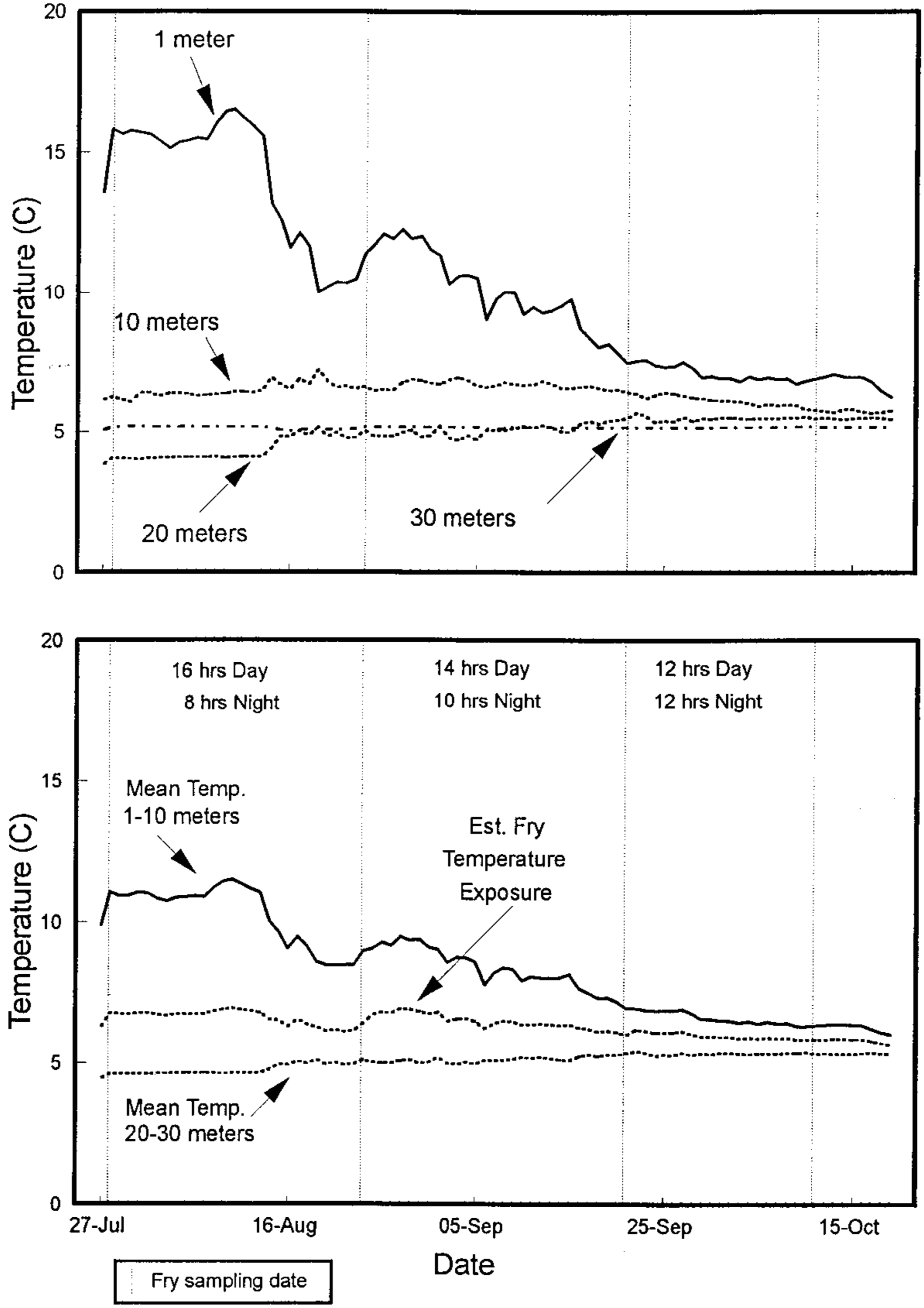


Figure 7: Time series of water temperature in Coghill Lake from July to October, 1993, and estimated temperature exposure history of sockeye salmon fry in the lake.

a.

b.

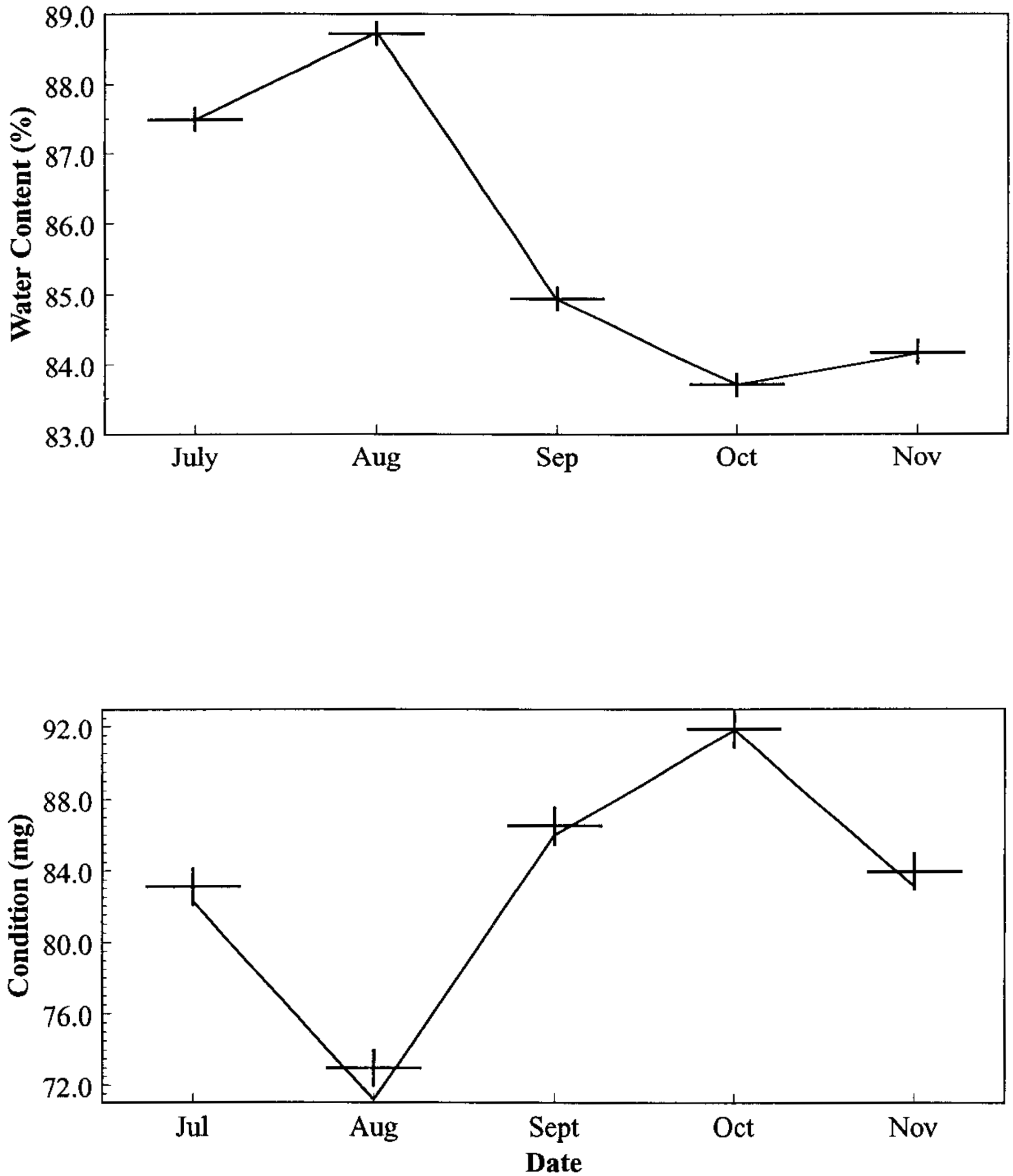


Figure 8: Mean (a) water content and (b) condition of sockeye fry in Coghill Lake, 1993. Vertical bars indicate the standard error of the mean.

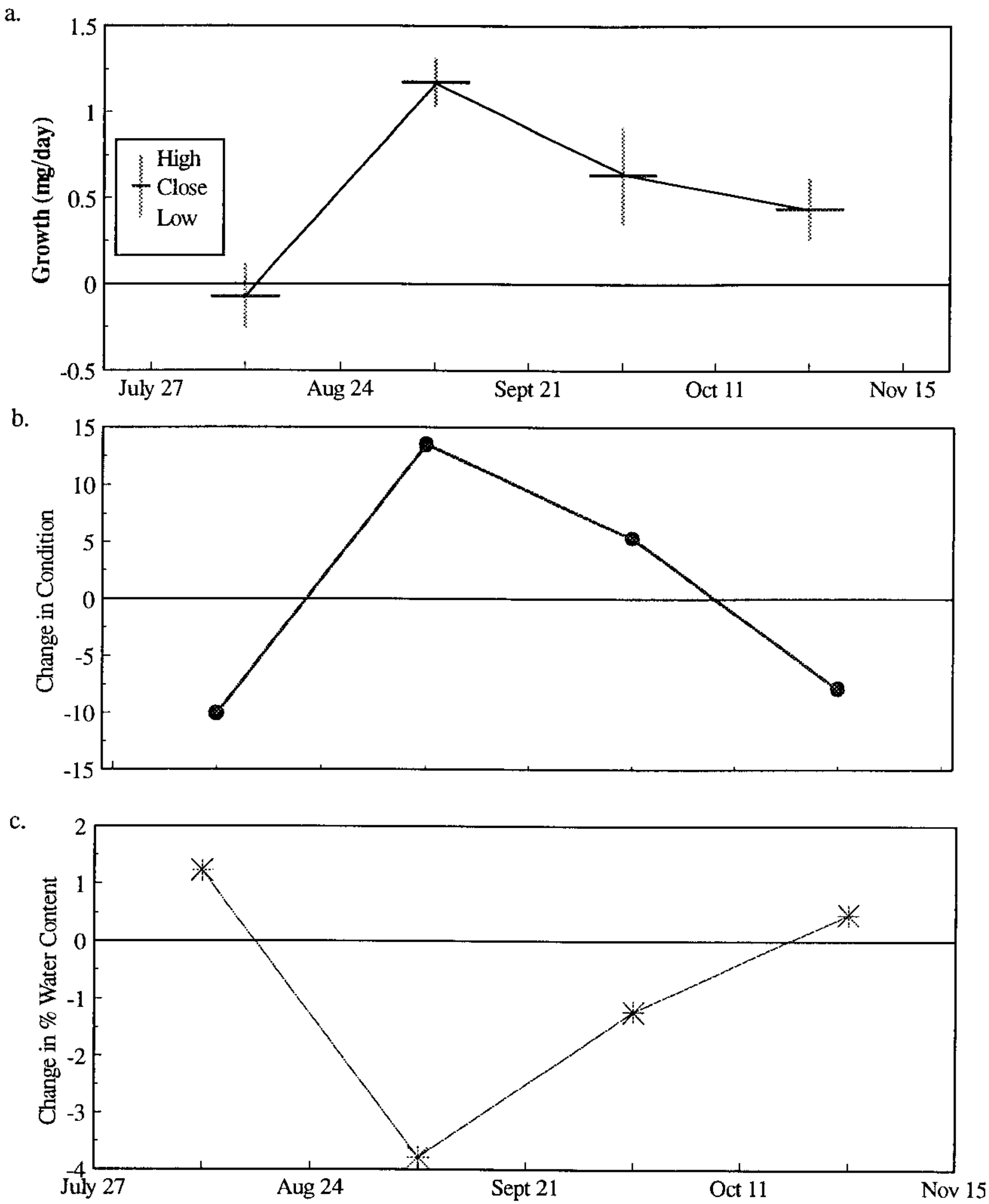


Figure 9: Changes in the (a) growth, (b) condition, and (c) water content of fry in Coghill Lake, 1993.

