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ALASKA SALMON STUDIES

The Study of Red Salmon in the Nushagak District

by

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INTRODUCTION

The Fisheries Research Institute began investigations of sockeye (red) salmon in the Nushagak District of Bristol Bay in 1946 and by the end of the 1960s we had determined that the freshwater growth of juvenile sockeye played an important role in the ultimate production of adult sockeye salmon in the Wood River lake system. We conducted an experiment on the effects of lake fertilization on the growth and survival of juvenile sockeye salmon in Little Togiak Lake (Wood River system) during the 1970s and the results of our observations through the spring of 1980 were published by Rogers et al. (1982)¹.

Since we began many of our observations in Little Togiak Lake in 1973 and then began fertilizing in 1974 and ended in 1978, we had relatively few observations of some parameters during natural (unfertilized) conditions. Therefore, we continued our sampling in the lake through the summer of 1982 to obtain more data from natural conditions. In addition, in 1982 we still had adult salmon returns to come from the years of fertilization and could not reach a conclusion on the effects of the fertilization on the survival of juveniles to adults. Through 1982 we have nearly all of the adult returns, only age 2.3 from the 1977 brood year are yet to come.

The purpose of this report is to update the limnological, and juvenile fish data to determine whether the conclusions reached in 1980 with regard to the effects of fertilization are still valid and to evaluate the effect of the fertilizations on the abundance of returning adult sockeye salmon.

METHODS

The sampling methods employed after 1979 were essentially the same as those reported in Rogers et al. (1982) with the following exceptions. Limnological measurements in Little Togiak Lake were made every two weeks rather than weekly and terminated about September 10 rather than late September. Chlorophyll sampling extended down to 20 m rather than 45 m because there was little annual variation in chlorophyll densities below 20 m and the densities were relatively low below 20 m. The Lake Aleknagik insect traps were not used in 1980 until mid-July and no water chemistry measurements were made in Little Togiak Lake.

The smolt sampling in Little Togiak River began late in 1979 and 1981 relative to the beginning of the migrations in those years when ice breakup was early and only a few samples were collected in 1982 because we did not have a smolt project that year. The sampling of Arctic char

¹This report is appended for a description of the fertilizations, detailed methods, and references.

in Little Togiak River was also reduced in 1981 and 1982. Most of the reduced sampling after 1979 was caused by reductions in funding and/or the personnel needs of other projects that we conducted in the Nushagak District.

The adult sockeye salmon returns to the individual lakes and spawning grounds in the Wood River system in 1982 (except Little Togiak Lake) were based on preliminary aerial survey counts obtained from Mr. Wesley Bucher (ADF&G). The escapements to Little Togiak lake from 1975 through 1982 were estimated from 30 minute counts out of each daylight hour (expanded to 24 hours and summed over days). The age composition in the escapement was determined from otoliths collected on the spawning beaches in Little Togiak Lake. Usually 100 male and 100 female otoliths were collected; however, in 1982 we only collected 50 male and 63 female otoliths because exceptionally high water in mid-September made it difficult to find the carcasses.

RESULTS

The emphasis in the presentation and discussion of the results will be on the observations collected over the past three years since results from earlier years are covered in Rogers et al. (1982).

Limnological Data

Physical Parameters. The mild winters that began in Bristol Bay with the winter of 1976-77 continued through the winter of 1981-82 although the 1981-82 winter was only a little warmer than normal (Fig. 1). The spring of 1981 was exceptionally warm, whereas both the spring and summer of 1982 were much colder than normal. Precipitation during the summer months was below normal from 1978 through 1981, but then exceptionally high in 1982, particularly in September (Fig. 2).

Water temperatures were exceptionally warm for June in 1981 and exceptionally cold for the summer in 1982 (Fig. 3, Tables 1 and 2). The 1982 average daily solar radiation for the summer was the lowest recorded since observations began in 1961. Lake levels were above normal in June, July, and September in 1982. The conductivity of the water in Little Togiak Lake declined somewhat after 1979 but the conductivity in Lake Aleknagik was low only in 1981. Water transparency (Secchi depth) was generally lower during the summers of 1980-82 in Lake Aleknagik but only in 1981-82 in Little Togiak Lake.

The changes in transparency generally correspond to the changes in phytoplankton (chlorophyll a) density; however, the water may also become turbid from heavy rainfall, as occurred in September 1973, August 1979, and in mid-September 1982, although no Secchi depths were measured then.

Phytoplankton

The standing crop of phytoplankton is largely determined by the rate of primary production and the rate of predation by zooplankton. We measured the concentration of chlorophyll a as an estimate of the relative standing crop of phytoplankton and in each of the years that we fertilized there was an increase in chlorophyll -- in the upper basin in August 1974 and 1975, and in both basins in July 1976-1978. The extent of the increase was generally proportional to the amount of fertilizer added and the standing stock of zooplankton (Fig. 4). During the summer of 1982 the chlorophyll concentrations in Little Togiak Lake during June and July were generally higher than occurred in any of the years of fertilization (Table 3). Only the high values in the upper basin in August 1974 and in both basins in late-July and early-August 1977 exceeded the concentrations in 1982 that occurred under natural conditions but with very low volumes of zooplankton.

Zooplankton

Following the last year of fertilization (1978), the abundances of the larger zooplankters (calanoid copepods, Daphnia and Holopedium declined in Little Togiak Lake (Figs. 5 and 6). Abundance of Cyclops was low only in 1982 and Eubosmina was low in 1980 and 1982. The rotifer Asplanchna was exceptionally abundant in mid-summer 1979 in Little Togiak Lake when Cyclops were also exceptionally abundant and this rotifer has increased in abundance in Lake Aleknagik since 1980. Asplanchna is the smallest zooplankter retained by our net and Holopedium is the largest.

Since 1974, the sockeye escapements to both Little Togiak Lake and Lake Aleknagik have generally increased and correspondingly, there has been a general decrease in the abundance of large zooplankters and a decrease in the average size (volume) of an individual zooplankter, particularly in early September (Fig. 7).

The abundances of calanoid copepods and Daphnia increased from late-August to early September in the years of fertilization in Little Togiak Lake, but either did not change or decreased during this period in the years following fertilization (1979-82). However, in 1981, the seasonal abundances of these zooplankters peaked earlier than normal because there was an early ice breakup and unusually warm temperatures that year.

Benthos

The abundances of emergent chironomids in the main basin of Little Togiak Lake (stations 3-5) were higher in 1977 and 1978 than in the years preceding fertilization and the catches were also higher relative to the catches in Lake Aleknagik in those years (Tables 4 and 5). However, there were also high catches in 1982 in Little Togiak Lake and they were about equal to the catches in Lake Aleknagik that year; so

there was little evidence that the fertilization caused an increase in chironomid abundance.

Benthic sampling did not begin until August 1974 and it was not until 1976 that consistent sampling depths (3, 5, 7 and 10 m) and times (six per year) became consistent. Therefore, the sampling in 1974 and 1975 was not directly comparable to the later years and we also began fertilizing the upper basin (west end) in 1974, so we had no pre-fertilization measurements there. The abundances of oligochaetes, snails and clams were lower in 1980-82 than in prior years but there were no significant changes in the abundances of chironomids (Fig. 8).

The east end of the lake was not fertilized until 1976 and there the abundances of benthic organisms began increasing in 1977 (Fig. 9). Chironomids and clams were most abundant in 1978 and oligochaetes in 1979 — one year after the last fertilization. Chironomids are the only benthic organisms commonly eaten by juvenile salmon and the abundant other small fishes (mainly threespine stickleback). Chironomids were typically more abundant at 3-5 m than 7-10 m at both locations and their abundance at 7-10 m did not change significantly from 1977 to 1981. Most of the predation on chironomids by the small fishes probably occurs at the shallower depths.

Summary

Little Togiak Lake was fertilized during 1974-1978; however, only the shallow upper basin was fertilized in August of 1974 and 1975, and there was no significant effect on the primary production in the main basin of the lake which contains about 72% of the lake surface area and 92% of the zooplankton. The main basin was fertilized in the last half of July during 1976-1978 and the lake averages for those years were compared to the averages for 1973-75, 1979-82, according to observations made prior to and after mid-July (Table 6).

Although ice breakup was later during the fertilized years than during the unfertilized years, there were no significant ($\alpha = .10$) differences in the means of the other physical parameters, except for Secchi depth during 7/16-9/1. In the unfertilized years the mean was 9.5 m (8.3, 10.7), whereas the mean for the fertilized years was 7.8 m, and in Lake Aleknagik the Secchi depth averaged 9.5 m for 1976-78 and 8.4 m for the other years. Thus, the fertilizations in the main basin of Little Togiak Lake significantly lowered the water transparency.

The mean amount of chlorophyll *a* in the upper 20 m was significantly higher during 7/16-9/1 in 1976-78 (39.0 mg/m^2) than in the other years when the average was 27.3 mg/m^2 (21.2, 33.4). There was no significant difference between the means for Lake Aleknagik and Little Togiak Lake during 6/20-7/15 in the unfertilized years and the mean for Lake Aleknagik in the fertilized years (24.9 mg/m^2) was lower than in the other years (26.8 mg/m^2). So the fertilizations increased the standing crop of phytoplankton in Little Togiak Lake during the mid-summers of

1976-78; however, in 1982, the concentration of chlorophyll under natural conditions was higher than the average for 1976-78.