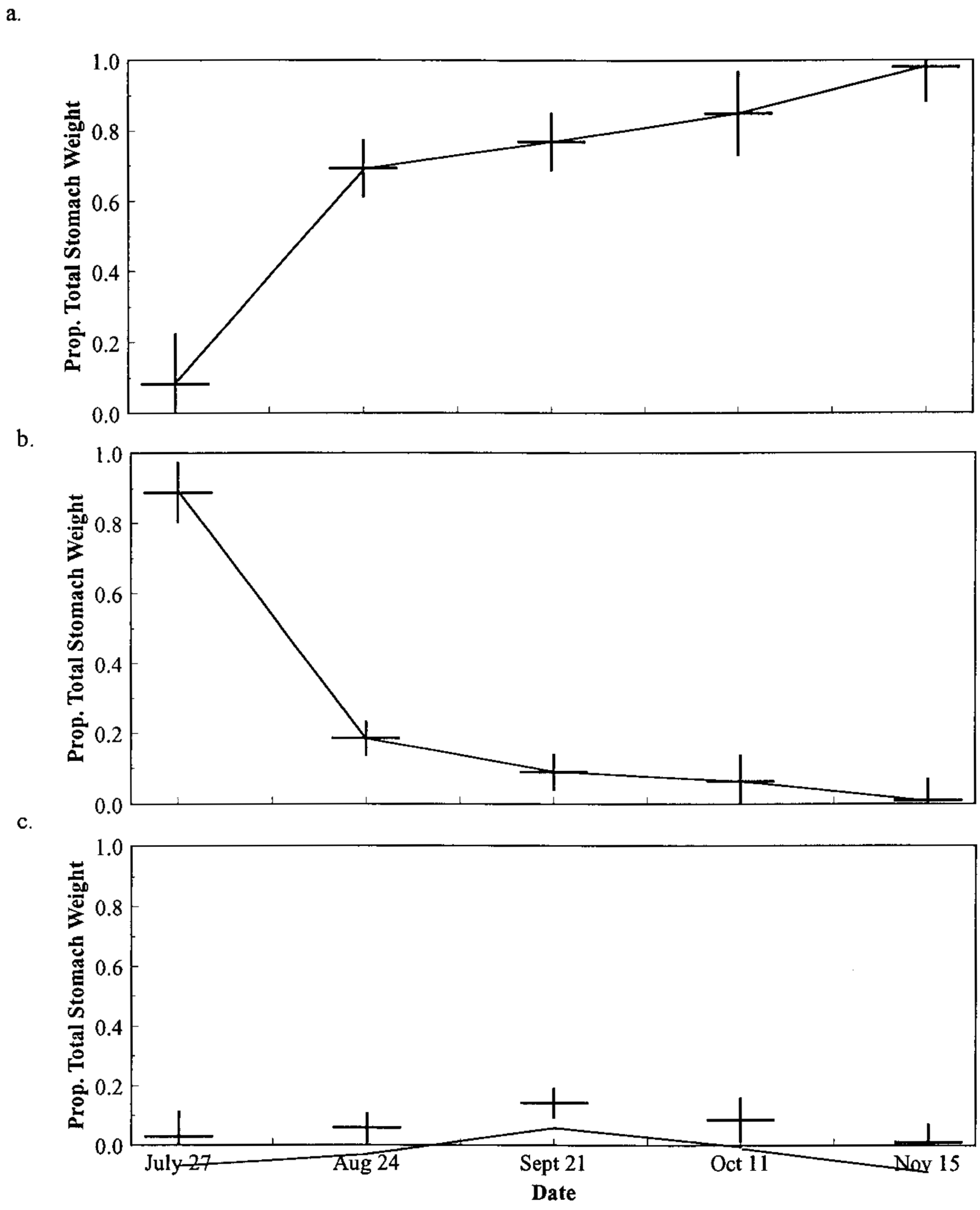


Figure 10: Mean proportion of sockeye salmon fry total stomach contents weight comprised of (a) *Cyclops spp.*, (b) *Chydorinae spp.*, and (c) *Bosmina spp.* Vertical bars indicate the standard error of the mean.

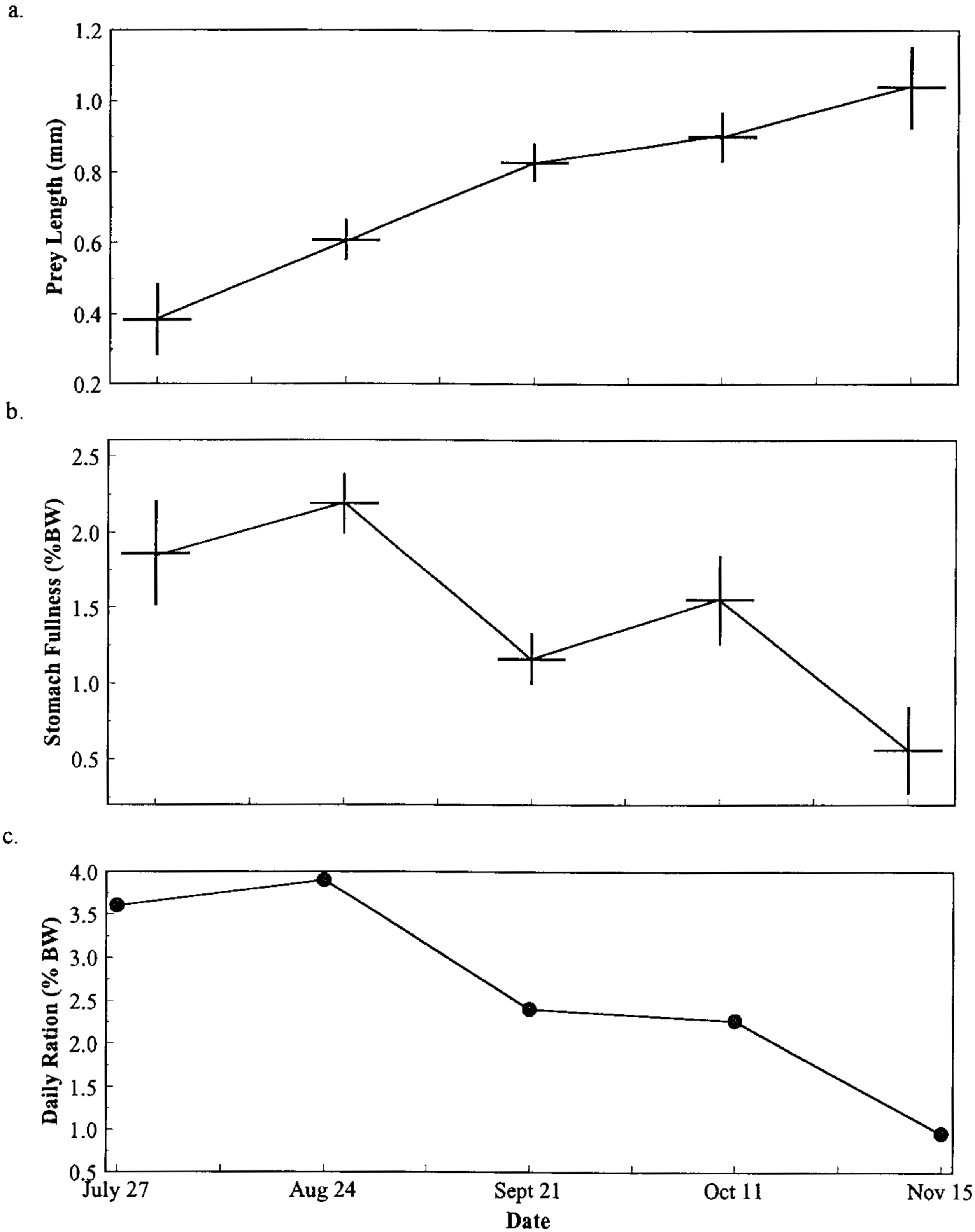


Figure 11: Mean (a) prey length and (b) stomach fullness, and (c) daily ration of sockeye salmon fry in Coghill Lake, 1993. Vertical bars indicate the standard error of the mean.

Appendix I: Summary of water quality parameters for Coghill Lake, 1986-1993 and results from multiple comparisons tests for differences in zooplankton density and biomass among years.

Table 1: Seasonal mean euphotic zone depth (EZD), turbidity (NTU), total phosphorus (TP), turbidity corrected total phosphorus (NTP), and chlorophyll a (Chla) for stations A and B combined in Coghill Lake, 1986 - 1993.

Variable	Year	Mean	S.E.
EZD	1986	8.6	1.300
	1988	9.6	
	1989	7.3	
	1990	5.4	
	1991	9.3	
	1992	11.3	
	1993	6.6	
NTU	1986	3.88	0.557
	1988	3.50	
	1989	9.60	
	1990	4.95	
	1991	2.63	
	1992	2.10	
	1993	7.06	
TP($\mu g\ L^{-1}$)	1986	8.06	0.496
	1988	6.34	
	1989	11.42	
	1990	7.49	
	1991	7.63	
	1992	7.31	
	1993	10.14	
NTP($\mu g\ L^{-1}$)	1986	7.16	0.373
	1988	5.88	
	1989	8.37	
	1990	6.07	
	1991	7.63	
	1992	7.31	
	1993	7.91	

Table 1: continued.

Variable	Year	Mean	S.E.
Chl*a*(μg L^{-1})	1986	0.30	0.175
	1988	0.24	
	1989	0.52	
	1990	0.84	
	1991	0.61	
	1992	0.70	
	1993	1.55	

Table 2: Type III probabilities (P) for multiple comparison tests for differences in mean density of *Cyclops spp.* among years.

	Year			
Year	1989	1990	1991	1993
1988	0.001	0.001	0.001	0.001
1989		0.134	0.055	0.019
1990			0.008	0.003
1991				0.396

Table 3: Type III probabilities (P) for multiple comparison tests for differences in mean density of *Daphnia spp.* among years.

	Year			
Year	1989	1990	1991	1993
1988	0.043	0.006	0.007	0.006
1989		0.113	0.149	0.113
1990			0.835	0.999
1991				0.835

Table 4: Type III probabilities (P) for multiple comparison tests for differences in mean biomass of *Cyclops spp.* among years.

Year	Year 1989	1990	1991	1993
1988	0.001	0.001	0.002	0.010
1989		0.465	0.365	0.048
1990			0.134	0.019
1991				0.169

Table 5: Type III probabilities (P) for multiple comparison tests for differences in mean biomass of *Daphnia spp.* among years.