Although there were no significant differences in the number or volume of zooplankton between the fertilized and unfertilized years during 7/16-9/1 in Little Togiak Lake, both were higher in the fertilized years, whereas they were lower during 6/20-7/15 in the fertilized years. In addition, zooplankton were significantly less abundant in Lake Aleknagik during 7/16-9/1, 1976-78 than in the same period in other years. So the fertilizations in Little Togiak Lake probably had some effect on the abundance of zooplankton prior to the first of September, but the greatest effect was most likely on the abundance after this time. Unfortunately, we had few observations on the abundance of zooplankton during September in unfertilized years.

The effects of fertilizations on benthic organisms, particularly chironomids, was unclear because sampling variability was quite high. There is a rather limited amount of mud bottom in Little Togiak Lake and chironomids are probably not as important as a source of food for juvenile sockeye salmon in this lake as they are in Lake Aleknagik.

During the years of our experiment in Little Togiak Lake (1973-1982), there were some significant changes from earlier years. Most notable were: 1) the warmer winters after 1976 and successive warm springs (1978-81); 2) the average concentrations of chlorophyll in Lake Aleknagik were significantly higher than in prior years (28.6 mg/m² vs. 19.4 mg/m², 1963-72) and Secchi depths were lower (8.7 m vs. 9.4 m); and 3) sockeye salmon runs and escapements were higher, thus there was more natural fertilization from carcasses.

Fish

The most difficult effects of lake fertilization to demonstrate are those on the growth and survival of fish, at least in large lakes. It is particularly difficult for sockeye salmon because they have both a littoral and limnetic phase in their freshwater life and then spend two to three years at sea where they are subjected to variable but largely unknown conditions. It is not unexpected that in other lake fertilization experiments with sockeye salmon, the weakest evaluations were the effects on the adult returns. Yet increasing the production of adults is the ultimate goal of lake fertilization.

Abundance and size of juveniles

Beach seine sampling was used to estimate the relative abundances and lengths of juvenile sockeye salmon and other small fishes in June and July and tow net sampling was employed to estimate relative abundances and lengths in late-August to early-September. Beach seine catches of sockeye fry were more closely correlated with the abundance of parent spawners than were tow net catches, but for both methods of sampling, there was a decline in sockeye fry catches relative to the

numbers of parent spawners between the 1960s and 1970s in Lake Aleknagik. This may mean that there has been a decline in the number of fry produced per parent spawner or a decline in the availability of fry to our sampling.

The sockeye fry usually move offshore in late July so we have used the average of the weekly geometric means of beach seine catches during June 25-July 18 as an estimate of their relative abundance (Fig. 10). The average annual catches of fry in Little Togiak Lake were correlated with the abundance of parent spawners through 1981 ($r=.75$, catch vs. ln escapement) but the very small catches in 1982 following a large escapement reduced the correlation to $.42$. The average fry catches in 1976-78 were high relative to the number of parent spawners and the catch in 1982 was exceptionally low.

In Lake Aleknagik the average catch of sockeye fry was more highly correlated with the abundance of parent spawners ($r=.82$, catch vs. ln escapement, 1973-82). The catches in 1976-78 were about as expected from the abundances of parent spawners but the catches in 1980 and 1982 were exceptionally low.

The fertilizations of Little Togiak Lake may have had some effect on the survival of fry but the effect was small if at all. The relative abundances of the other small fishes (except sculpins) did not change significantly after fertilization began. The annual average catches of sculpin from 1978 to 1987 (mean = 4, range = 2-6) was significantly lower than during 1973-77 (mean = 13, range = 8-18); however, sculpins were consistently less abundant than sockeye fry, threespine stickleback and Arctic char fry.

The growth of sockeye fry in Little Togiak Lake was of particular interest because an objective of fertilization is to increase the food supply and thus growth of the fish. Unfortunately, the growth rate of sockeye fry in Little Togiak Lake was difficult to determine during early summer (June-July) because small, recently emerged fry continue to be recruited into the population until the end of July. This does not typically occur in Lake Aleknagik where spawning is about one month earlier and occurs over a shorter period.

In Lake Aleknagik the growth of sockeye fry in June-July is largely determined by the water temperatures; for example, the mean lengths of fry on July 20 was significantly correlated with the average surface temperature from June 1 to July 20 ($r = .91$, $n = 13$). However, most of the summer growth of the fry occurs during August-September when they are in the limnetic zone and feeding on zooplankton. At this time their growth is inversely related to their density; for example, the growth rate (mm/day) from July 20 to September 1 was correlated with the ln of the number of parent spawners ($r = .93$, 1973-82).

The annual tow net catches and mean lengths of juvenile sockeye salmon in Little Togiak Lake are presented in Table 9 according to the

abundance of parent spawners. The tow net catches are quite variable and not closely related to the escapements, whereas the mean lengths are usually consistent among sampling areas within a year and are inversely related to the escapements. The annual mean lengths on September 1 were converted to mean weights based on a common weight-length regression and compared to the mean weights from Lake Aleknagik for the years since 1968 when we had annual estimates of zooplankton (Fig. 11).

The annual weights of the fry generally correspond to the annual volumes of zooplankton from mid-June to mid-August. The fry were significantly larger in Little Togiak Lake than in Lake Aleknagik only in 1979. In the early summer of 1979, there was a very high abundance of Cyclops in Little Togiak Lake that may have been caused by the fertilization in 1978 since there was not a high abundance of Cyclops in Lake Aleknagik in 1979 (Figs. 5 and 7).

The density of parent spawners (number per km² of lake surface area) for the sockeye fry during 1973-82 was higher in Little Togiak Lake in 6 years, equal for 1979, and higher in Lake Aleknagik for the fry in 1976 and 1977. The fertilizations in 1976-78 did not significantly affect the size of the sockeye fry on September 1; indeed, the fry in Little Togiak Lake in 1977 were much smaller than expected from the density of parent spawners (Fig. 12). Even though the correlations between size of fry and (1 n) density of parent spawners is not very good (Aleknagik, $r = -.68$ and Little Togiak, $r = -.52$; $n = 25$), the regression lines are nearly the same for spawner densities greater than 2,000 per km² which includes nearly all of the spawner densities in the two lakes since 1973.

Considering that the fertilizations did not greatly affect the abundance of zooplankton until the end of August, it was not unexpected that the early summer growth of the fry during the years of fertilization was unaffected and that the only year in which the fry in Little Togiak were significantly larger than those in Lake Aleknagik was in 1979 (a year after fertilization) when parent spawner densities in the two lakes were equal.

Abundance and Size of Smolts

By extrapolating the lengths of the fry in Lake Aleknagik beyond September 1 by the observed growth rates in August, the fry reached the mean lengths of age I smolts (in the following spring) at about mid to late-October. The average surface temperatures in the Wood River Lakes decline to 4°C about the end of October and below this temperature sockeye fry growth ceases.

We had annual estimates of the mean lengths of fry on September 1 from 1958 to 1982, but estimates of the sizes of smolts for only the 1959-67 and 1975-82 migrations from the lake system at the outlet of Lake Aleknagik. Some smolt sampling was conducted in Little Togiak River during the 1950s, in 1961, and then from 1973 to 1982 (Tables 8

and 9). Estimates of the number of smolts in the total migration were made only in 1961, 1976-78, and 1980.

The mean lengths of age I smolts from Little Togiak Lake were compared to the mean lengths of smolts in the migrations from the lake system (Fig. 13). In the three years following fertilization (1977-79), the mean lengths of the Little Togiak smolts were equal or longer than the lengths of the smolts from the lake system even though in the preceding summers, the fry in Little Togiak were equal or shorter than those in the lake system. The Little Togiak smolts were larger in the 1980 migration (but so were the fry in 1979) and they were shorter or equal in length in the 1981 and 1982 migrations when the fry in Little Togiak Lake were about the same length as those in the lake system. Similar comparisons for age II smolts and yearlings in the lakes were difficult to make because yearlings and age II smolts were usually not very abundant. They also tend to migrate earlier than age I smolts and we failed to obtain representative samples from the 1979-81 migrations.

The mean length of age I smolts from the first ten days of the migration from Lake Aleknagik was regressed on the mean length of fry in Lake Aleknagik the preceding year ($r = .92$, $n = 16$) and the observations from Little Togiak were compared to the Aleknagik data (Fig. 14). Fertilizer was first added to Little Togiak Lake in 1974 and the smolts migrating from the lake from 1975 through 1979 (following the last year of fertilization) were all larger than expected from the Aleknagik data.