Year	Year 1989	1990	1991	1993
1988	0.112	0.025	0.025	0.025
1989		0.268	0.268	0.268
1990			0.999	0.999
1991				0.999

Appendix II: Summary of sockeye fry and smolt data for Coghill Lake, 1989-1993.

Table 1: Summary of catch species composition (%) of tow net catches in Coghill Lake, 1989-1993.

Month/ Year	n	Slimy Sculpin	Sockeye Salmon	Coho Salmon	Dolly Varden	3-Spine Stickleback
10/89	21	5	62	0	5	29
8/90	97	0	100	0	0	0
10/91	44	0	100	0	0	0
10/92	108	0	100	0	0	2
7/93	144	0	71	14	2	12
8/93	199	0	98	0	0	2
9/93	194	1	86	0	1	12
10/93	44	0	93	0	5	2
11/93	130	10	81	0	0	9

Table 2: Summary of smolt population estimates from mark-recapture experiments, 1989-1994.

Year	Obs.	Sockeye Count	No. Marked	No. Recaptured	Trap Efficiency	Estimated Population
1989	1	255,407	1,000	664	0.664	374,376
1990	1	3,653	360	71	0.197	18,632
1991	1	2,153	60	5	0.083	30,294
	2	1,488	300	66	0.220	6,762
	3	1,531	150	35	0.233	6,551
	4	3,339	100	12	0.120	29,828
	5	2,778	200	8	0.040	77,690
	6	1,276	200	21	0.105	12,583
1993	1	13,526	256	106	0.414	31,196
	2	62,773	250	61	0.244	258,415

Table 3: Type III probabilities (P) for multiple comparison tests for differences in length-adjusted weight (condition) of sockeye smolt among years.

Year	Year: 1989	1990	1991	1993
1989		0.001	0.001	0.001
1990			0.001	0.001
1991				0.315

Table 4: Type III probabilities (P) for multiple comparison tests for differences in mean length of age 1 sockeye smolt among years.

Year	Year: 1989	1990	1991	1993
1989		0.002	0.001	0.001
1990			0.168	0.420
1991				0.004

Table 5: Type III probabilities (P) for multiple comparison tests for differences in mean weight of age 1 sockeye smolt among years.

Year	Year: 1989	1990	1991	1993
1989		0.001	0.001	0.001
1990			0.329	0.159
1991				0.003

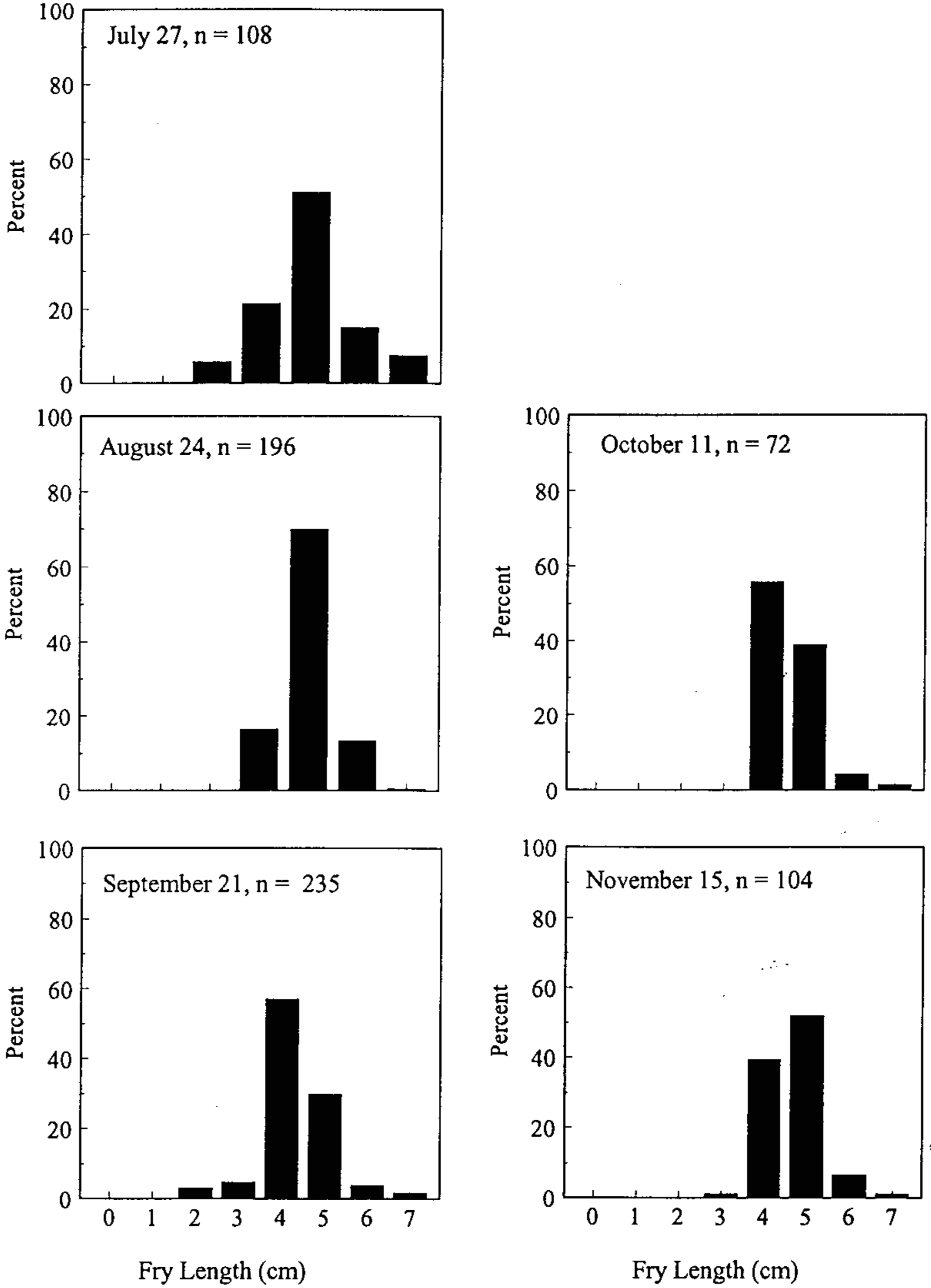


Figure 1: Length-frequency distributions for sockeye salmon fry sampled at Coghill Lake, 1993.

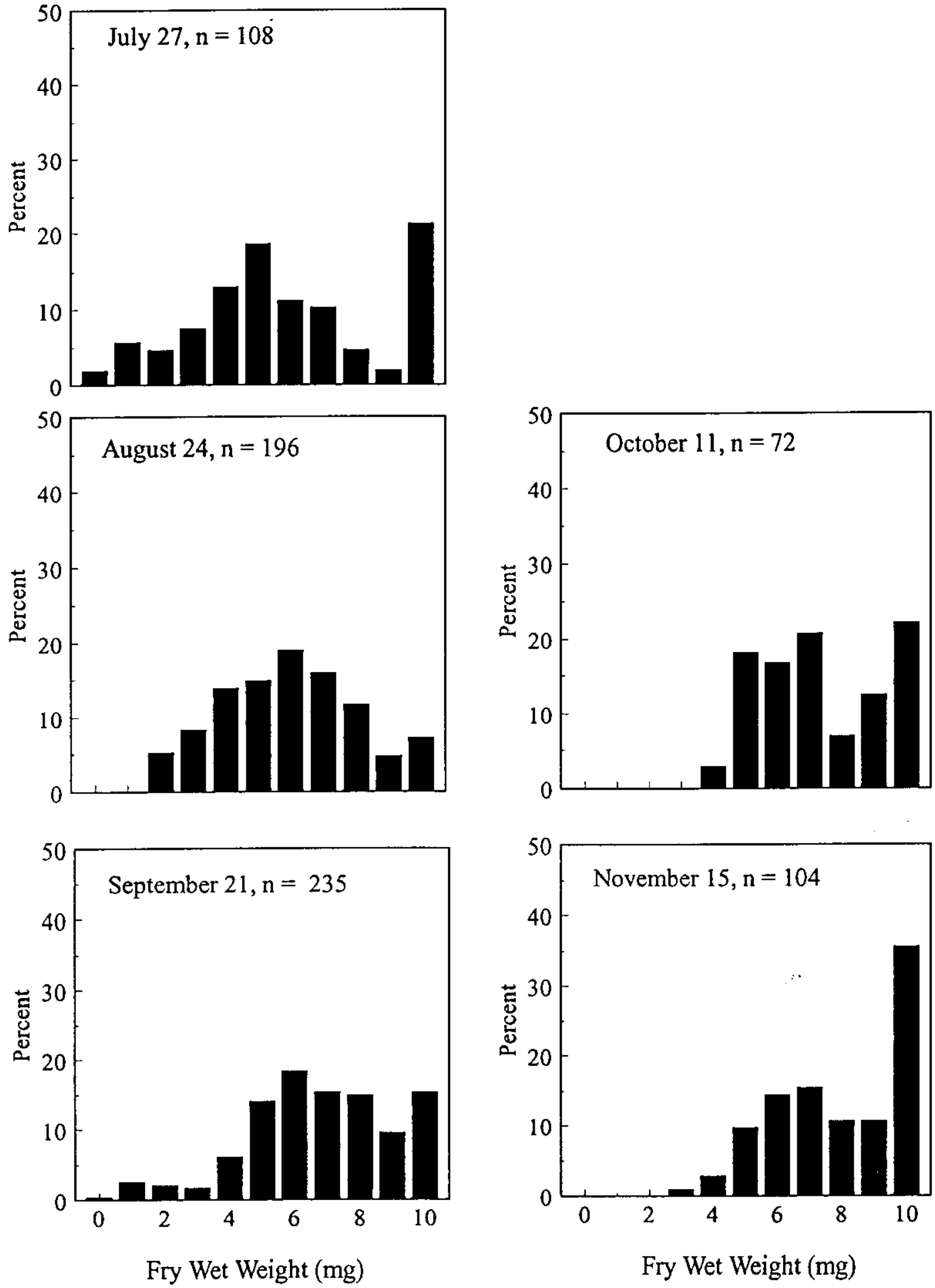


Figure 2: Frequency distributions of body weights of sockeye salmon fry sampled at Coghill Lake, 1993.