Measurements of the weights of smolts from Little Togiak Lake were made each year except 1975 and 1982. An average weight-length regression was used to estimate the mean weight for 1975 and weight-length regressions from 1980-81 data were used to estimate the mean weight from the mean length in 1982. The annual mean weights of age I smolts were then plotted on the mean weights (constant weight-length regression) of fry on September 1 of the preceding year (Fig. 15)¹. The mean weights of the Little Togiak smolts in the 1976-79 migrations were all much heavier than expected from the size of the fry in Aleknagik or those from Little Togiak Lake in unfertilized years. Therefore, the fertilizations of Little Togiak Lake probably increased the growth of the sockeye fry during September-October. However, the extent of the increase cannot be determined accurately because not all of the fry measured about September 1 migrated to sea the following spring.

Predation on Smolts. Arctic char are the main predator on sockeye salmon smolts in the Wood River Lakes and we sampled the char in Little Togiak River during the smolt migrations to determine the incidence and average number of smolts per stomach (Table 10). If the fertilizations

¹There was no significant difference in the average size of the smolts between the first 10 days or the first 20 days. The first 20 days were used for weights to obtain a larger sample size, although for Aleknagik this meant including some smolts from the upper lakes.

enhanced the average size or condition of the smolts then presumably they would be better able to avoid their predators. However, predation by the char on smolts is likely to be affected by other factors as well, e.g., the sizes of the char, water temperature, water level or flow, and the temporal and spacial distribution of the smolt migrations.

Until 1980 the average number of smolts in char stomachs was higher in samples collected in the day (0800-1000 hr.) than at night (2200-2300 hr.). This was expected because char caught in the morning would have had the opportunity to feed both in the late evening and early morning of the typically nighttime smolt migrations. However, during the 1980-82 migrations the char collected at night contained more smolts than those collected in the morning. The 1980 migration was large and there was a considerable amount of daylight migration that year. We don't know the extent of daytime migration in 1982 because our sampling was very limited.

Although a number of factors can affect the consumption of smolts by the char, the fact that the incidence and average number of smolts in the char stomachs in the 1977-79 migrations was quite low relative to the other years would indicate that the fertilizations in 1976-78 probably had a positive effect on the survival of the smolts.

Adult Returns from Smolts

Statistics on the abundance of smolts and subsequent adult returns for the Wood River lake system and Little Togiak Lake are very limited (Table 11). All that we can conclude for Little Togiak Lake is that after fertilization began, the survival from smolts to adult returns was higher than in the one prior year (1961 migration, 1958-9 brood years) and that the survival for Little Togiak smolts was apparently higher than survivals for the lake system. However, it could be that we underestimated the number of smolts migrating from Little Togiak Lake even in years when our sampling began soon after ice breakup and continued into August.

The largest smolt migration estimated was in 1980 (primarily from the 1978 brood year) and the first returns from that migration were few (12,000) age 1.2 in 1982). The 1978 brood year also produced a relatively low number of age 1.2 adults in the lake system; however, there were almost as many age II smolts produced from that brood year. We should have a better evaluation of the effects of the fertilizations on smolt survival when the returns from the 1978 brood year are complete.

Adult Returns from Spawners. The escapements to Little Togiak Lake were estimated from aerial surveys (1946-82) and visual enumeration (1961, 1975-82). The aerial estimates on the average were within 14% of the enumeration estimates (annual range: 0-23%). The Little Togiak escapements lagged the Wood River escapements by an average of 4 days (range: 2-7 days) and the daily pattern of the escapements usually corresponded between the two locations. We thus assumed that adults

bound for Little Togiak Lake were equally represented throughout each year's escapement to the lake system and that they were subjected to the same rate of exploitation (by age and within a year) as adults bound for other spawning areas in the lake system.

Over 95% of the spawning in Little Togiak Lake usually occurs on beaches, mainly at the upper end of the lake. It was thus desirable to compare the runs and returns to Little Togiak Lake with other beach spawning populations or other lakes with predominant beach spawning. The aerial surveys provided annual estimates of the numbers of spawners on the spawning grounds in the lake system and the annual total escapements to the lake system were prorated to the types of spawning grounds and to the individual lakes. The surveys during 1946-49 were considered to be less accurate than those in more recent years and those brood years were not used in the following analyses.

Since 1950 Little Togiak Lake has received an average of 2.4% of the lake system escapements, whereas the lake contains 1.4% of the surface area in the system. From 1950 to 1976 the runs and escapements to Little Togiak Lake (prior to any possible fertilization effect) averaged about 6% (range: 2-18%) of the runs and escapements to the beach spawning areas of the lake system (Tables 12 and 13). Since 1977 they averaged about 11% (range: 4-18%) of the beach spawners in the system. Prior to 1977, the only years in which Little Togiak Lake contained more than 10% of the beach spawners in the system were years of very small runs to the lake beaches (1965 and 1973).

The sockeye salmon runs to all of the spawning areas in the Wood River Lakes increased in 1978 (Figs. 16-17, Tables 13-15). This increase in abundance was accompanied by a general increase in salmon abundance throughout western and central Alaska and appears to be related to improved ocean survival. For Bristol Bay sockeye salmon, the increase was first reflected in exceptional returns of age 1.3 (5_2) fish from the 1973 brood year which had a record low escapement, and strong returns of age 1.2 (4_2) fish from the 1974 escapements which were generally above average.

Simple Ricker-type spawner-return curves were fitted by regressing (\ln) return per spawner (escapement) on the number of spawners. Curves were fitted to the data from the 1950-74 brood years because the 1975-77 brood years were subjected to whole-lake fertilizations in Little Togiak Lake and we wanted to compare the observed returns from those brood years to the returns predicted from other largely unfertilized brood years (Fig. 16). Curves were then fitted that included the 1975-77 brood years to determine whether there was a significant change in the spawner-return relationship.

The returns to Little Togiak Lake from the 1975-77 brood years were all larger than any prior year; however, only the return from the 1977 brood year was significantly ($\alpha = .05$) greater than expected from the variability in R/S from past years. By including the 1975-77 brood

years (curve B, Fig. 16), the calculated optimum escapement for the lake was increased from 21,000 to 26,000.

The most dramatic change in the sockeye salmon runs to the Wood River lake system was in the runs to the large rivers (Agulowak, Agulukpak, and Wood). These river populations contain a high percentage of 3-ocean fish which have historically been subjected to higher rates of exploitation than the 2-ocean fish which are predominant in most beach and creek spawning populations (Fig. 17).

The returns from the 1975-77 brood years to the large rivers came from relatively large escapements and thus they greatly altered the spawner-return relationship (Fig. 18). The optimum escapement changed from 170,000 to 470,000 but this may well change after the returns from the 1978-82 escapements since these were considerably larger than prior escapements to the rivers.

The returns from the 1976-77 brood years to the beaches and creeks were above normal but did not alter the spawner-return curves. Only the return from the 1976 brood year to the creeks was exceptionally large but the $\ln R/S$ was not significantly different from past years ($\alpha=.05$).

The returns to the individual lakes in the system were plotted on the number of spawners and only in the lakes containing the large rivers (Aleknagik and North Nerka) did the returns from the 1975-77 brood years exceed all other years as was the case for Little Togiak Lake (Figs. 19 and 20). For the other lakes that contain primarily beach or creek spawners the returns from the 1975-77 brood years were the highest in Central Nerka into which Little Togiak Lake drains. For the spawning grounds in Central Nerka, the 1975-77 returns were highest in Little Togiak River and next highest in Pick Creek which is located a short distance from the river (Fig. 21). The returns to N4-N6 beach from these brood years were relatively poor and this beach is located about 4 miles from Little Togiak River.

The relative deviations (%) from the predicted returns from the 1975-77 brood years were all higher for Little Togiak Lake than for the other beach spawning populations and for two of the three years for the creek spawners (Table 16). The total returns from the 1975-77 brood years to Little Togiak Lake would have totaled 295,000 rather than 747,000 if the R/S observed for the other beach spawners was applied to Little Togiak Lake. Thus, the fertilizations of Little Togiak Lake may have increased the adult returns to the lake by as much as 452,000.

SUMMARY

Little Togiak Lake was fertilized during the summers 1974-1978 to enhance the growth and survival of juvenile sockeye salmon, and thus increase the numbers of returning adult salmon. Observations collected since the spring of 1980 generally substantiated our conclusions regarding the effects of fertilizations on primary and secondary pro-

ducers and the growth of juvenile sockeye. The standing crop of phytoplankton was increased in August while the abundance of zooplankton was increased in September and the growth of juvenile sockeye was increased in September-October. The smolts migrating from Little Togiak Lake following the years of fertilization were larger relative to their abundance and the sizes of smolts from the other lakes in the system.

The smolts from Little Togiak Lake appeared to have experienced higher marine survival than those from the rest of the lake system, but few observations on marine survival were available. The adult runs to the lake system have been exceptionally large since 1978; so, to evaluate the effects of the fertilizations, we compared the returns to Little Togiak Lake with the returns to other beach spawning populations. Each of the three brood years subjected to whole lake fertilization (1975-1977) produced relatively greater returns to Little Togiak Lake than to the other beach spawning areas and the increases were progressively greater from the 1975 to 1977 brood years. It may be that the fertilizations had some cumulative effect on the adult production from Little Togiak Lake, but this will not be determined until the returns from the 1978-79 brood years are completed.

Additional experimentation is needed, particularly on the effects of inshore rather than offshore fertilization and on the timing and schedules of applications. The Wood River lakes are ideally suited for such experiments because there is an extensive data base for the evaluation of effects. However, one of the assumptions in our evaluation of the effects on adult returns was that the various populations in the lake system were equally represented during the course of an annual run. Tagging experiments are needed to substantiate this assumption.

During the course of our analyses to determine the effects of the Little Togiak Lake fertilizations, some significant trends were discovered; e.g., the average annual standing crop of phytoplankton increased between the 1960s and 1970s, the relative abundance of sockeye salmon fry per adult spawner decreased, the growth of the fry increased relative to the abundance of spawners and the adult returns have increased. These phenomena need additional study because they may provide insight to the cause of the large returns of salmon to all of Western and Central Alaska since about 1978.

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We are particularly indebted to the ADF&G biologists at the Dillingham office--Mike Nelson, Jeff Skrade and Wes Bucher,--for their assistance in the field and for providing their data on smolts and adults soon after the field season. Dr. John Clark (ADF&G, Juneau) was very supportive and also provided critical review of our work.

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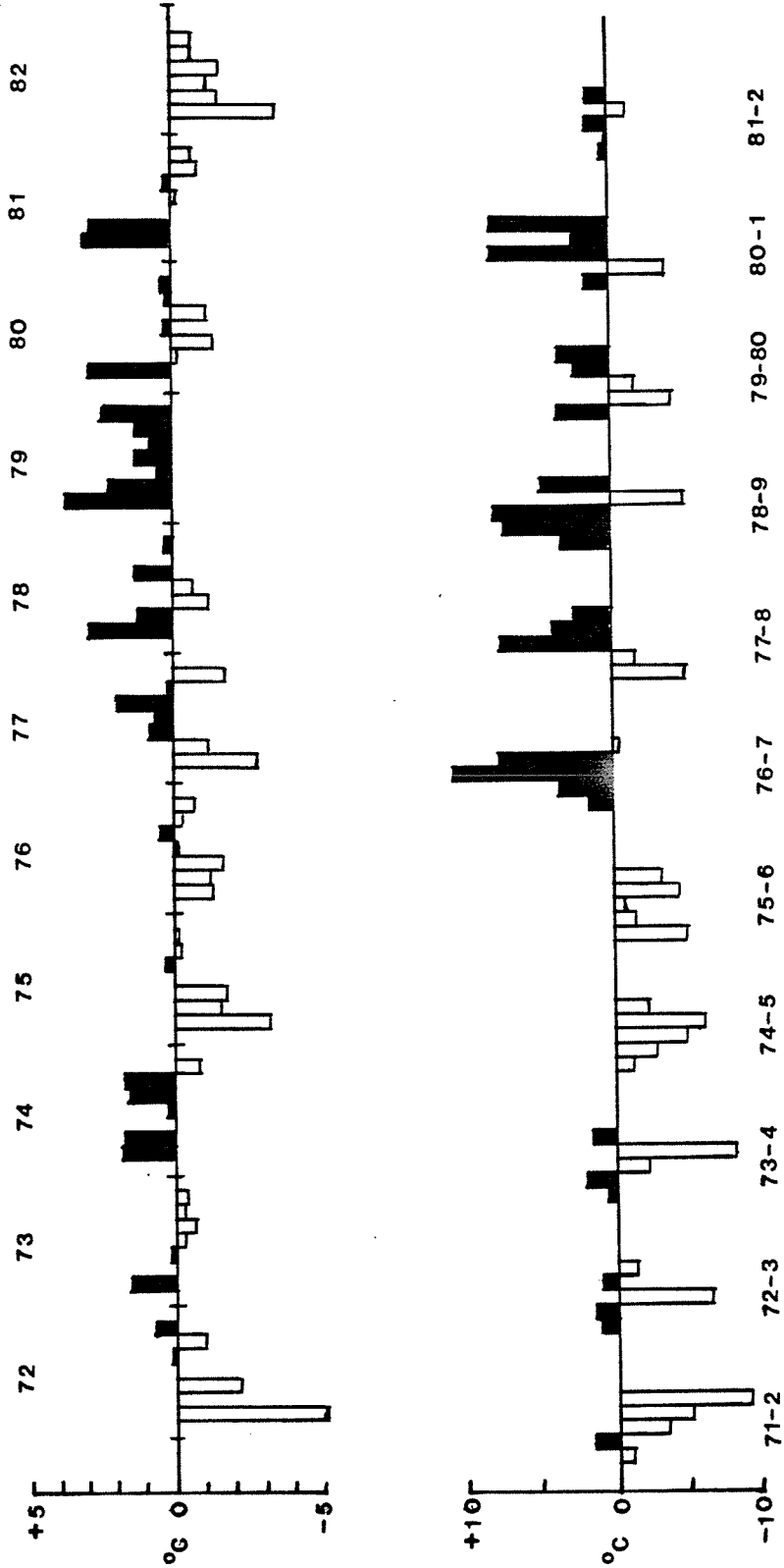


Fig. 1 Deviations from 60-year monthly means of air temperature at Dillingham and King Salmon (average) for summer months, April-October (top) and winter months, November-March (bottom); Nov., 1971 through Sept., 1982.

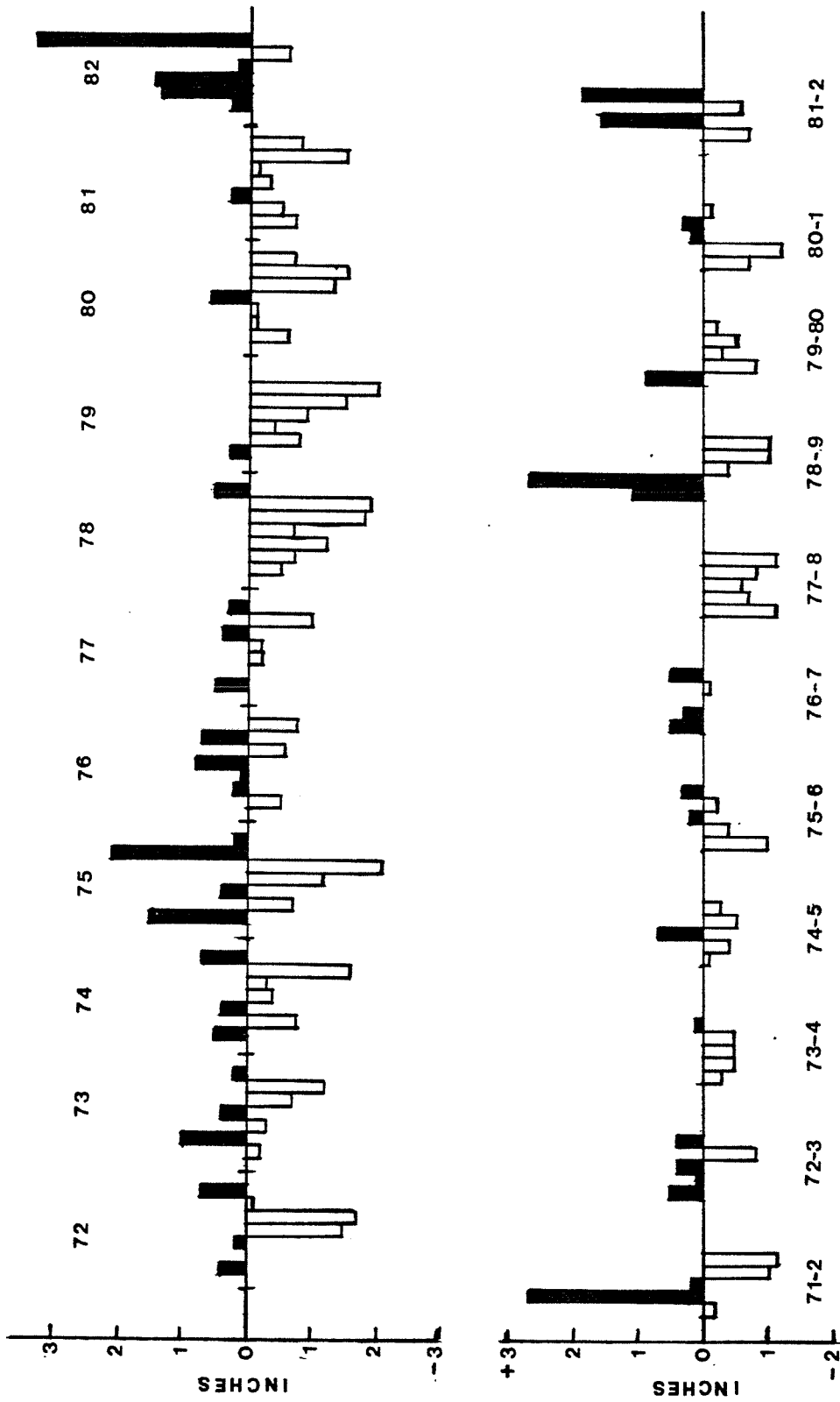


Fig. 2 Deviations from 60-year monthly total precipitation at Dillingham and King Salmon (average) for summer months, April-October (top) and winter months, November-March (bottom); Nov., 1971 through Sept., 1982.