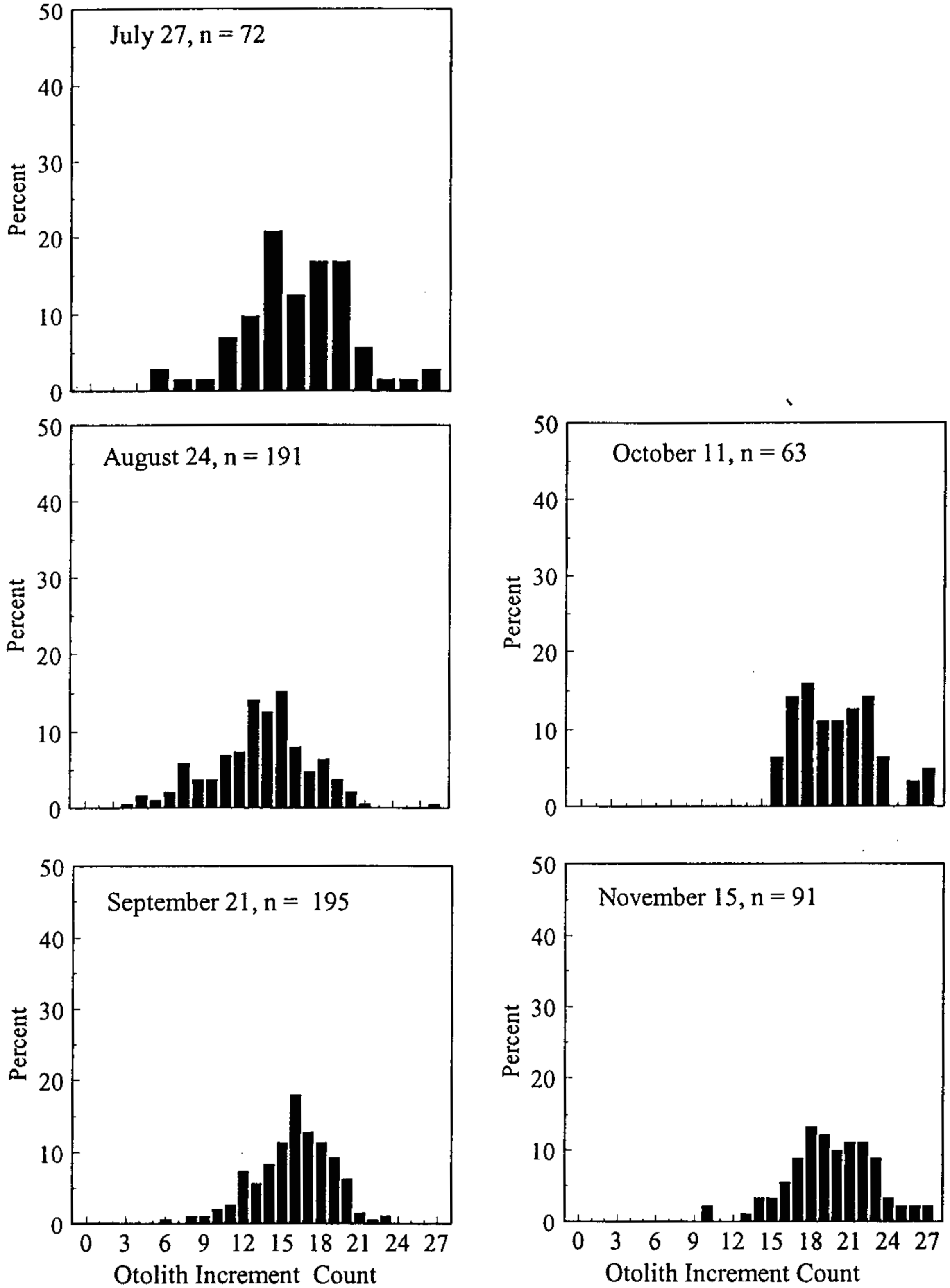


Figure 3: Frequency distributions of otolith increment counts for sockeye salmon fry sampled at Coghill Lake, 1993.

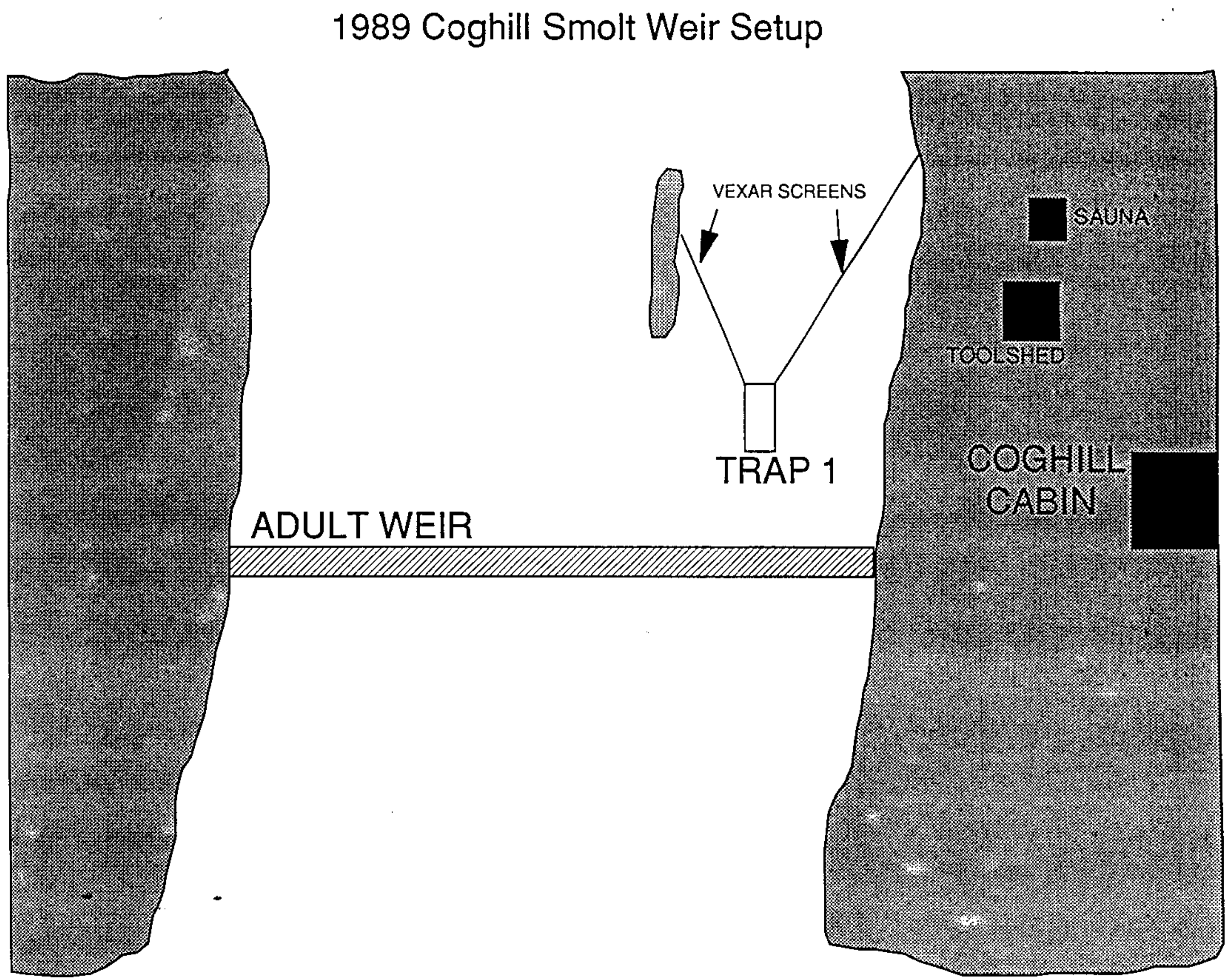


Figure 4: Smolt trap configuration at Coghill River, 1989.

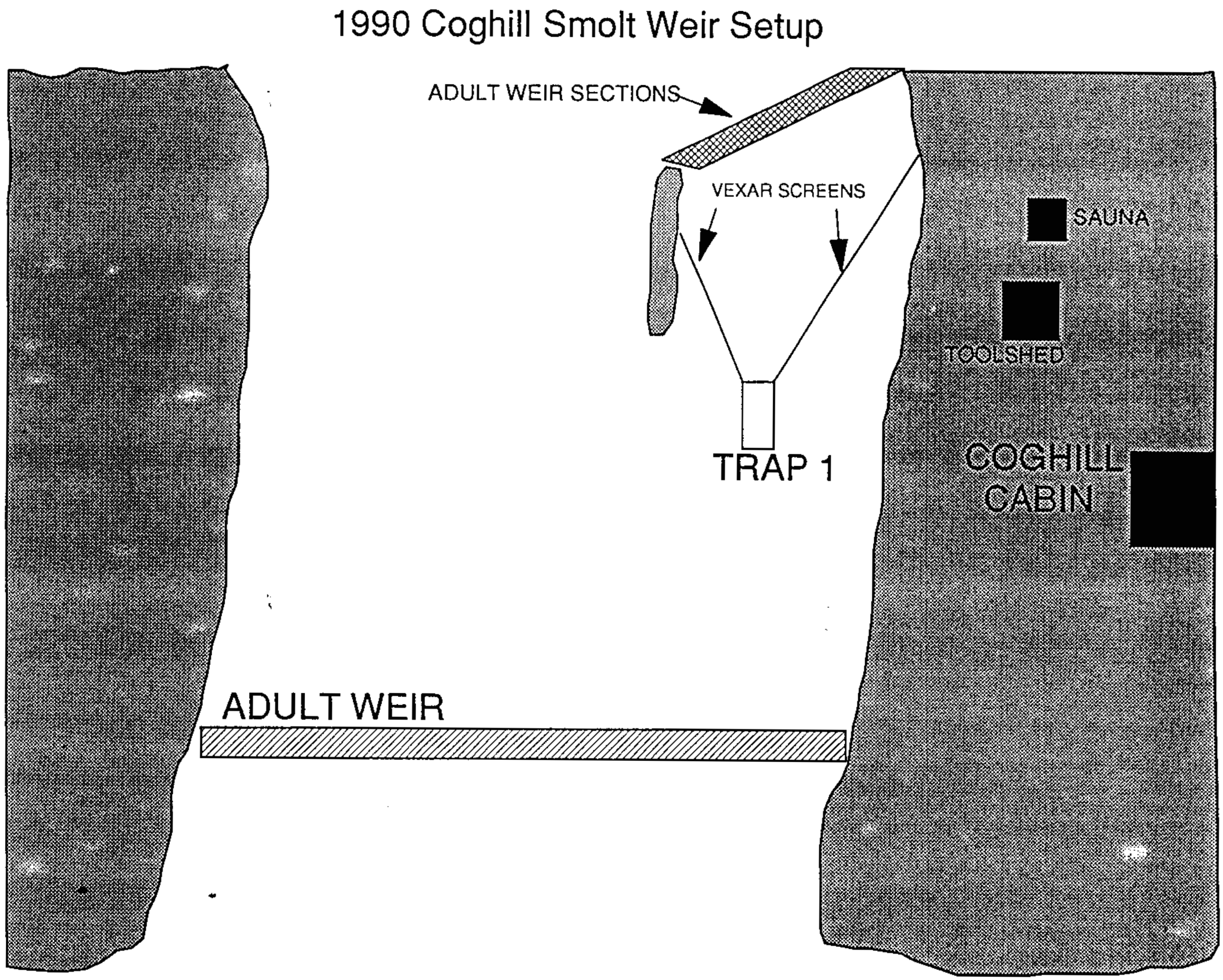


Figure 5: Smolt trap configuration at Coghill River, 1990.