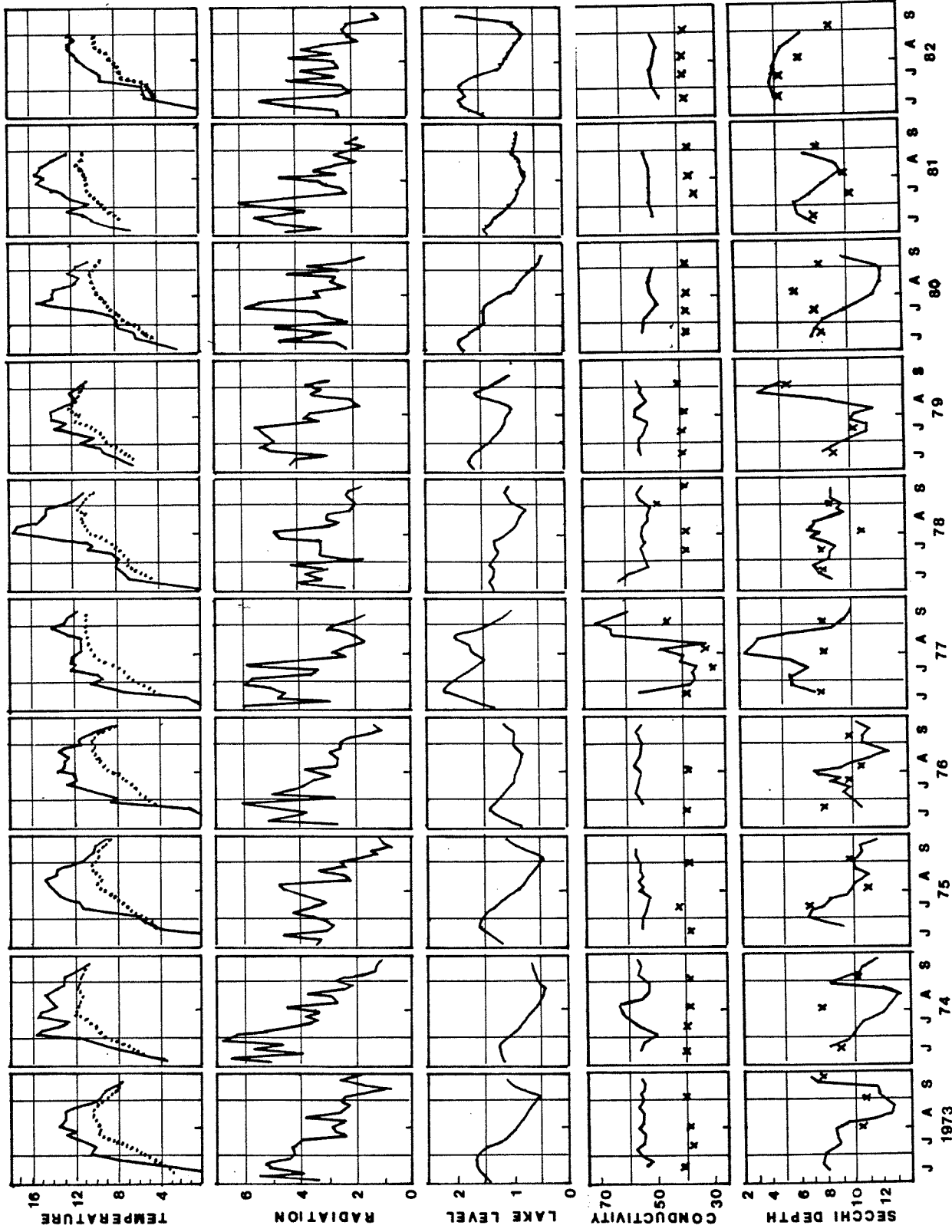


Fig. 3 Average water temperature (C) at the surface (solid line) and 0-20 m (dotted line) in Little Togiak Lake; five-day means of solar radiation (gm cal/cm²) and relative lake level (cm); and average conductivity (micromhos/cm) and Secchi depth (m) in Little Togiak Lake and Lake Aleknagik (x) during the summers of 1973-1982.

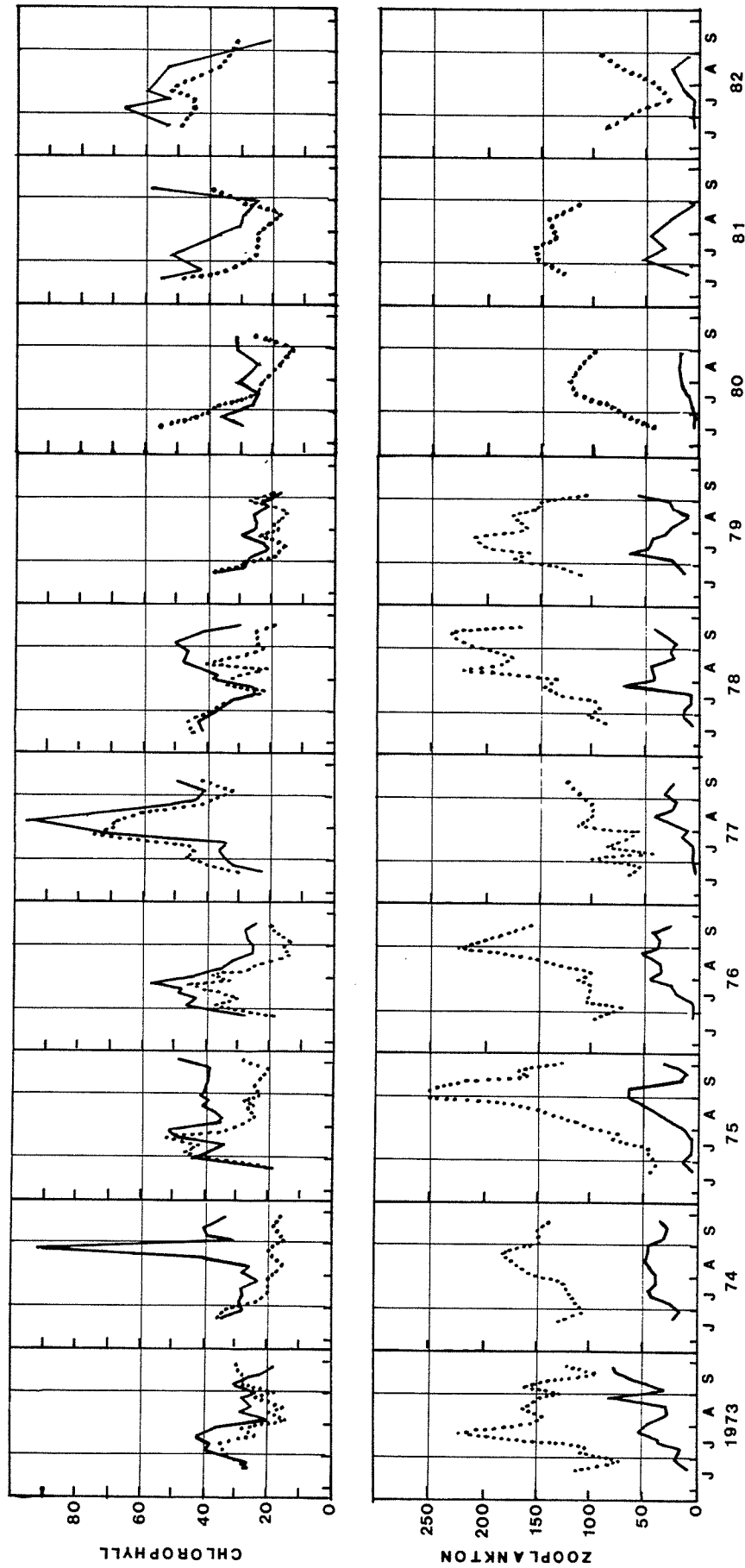


Fig. 4 Amounts of chlorophyll a; mg/m², 0-20 m (top) and the volumes of zooplankton, mL/m² (bottom) in the upper basin (solid line) and lower basin (dotted line) of Little Togiak Lake during the summers of 1973-1982.

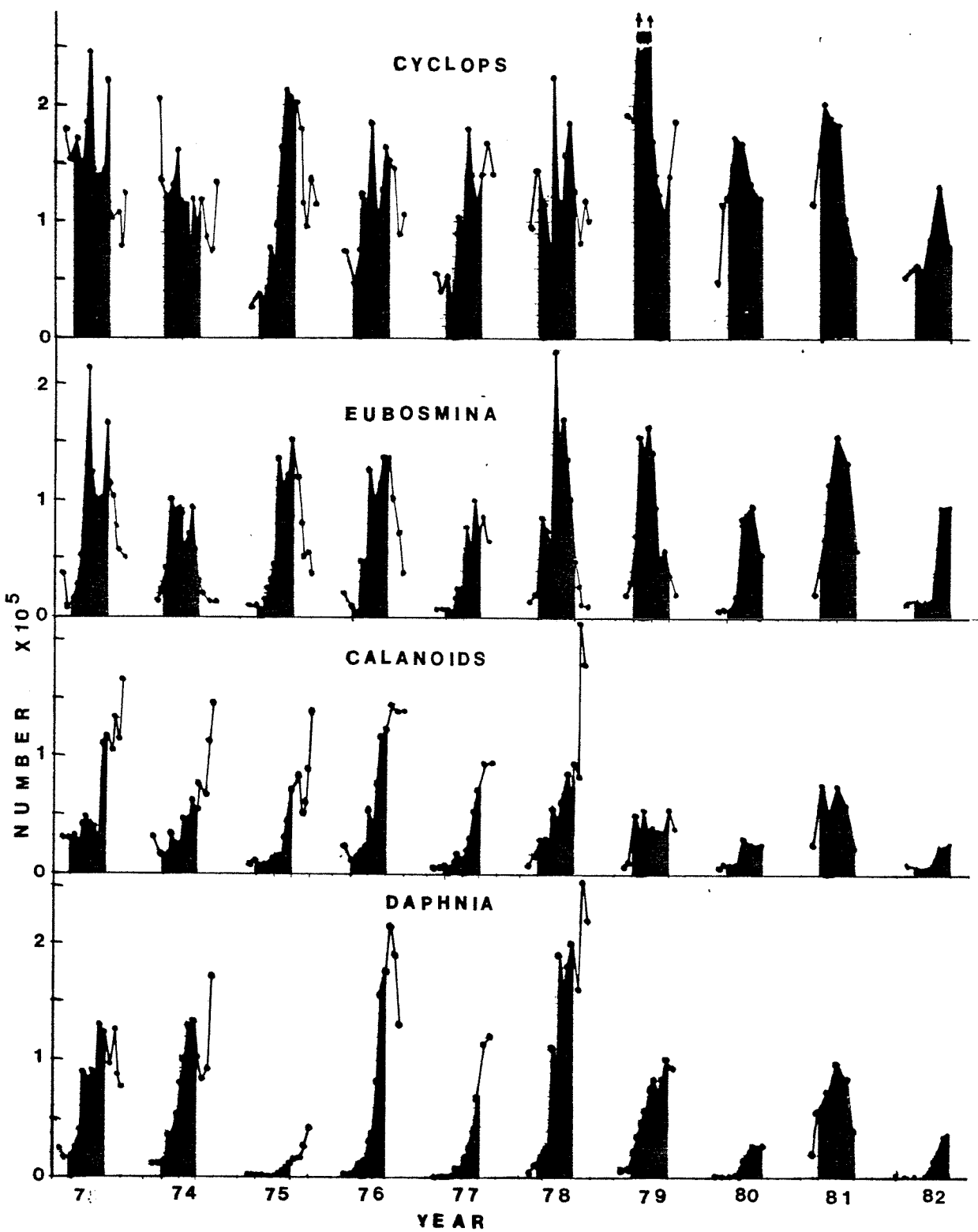


Fig. 5 Densities (thousands per m²) of zooplankton in Little Togiak Lake during the summers of 1973-1982. Geometric means from six hauls per date. Period July 1-August 31 is shaded.

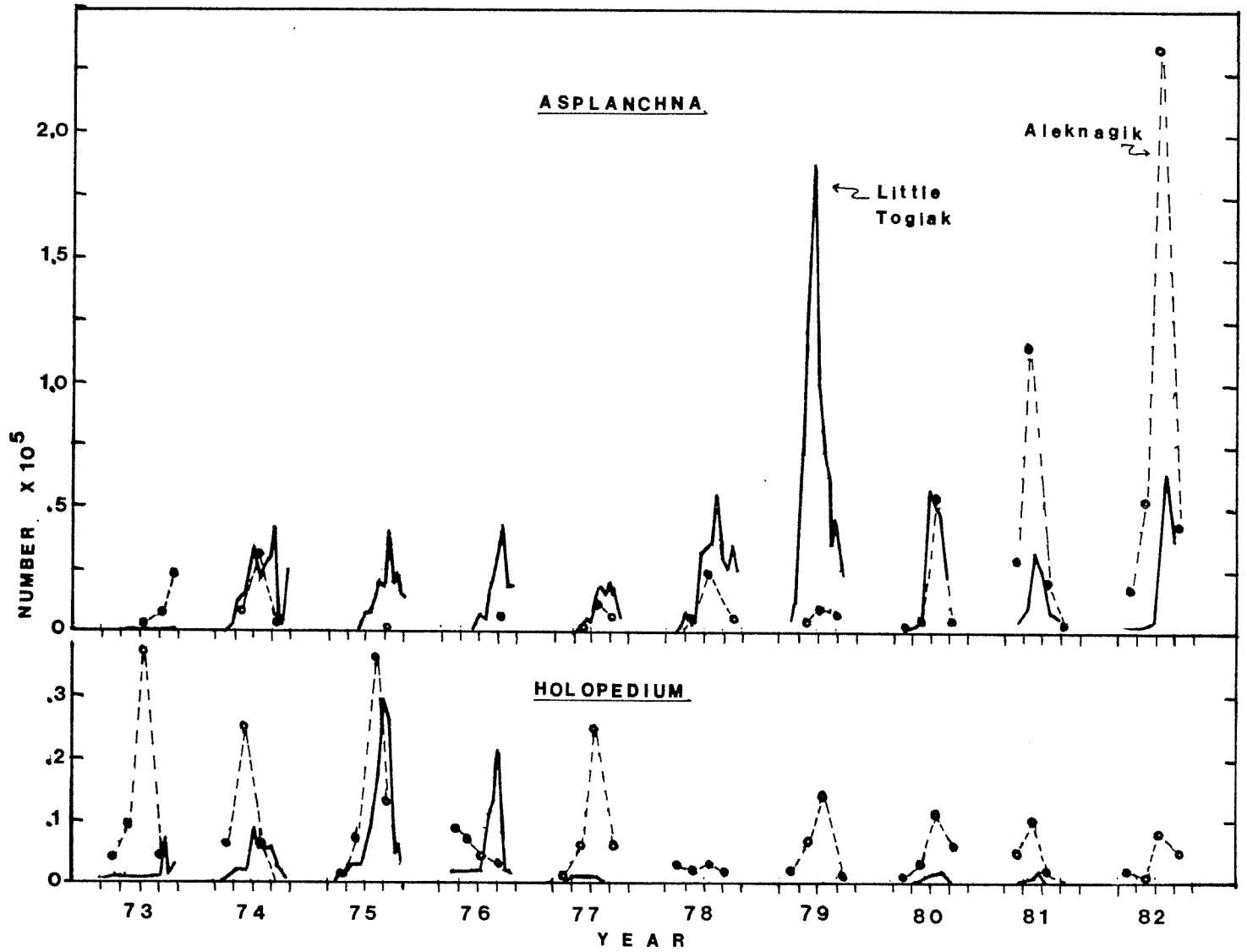


Fig. 6 Densities (1,000's/m²) of Asplanchna sp. (rotifer) and Holopedium gibberum during the summers of 1973-1982 in Lake Aleknagik and Little Togiak Lake.