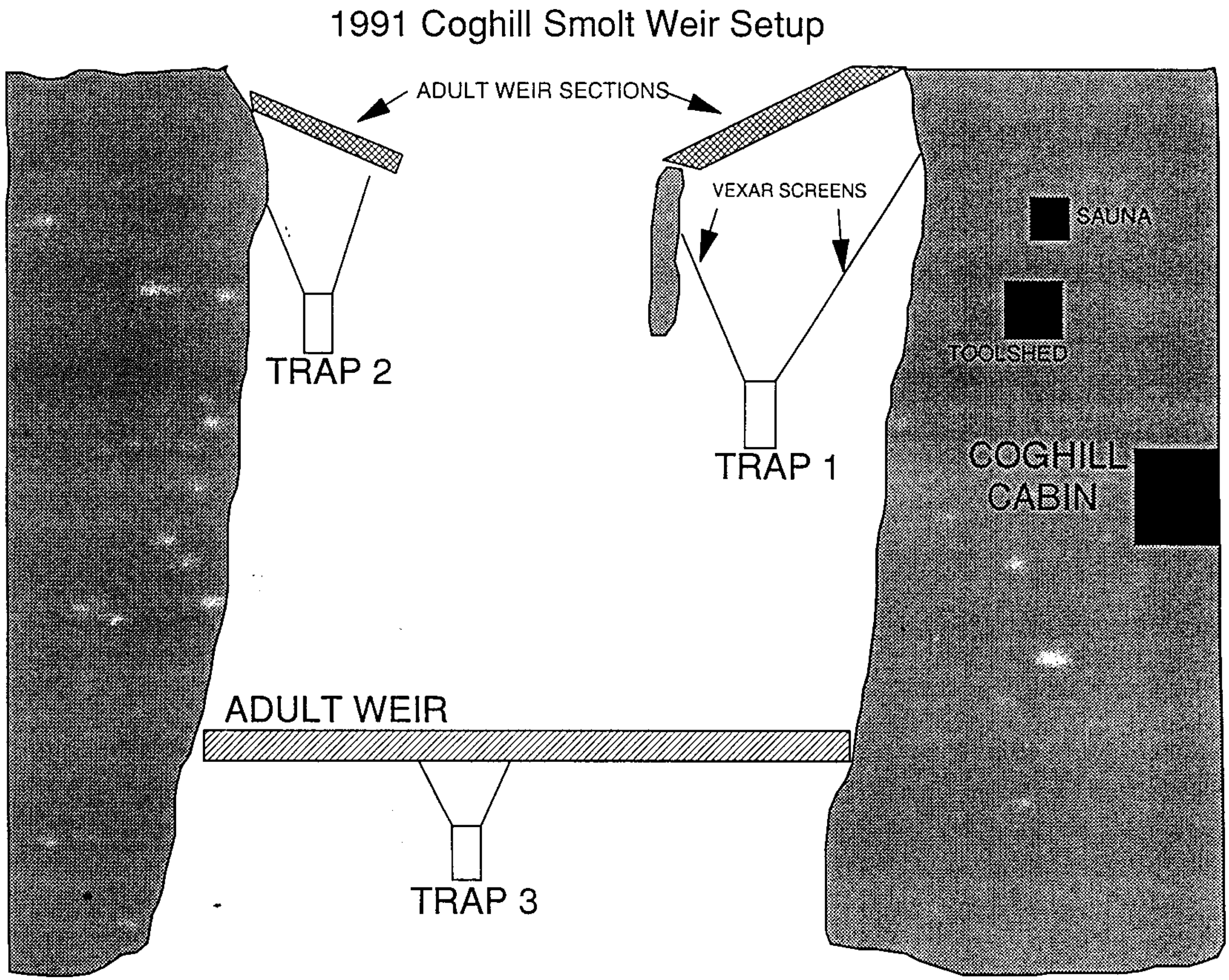


Figure 6: Smolt trap configuration at Coghill River, 1991.

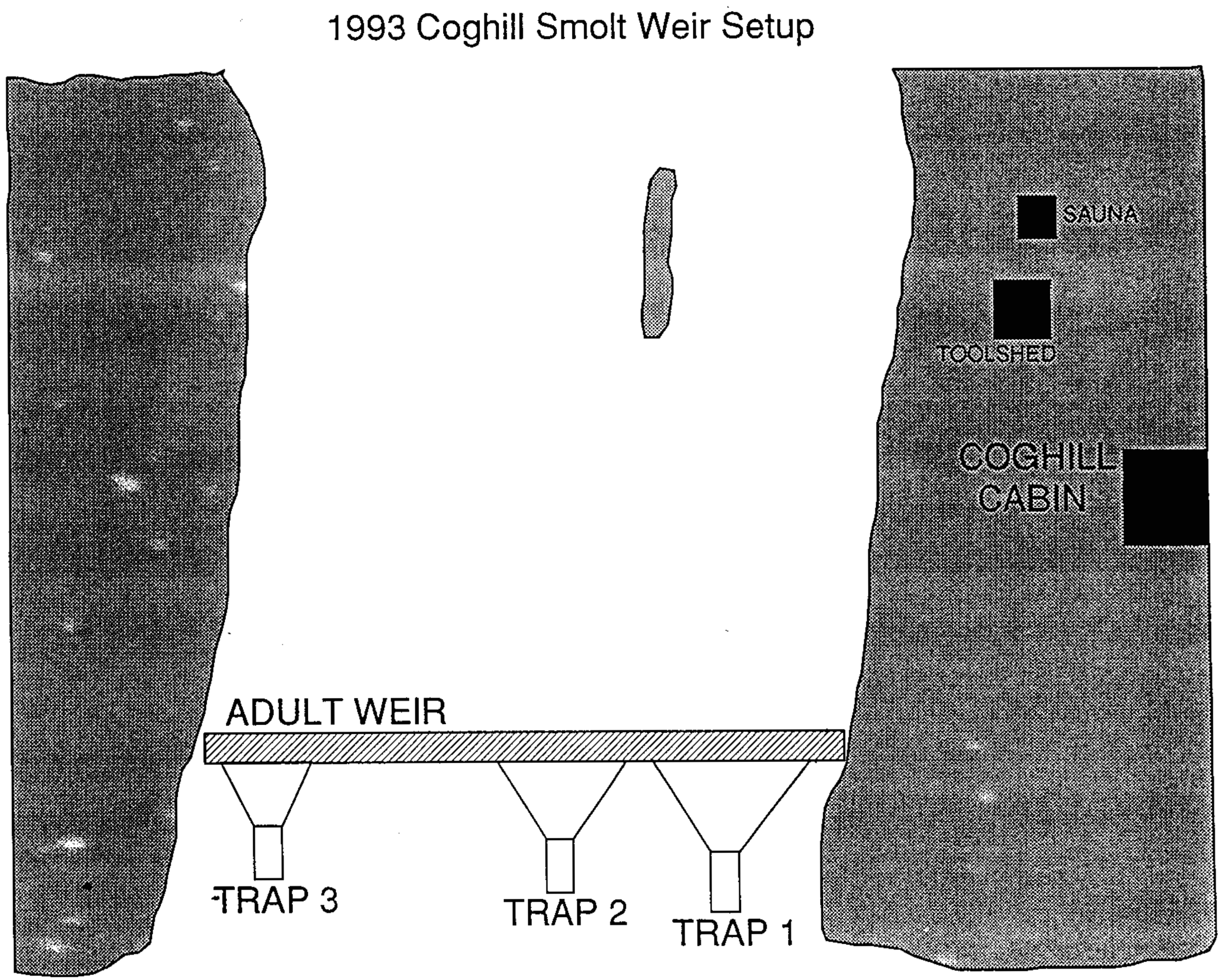


Figure 7: Smolt trap configuration at Coghill River, 1993.

Appendix III:

Acoustic assessment of juvenile sockeye salmon abundance and distribution in Coghill Lake, Fall 1993, Prince William Sound, Alaska

G.L. Thomas, Jay Kirsch and Becki Shipman[1]

ABSTRACT

Acoustic surveys were conducted in Coghill Lake in 1993 to estimate the population of juvenile sockeye salmon. A stratified-random survey design was used to allocate acoustic transects throughout the lake. A 120 kHz BioSonics 101 dual beam scientific echosounder was used to acquire fish echoes. Duration-in-beam echo counting and BioSonics echo signal processing (ESP) software were used to estimate fish density. Interactive Data Language (IDL) was used to analyze fish distribution, target strengths and population size parameters. The fish showed a strong preference for the surface on all surveys which could have resulted in underestimation of the fish population with the downlooking transducer. This deployment required that the fish density 0-2 meter interval be estimated by either the regression of fish density by depth or by simply extrapolating the fish density in the 2-5 meter interval to the surface. With 47-75% of the fish being observed in the 2-5 m interval, the latter, more conservative extrapolation was used to estimate population numbers. Uplooking data needs to be collected in the future to correct this bias. The population in July, September and October was $2.33(10^6) \pm 3,47(10^5)$, $3.45(10^6) \pm 1.51(10^5)$ and $6.54(10^5) \pm 7.82(10^4)$, respectively. Although the lake population is predominantly sockeye fry, these numbers still need to be portioned into species or size classes with the tow net catch information.

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Acoustic assessment of juvenile sockeye salmon abundance and distribution in Coghill Lake, Fall 1993, Prince William Sound, Alaska

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INTRODUCTION

The Coghill Lake dilemma

Since 1975, Coghill Lake has supported an average total return of about 270,000 fish. Although the total return has been declining from over 600,000 in 1987, to about 150,000 in 1988-89, the total returns collapsed to about a third of the previously recorded low of 21-25,000 in 1990-1991. The cause for this collapse is unknown but it was subsequent to the EXXON VALDEZ oil spill. The Trustee Council of the EXXON VALDEZ oil spill settlement has funded recent research on Coghill Lake as part of its fisheries restoration program. The rehabilitation or restoration of the Coghill sockeye salmon is important to the economy of Prince William Sound. Historically, it represents an average catch of about 194,000 fish worth several million dollars a year. The U.S. Forest Service (USFS) and Alaska Department of Fish and Game (ADF&G) are cooperating on a lake fertilization project to enhance sockeye salmon production in Coghill Lake, Alaska.

Fertilization of northern temperate oligotrophic lakes to enhance fish production has been successful in the past, especially for sockeye salmon *Oncorhynchus nerka* (Hyatt and Stockner 1985; Koenings and Burkett 1987). The Alaska Department of Fish and Game (ADF&G) has conducted extensive analysis of 23 sockeye salmon nursery lakes to identify where nutrients may limit the productivity of the stock (Edmonson et al. 1992). As a result, ADF&G presently fertilizes several lakes representing over 8900 hectares per year.

In coastal sockeye nursery lakes, the effects of fertilization have been shown to almost immediately enhance cyanobacteria (pico- and nanoplankton) production, which is subsequently consumed by zooplankton, primarily cladocerans (Stockner 1987). Stockner (1987) concludes that the successful fertilization projects occurred where increases in lower trophic level production were efficiently converted to zooplankton forage available to juvenile sockeye. However, he also pointed out that glacial lakes may be an exception because their primary production appears to be constrained by high turbidity and low temperatures. Given that Coghill is coastal, glacial and meromictic, it could be classified as being severely ultraoliogotrophic, which makes it more difficult to predict the effects of fertilization.

Measuring the effects of fertilization in Coghill Lake

Sockeye juveniles can rear in freshwater up to two years before reaching the minimum size for outmigration (Koenings and Burkett 1987). For this reason, shifts from age 1 to age 2 smolts in system are often as an indicator limited food in the nursery lake. This is not the case in Coghill Lake where the average age at smolt outmigration is after one year of freshwater rearing (Edmondson et al. 1992). Since the sockeye rear in the lake for at least one year, the fastest measure of the anticipated increase in fish production due to fertilization will be through monitoring the pre-smolt population rearing in the lake (Thomas 1981). Hydroacoustic assessment of pre-smolt population estimation technology was developed by the Fisheries Research Institute at Tustumena Lake in the early 1980's (Thorne and Thomas 1981a, 1981b, 1982, 1983, 1984; Thomas and Thorne 1988). These techniques have allowed

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for the determination of pre-smolt distributions and abundance in lakes so that seasonal and annual estimates of mortality and response to management programs (hatchery supplementation, habitat restoration, and fertilization) could be evaluated without waiting two years for all the smolts to outmigrate or up to six years for all the adults to return.

Program purpose, goals, objectives and tasks

The goal of this research is to develop a better understanding of the processes that influence production of sockeye salmon in Coghill Lake. The purpose is to rehabilitate the currently depressed sockeye salmon stock so that adult returns are similar to historical levels. This is an ongoing cooperative program between the USFS and ADF&G, which was recently joined by the Prince William Sound Science Center in 1993. The Center conducted hydroacoustic population assessments of juvenile sockeye salmon abundance distribution and behavior in Coghill Lake. A series of four pre-smolt assessment surveys were conducted in the lake (July, August, September and October) to examine fry distributions relative to lake conditions. These assessments provided estimates of oversummer mortality and fall pre-smolt biomass for evaluation of overwinter survival under ice cover.

METHODS

Study Site

The study site is Coghill Lake, Alaska, located in northern Prince William Sound. The lake lies at 61°4' north latitude, 147°54' west longitude, and approximately 130 km north of Cordova. It has an area of 12.7 km^2, volume of 587.5 * 10^6 m^3, maximum depth of 78 m and mean depth of 46.3 m (Edmundson et al. 1992). The area of the lake was estimated to be 14.4 million square meters by using a polygon filling algorithm on geo-referenced USGS contour data.

Equipment

The hydroacoustic equipment used consisted of a 120 kHz BioSonics 101 dual beam sonar system (101 echosounder, 111 chart recorder, 171 interface), a Tectronics oscilloscope, digital voltmeter and SONY DAT tape recorder. The transducer was a preamplified, dual beam design with nominal beam widths of 6 and 15 degrees. The transducer was towed just below the surface in a two-foot Braincon v-fin from a bow mounted boom. Data was stored on digital magnetic tapes and thermal chart paper. Oscilloscope and voltmeter measurements were recorded in the survey log book. A 1.5 m pito tube was used to measure boat speed.

Survey Design and data acquisition

The 1993 surveys were conducted during the darkest diel period at boat speeds of approximately 2 meters per second. Techniques of data collection were similar to those used at Tustumena Lake in the 1980's (Thorne and Thomas 1981b, 1982, 1983, 1984; Thomas and Thorne 1988). A reconnaissance survey in July suggested there were five areas in the lake where the fish concentrated. The lake was then divided into five strata for surveying purposes (Figure 1). In each strata, a series of random transects were run to collect acoustic data. An effort was made to place more transects in the higher density, nearshore strata to minimize variance (Cochran 1977).

A pulse width of 0.2 ms was used in July and August, and 0.4 ms in September and October. The pulse repetition rate was 0.3 seconds. The transmitter and receiver gains were set at 0 dB and 6 dB, respectively. An alpha of 0 was used to reflect the freshwater conditions, short range of the targets (0 to 30 meters), and frequency of the sounder (120 kHz). The August survey was recorded on tape without a sync pulse which made processing too labor intensive for this project.

Data analysis

Given that the fish densities were sufficiently low, echo counting techniques were employed (Thorne 1983). Numbers of echoes from fish were counted along transects and for nine depth intervals (2-5, 5-9, 9-14, 14-19, 19-24, 24-29, 29-34, 34-39 and 39+ m). The density in the 2-5 m interval was used to represent the 0-5 m depth interval since 0-2 m was not sampled with the downlooking deployed transducer. Taped data were processed using BioSonics Echo Signal Processor-Dual Beam (ESP-DB) software on a 486-66 laptop computer (Ehrenberg 1974, 1983; Traynor and Ehrenberg 1990), and duration-in-beam analysis (Crittenden et al. 1988; Croker 1972; Dawson 1972; Thorne 1988). Estimation and visualization were conducted using the Interactive Data Language (IDL) programming environment on a workstation. ESP-DB analysis was used to count fish targets and estimate their target strength. DIB analysis was similar to Tustumena lake studies performed by Thomas and Thorne (1988).

Population estimation

The echo counts and sampling volume measurements were used to calculate densities of fish in the various depth strata and increments along the transects. The weighted mean density of fish in a transect of a stratum was computed to determine the fish distribution along the long axis of the lake (length) and to estimate fish population size and variance (Seber 1973). The density of fish from 2-5 meters was extrapolated to the surface to account for the 0-2 meter strata that was not sampled with the down looking transducer (see discussion). The population estimates were calculated by extrapolation of the weighted mean density of fish per square meter in a strata by the surface area of the strata. The delta method (Seber 1973) was used to extrapolate the weighted variance to a population variance. The strata populations and variances were summed to provide lake population size and variance. Lake population variance and the number of transects were used to calculate 95% confidence limits for the population estimates.

RESULTS

Acoustic data was initially post-processed from digital tapes using ESP-DB software. Several problems were encountered with the ESP-DB results. The target strength numbers were erroneous due to the use of a 0.2 ms pulse length in July and August which was too short for proper digitizing by the DAT. Also, a failure to range gate the bottom signals caused mistriggering and made data processing difficult. The ESP-DB count data were erroneous because of the presence of false bottom, gas bubble and multiple targets in the data. Subsequently, the digital tapes were manually processed by duration-in-beam (DIB) analysis on a digital oscilloscope. The DIB analysis discovered the electronic malfunction in the 101 sounder which caused the bottom signals to be larger than the sync pulse. This malfunction exacerbated the ability to trigger the tapes properly for post processing, but was overcome by using a holdoff feature for triggering criteria on the scope.

ESP-DB data were edited and reanalyzed and compared with the DIB data. Reanalysis showed that the population trends in DIB and ESP data tracked on a relative basis, but the ESP was still providing unreasonably high absolute values (Figure 2). Thus, ESP data were used to display spatial information whereas DIB data were used to estimate population size. Both the target strength and the August population count data could have been recovered with additional manual processing but there was insufficient time to complete this task. Thus, this report was limited to presenting population distribution and estimation data from the July, September and October 1993 surveys.

The vertical distribution of fish density was higher near the surface on all surveys (Figures 3a,b,c). The horizontal distribution of fish density (fish/m^2 and fish/m^3) is presented in Figures 4a,b,c. Table 1 shows the fish density and length of transects in the five strata. Population estimates, with their 95% confidence limits, are presented in Table 2, Figure 5.

DISCUSSION

Estimation of the sockeye fry population using DIB analysis is the most robust, accurate, precise and least costly method that fisheries science has to estimate low densities of midwater fish (Thorne 1988). This procedure relies primarily on the target strength of the fish seen by the acoustics to estimate its sample volume. It is robust since counts are calibrated by the field measurements of actual fish target strengths. The accuracy of the population counts has been widely documented in the literature when compared with known populations of fish (Thorne 1983; 1988). The precision is evident by the low 95% confidence limits and a coefficient of variation of 31, 9 and 23%, for the July, September and October surveys respectively.

Even though 31% in relative error is considered exceptional for fishery assessments with traditional methods, this is extremely low precision for acoustic surveys. Historically, the juvenile sockeye distribution early in the year is more nearshore and surface oriented and more patchily distributed, therefore attributing to a lower precision estimate. However, there are other explanations for this on our July survey. First, the July survey used a 0.2 ms pulse length which may have caused some underestimation of fish targets. The target strengths of fish observed in July and August were shifted noticeably to the left suggesting a bandwidth limitation in recording. This can be avoided in the future by real time data processing or by using a longer pulse length. The effect of the 0.2 ms pulse is also shown in the reduced durations for targets. Thus, the sample volume of July survey was restricted to about 6 degrees in comparison to about 9 degrees in September and October (Figure 6). The 9 degree beam width is the expected value for DIB analysis, which is about 1.5 the nominal, narrow beam width of 6 degrees (Thorne, personal communication). The reduced sample volume of the cone in July is another explanation for the lower precision of the July population estimates.

Problems caused by the near boundary distribution of fish and the species apportionment of the acoustic targets require special attention. This report does not address the use of uplooking sonar data to estimate the potential bias that a strong nearsurface or nearshore preference by fish could have on the data (underestimation), nor does it use the relative composition of net catches or target strength information to apportion the fish targets by species and cohorts. Since corrections of these bias have been applied successfully at other sites (Thorne and Thomas 1984), this analysis is not complete. In addition, comparison of acoustic estimates with adult escapement, smolt and pre-smolt catch data, and past acoustic surveys will be important to improving the methods used to study Coghill Lake.

Estimation of fish densities in the lake during the year is valuable for evaluating the processes of mortality and making short term predictions. The development of real time, automated processes, for estimation using software such as ESP, is a goal that has not yet been achieved. This will require the development of a quality assurance-control (QA/QC) program that recognizes non-fish targets and excludes them from processing. The development of a QA/QC program is a pre-requisite for elevating a research to a management application. Since false targets have site specific dependencies (gas bubbles, depth, rapid change in depths, current velocities, buoy chains, trees and bottom debris, kelp and eel grass, etc.), the QA/QC programs are site specific. As we develop the counting software, manual DIB analysis techniques will continue to be used as the standard of comparison.

RECOMMENDATIONS

Analysis of the 1993 surveys showed that several improvements could be made in the monitoring of the sockeye fry. These are:

(1.) The acoustic assessment of target strength and DIB analysis require multiple detections per fish target. To get a maximum number of detections, the echosounder pulse repetition rate is increased. Unfortunately, at the bottom depths of Coghill Lake (60-80 m) the 120 Khz frequency echosounder produces a false bottom echo in the data at pulse repetition rates over 0.5 second. False bottom echos occur when the return from one pulse has not been received before a second pulse is received so a false target is recorded in the water column. The accepted way to collect data at faster rates than 0.5, which is desirable, is to use higher frequencies(200 or 420 kHz), that are absorbed sufficiently so the false bottom target is below the detection threshold for fish targets. In light of the magnitude of the false bottom problem created by using 120 kHz, the recent concerns by the Alaska Department of Fish and Game over attenuation of higher frequency sonars (420 kHz specifically), are unwarranted at Coghill Lake.

(2.) ESP-DB is not ready for use as an automated echocounter, therefore DIB analysis will remain as the standard of comparison.

(3.) Vertical distribution suggested that the uplooking sonar needs to be deployed to estimate the potential bias due to nearsurface (0-5 meter) distribution of fish. Also, the counting procedures need to take into account the starting depth of the TVG since prior to that depth amplification can be several dB higher than the calculated threshold.