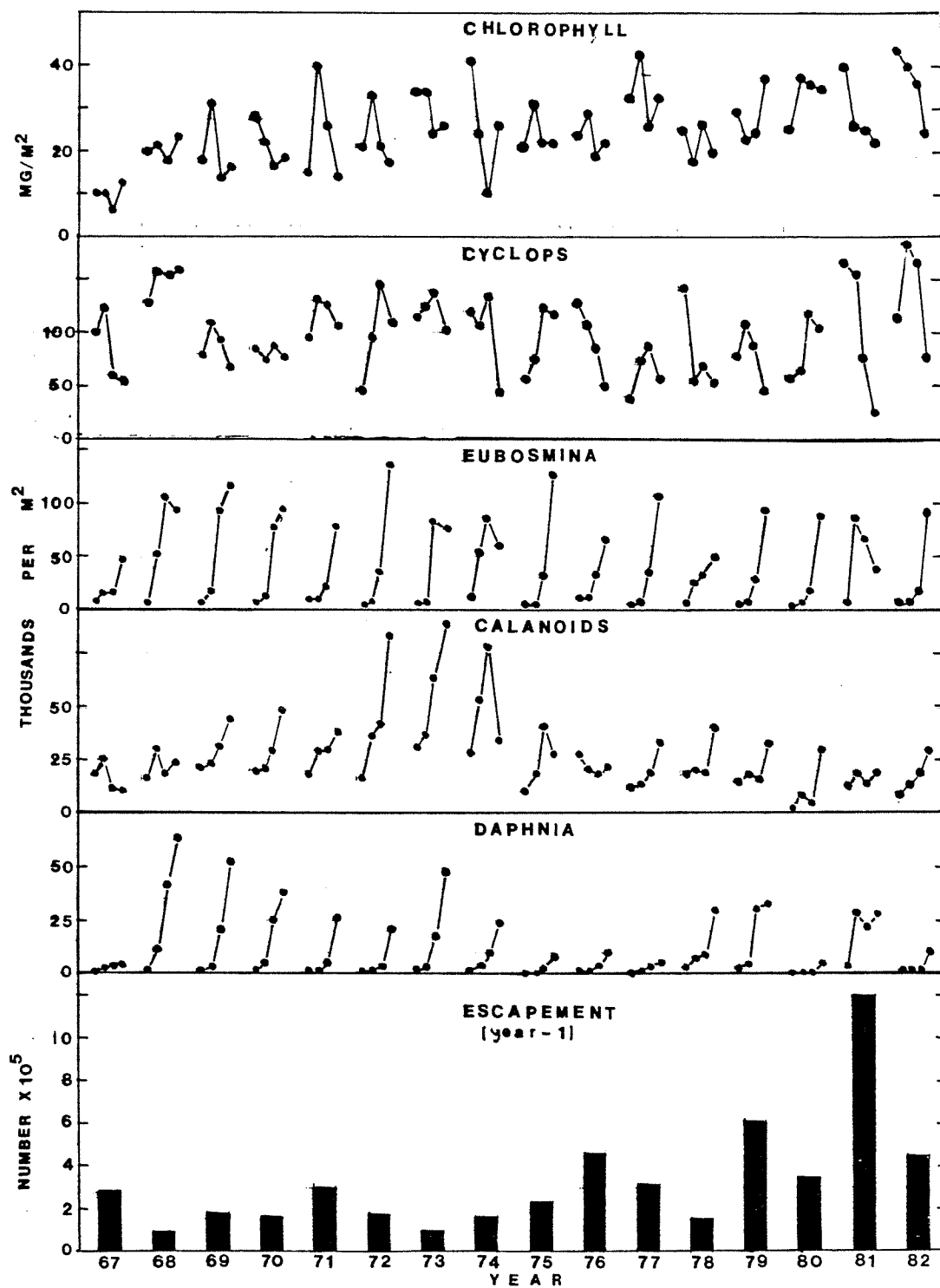


Fig. 7 Densities of chlorophyll a (0-20 m) and major zooplankters about June 24, July 15, August 5, and September 5, 1967-1982 in Lake Aleknagik and the sockeye escapement to the lake in the previous year.

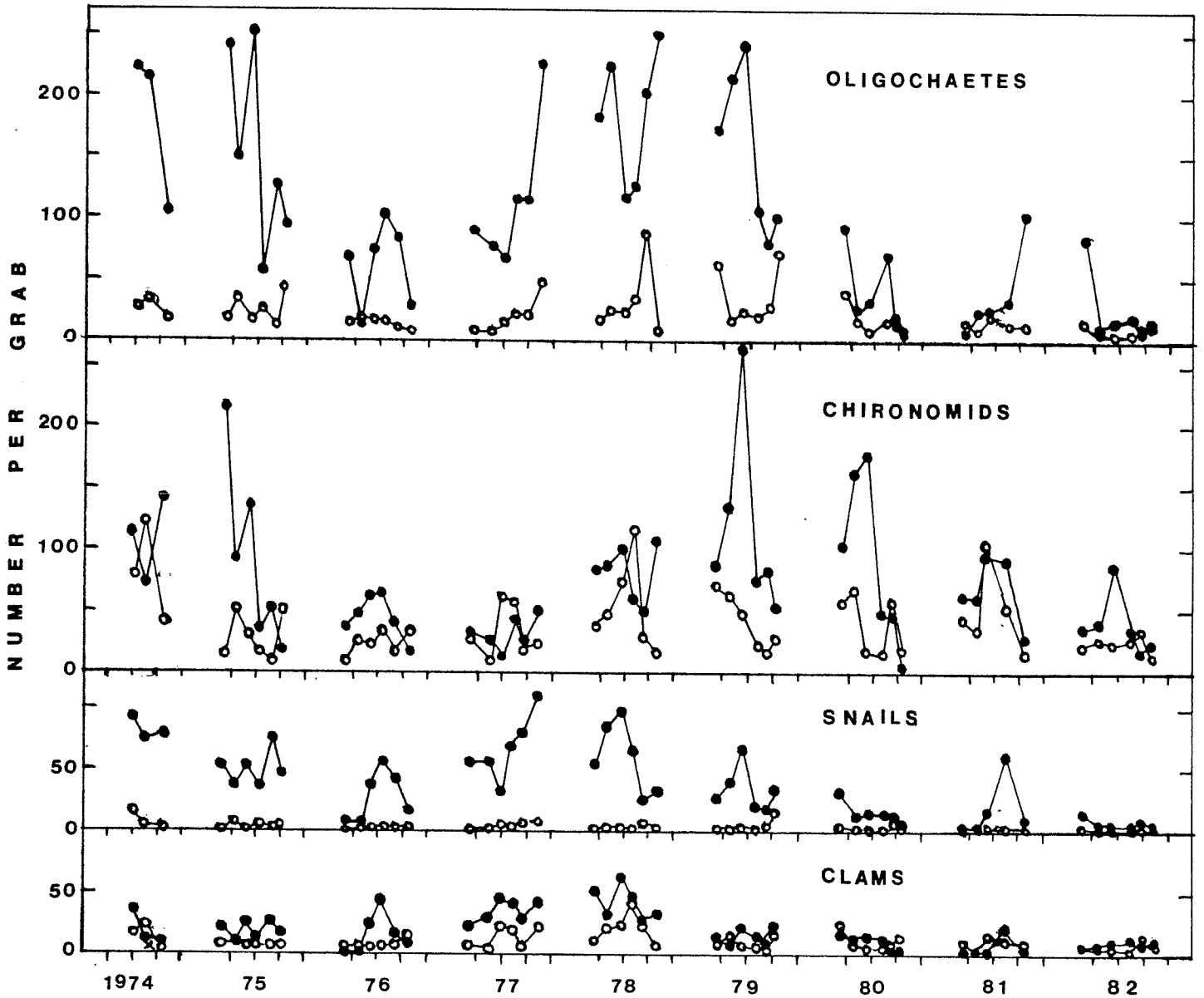


Fig. 8 Geometric means of the numbers of major benthic organisms (per 225 cm²) from sampling between 3 and 10 m at the west end (solid) and east end (open) of Little Togiak Lake. From 1975 through 1982 sampling began about June 20 and ended about September 8 (4 samples per date per location).

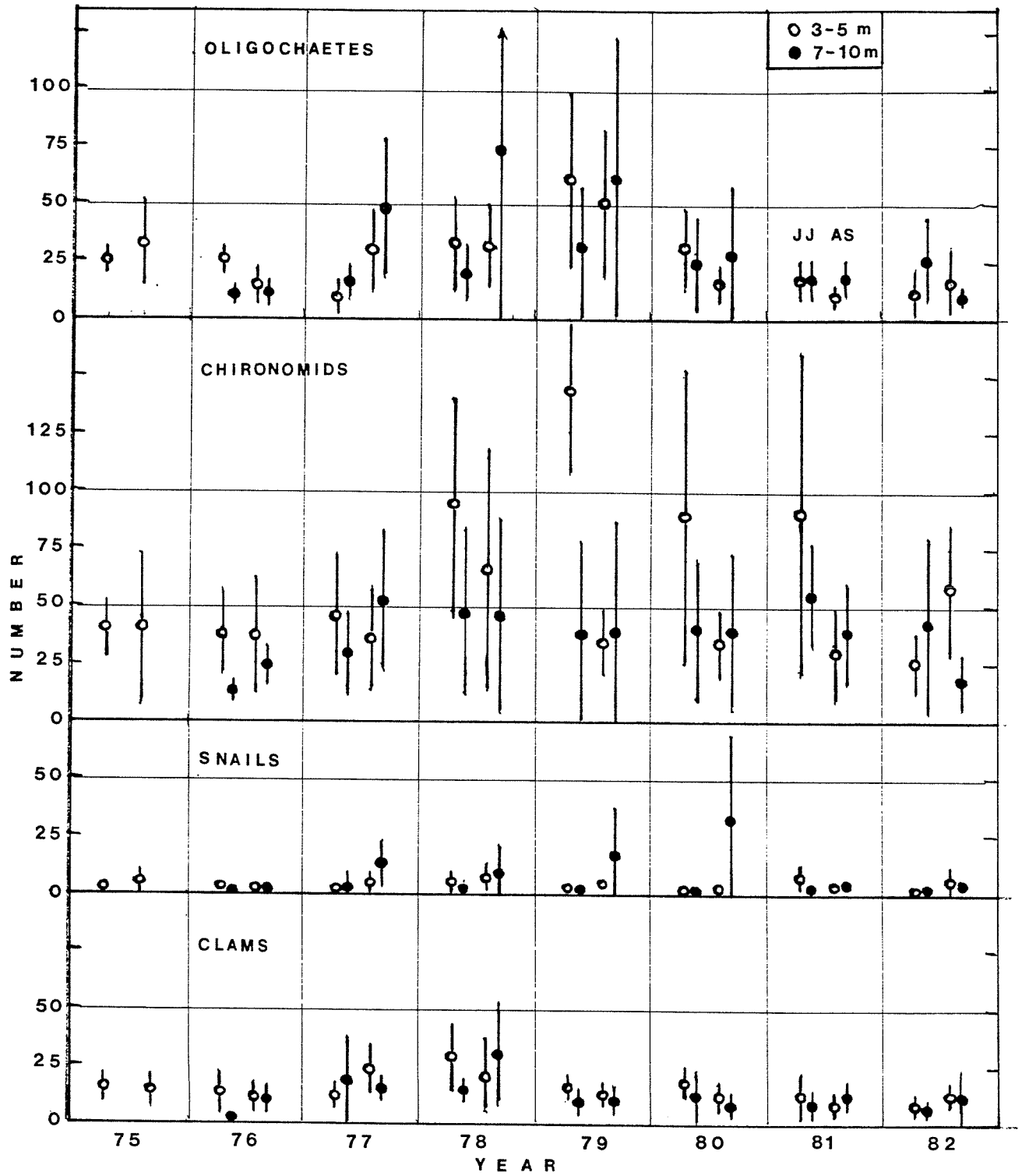


Fig. 9 Arithmetic means ± 2 SE of the number of major benthic organisms (per 225 cm²) at the east end of Little Togiak Lake, 1975-1982. Data stratified by months June-July and August-September and depths 3-5 m and 7-10 m.