(4.) Sub-monimolimnion targets are a source of error, so dissolved oxygen profiles of the water column should be made for every survey to define the depth of the chemocline.

(5.) Analysis of the net catch data from the lake, the outlet, and adult escapement needs to be integrated into these results.

(6.) Target strength data need to be used to assist in the segregation of juvenile sockeye from other fish targets and to establish uniform target counting criteria.

(7.) Surveys need to be unstratified and repeated at least one time each trip.

(8.) A QA/QC program needs to be developed for Coghill Lake acoustic surveys.

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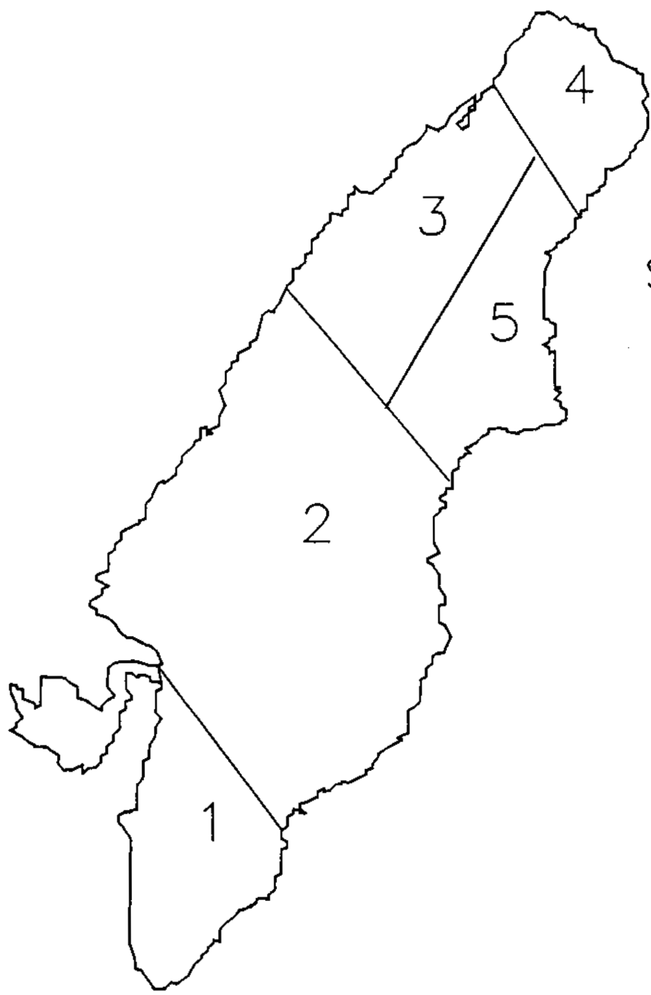

Strata Area, m^2
1980000
6980000
2400000
1120000
1910000
14390000

Figure 1. Strata definitions. The lake population has been split into one offshore and four nearshore strata.

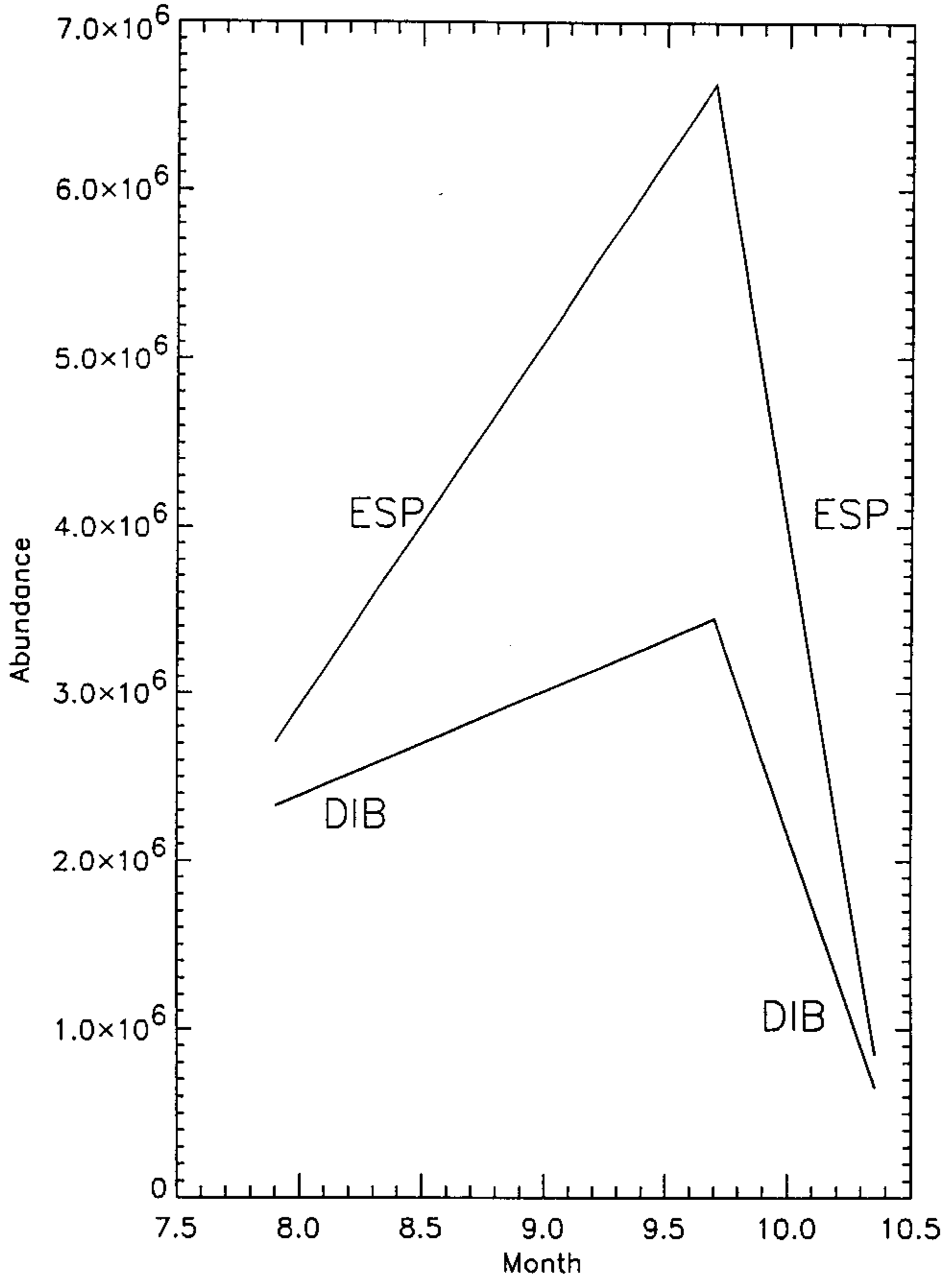

Figure 2. A comparison of Echo Signal Processor (ESP) and Duration–in–beam (DIB) techniques. ESP is more susceptible to false targets.

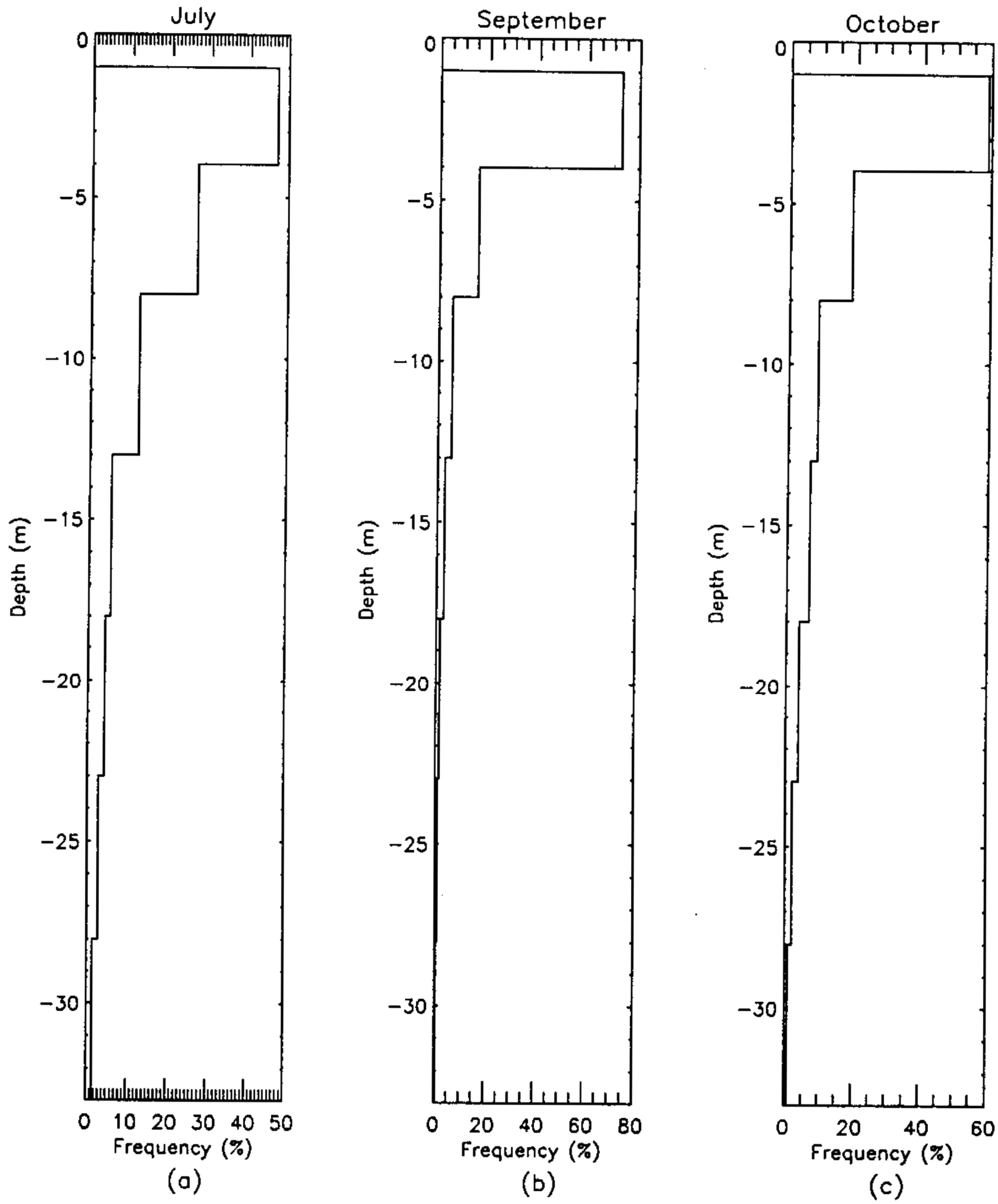

Figure 3. Vertical distribution of targets. Fish are concentrated at the surface, especially in September.

Figure 4. Horizontal distribution of fish density.

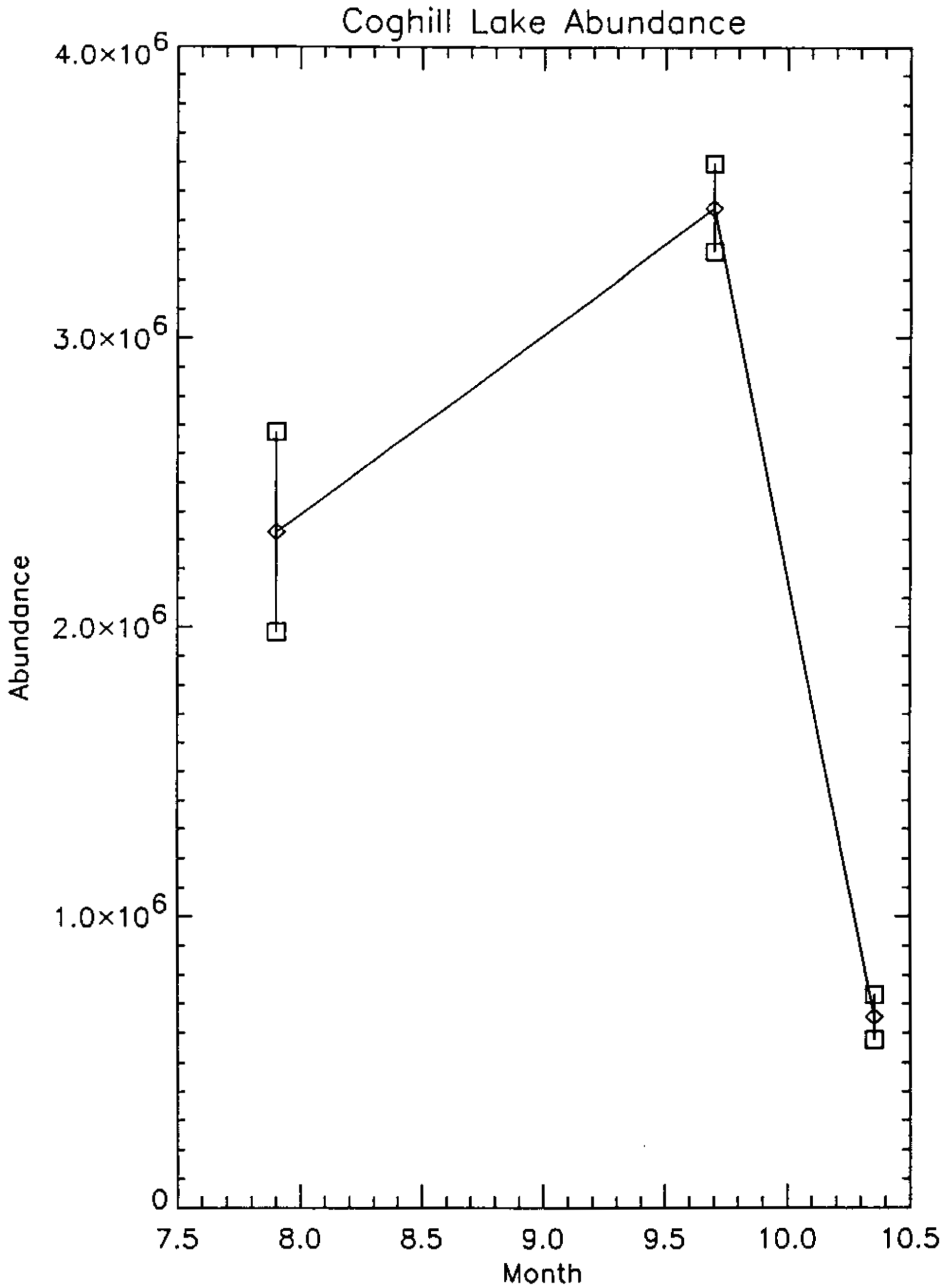

Figure 5. Fish abundance vs. month in 1993. Squares indicate 95% confidence intervals.

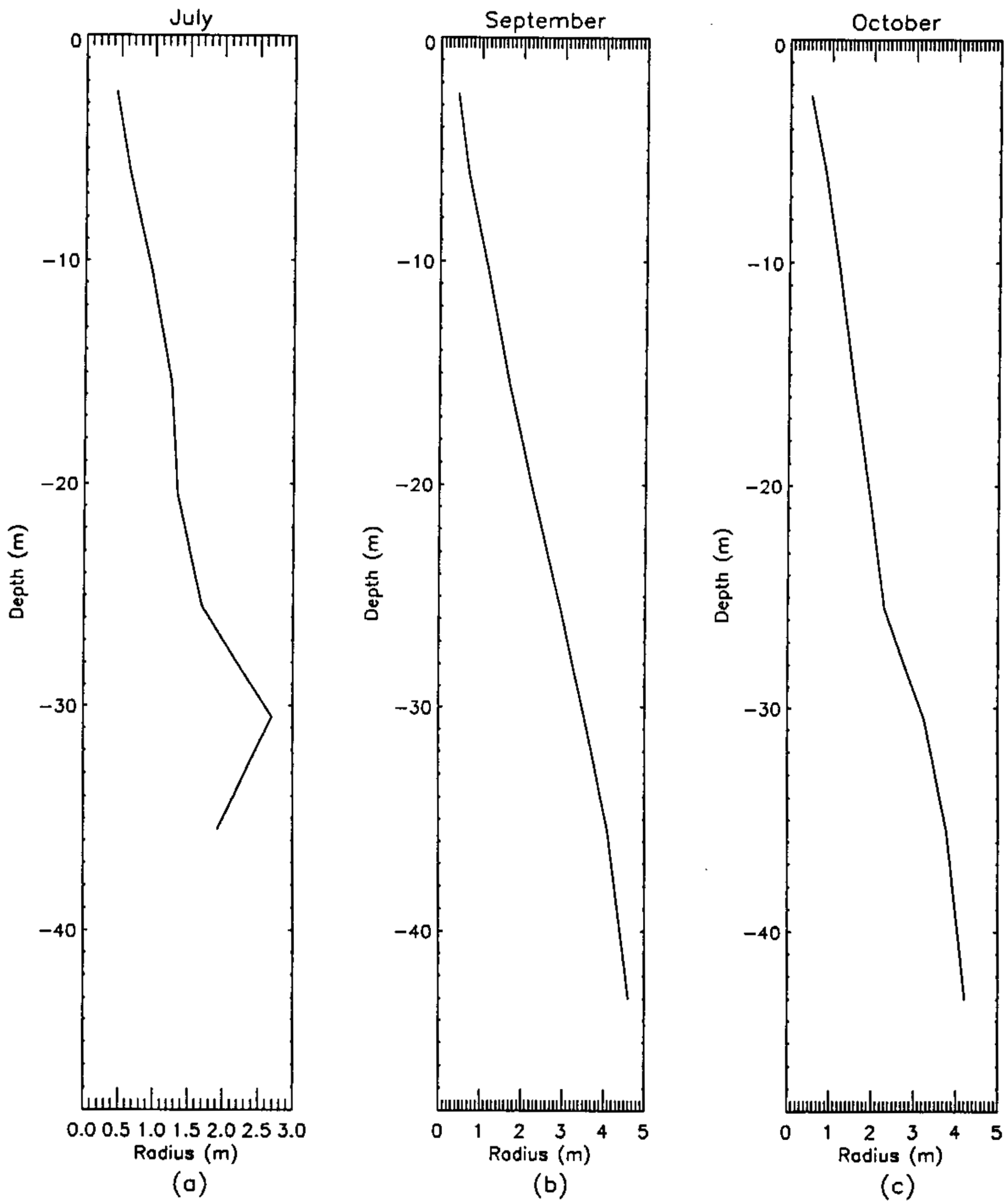

Figure 6. Sampled volumes vs. depth for each month in 1993. Cone radii determined by targets in beam. July incurred undersampling due to insufficient bandwidth for narrow pulse sampling.

Table I. Coghill Lake densities by transect. Page 1 of 2. Split transects indicate multiple strata. Weighted density means will yield strata densities in Table II. Densities are in fish per square meter.

Transect	Density	Length(m)	Strata
JUL			
1	1.40458	1281	1
2	0.454869	2486	1
3	0.148066	2822	1
4	0.0836019	5392	2
5	0.0604179	4982	2
6	0.173531	882	5
7	0.0647186	1008	5
8	0.113905	836	5
9	0.385662	1799	5
10	0.237998	1452	4
11	0.0416896	1323	4
12	0.0725129	1481	4
13	0.0496988	1311	4
14	0.0208947	1607	3
15	0.275355	1481	3
16	0.302579	270	3
17	0.248020	932	3
18	0.0811840	3686	3
19	0.0370594	2066	2
SEP			
1	0.291644	1255	1
2	0.422733	1681	1
3	0.502380	2524	1
4	0.426928	2662	1
5	0.284570	5237	2
6	0.143061	4698	2
7	0.205907	4210	2
8	0.293814	1980	3
8	0.154894	1980	5
9	0.279637	685	5
10	0.259079	2036	3
10	0.207058	2036	5
11	0.162705	959	3
12	0.136201	773	3
13	0.0783428	1369	5
14	0.102182	1373	5
15	0.353499	1507	3
15	0.118373	1005	5
16	0.257175	2593	4
17	0.0851048	1616	4
18	0.0743914	1373	4
19	0.156132	1290	4
20	0.168588	1126	4

Table I continued. Coghill Lake densities by transect. Page 2 of 2.

Transect	Density	Length(m)	Strata
OCT			
1	0.121349	1148	1
2	0.0491222	2174	1
3	0.0308200	2565	1
4	0.0649751	2853	1
5	0.0630543	3425	2
6	0.0239667	5103	2
7	0.0110894	6178	2
8	0.0367649	1143	3
9	0.0204130	1184	3
10	0.0825903	1346	4
11	0.0281542	1877	4
12	0.0527064	1638	4
13	0.0173307	1168	3
13	0.0259961	1168	5
14	0.00308882	1277	3
14	0.0844623	1915	5
15	0.126247	1067	5
16	0.439369	478	5
17	0.160477	1495	5

Table II. Coghill Lake densities by strata. A weighted mean of densities for transects within each strata was calculated, then multiplied by the lake surface area for that strata.

Month/ Strata	Strata Density	Density Variance	Strata Population	Population Variance
July				
1	0.508135	0.119391	1006106	4.68059e+11
2	0.0665889	0.000162156	464790	7.90033e+09
3	0.132074	0.00322985	316978	1.86039e+10
4	0.102987	0.00219015	115345	2.74733e+09
5	0.222603	0.00674410	425172	2.46032e+10
Total			2328391	5.21914e+11
			+/- 346890	
September				
1	0.428612	0.00163680	848652	6.41691e+09
2	0.214160	0.00177185	1494834	8.63251e+10
3	0.262345	0.00136488	629627	7.86173e+09
4	0.162267	0.00141411	181738	1.77386e+09
5	0.152255	0.000698019	290807	2.54644e+09
Total			3445658	1.04924e+11
			+/- 151090	
October				
1	0.0584154	0.000281952	115662	1.10537e+09
2	0.0276594	0.000218634	193062	1.06519e+10
3	0.0189405	4.82386e-05	45457	2.77854e+08
4	0.0515042	0.000243775	57684	3.05791e+08
5	0.126872	0.00301096	242326	1.09843e+10
Total			654191	2.33252e+10
			+/- 78158	