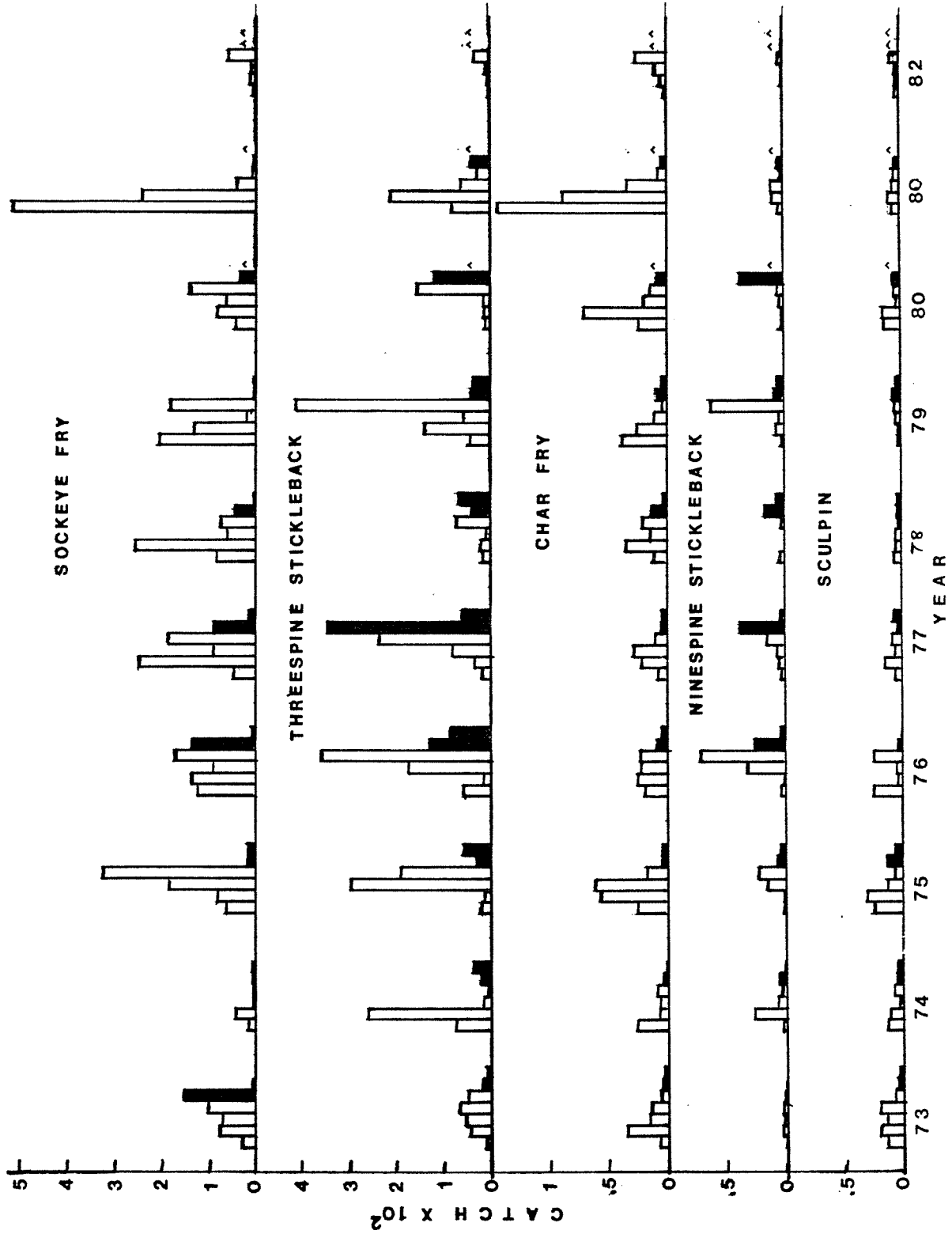


Fig. 10 Geometric means of beach seine catches from Little Togiak Lake during summers of 1973 through 1982. Weekly sampling between June 25 and July 18 (open bars) and July 23 to August 3 (solid bars). No sampling (^).

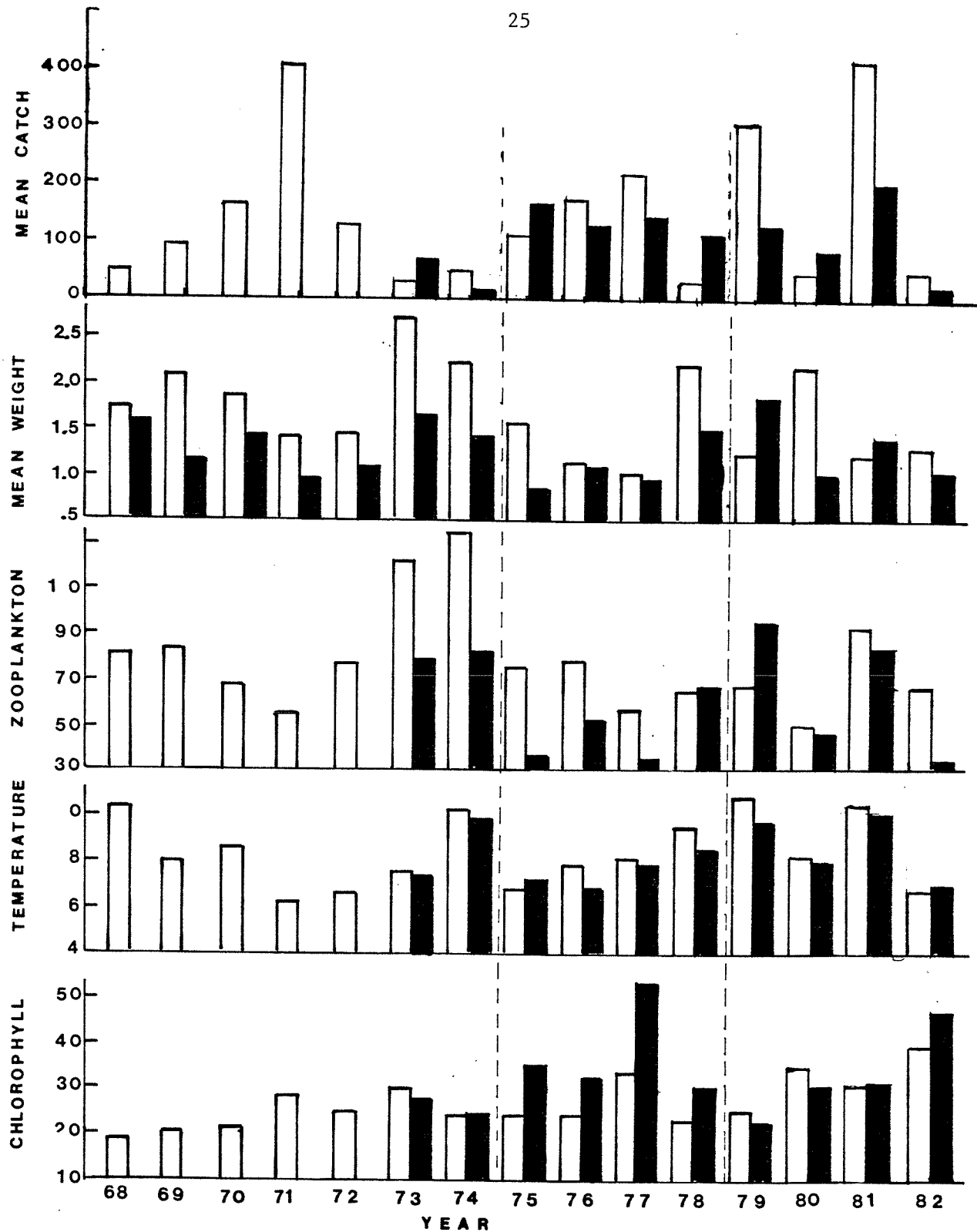


Fig. 11 Abundance of sockeye fry (mean beach seine catch), mean weight of fry on Sept. 1 (gm), and the average volume of zooplankton (ml/m²), water temperature (0-20 m), and chlorophyll a (mg/m², 0-20 m) during mid-June to mid-August in Lake Aleknagik (open bars) and Little Togiak Lake (solid bars).

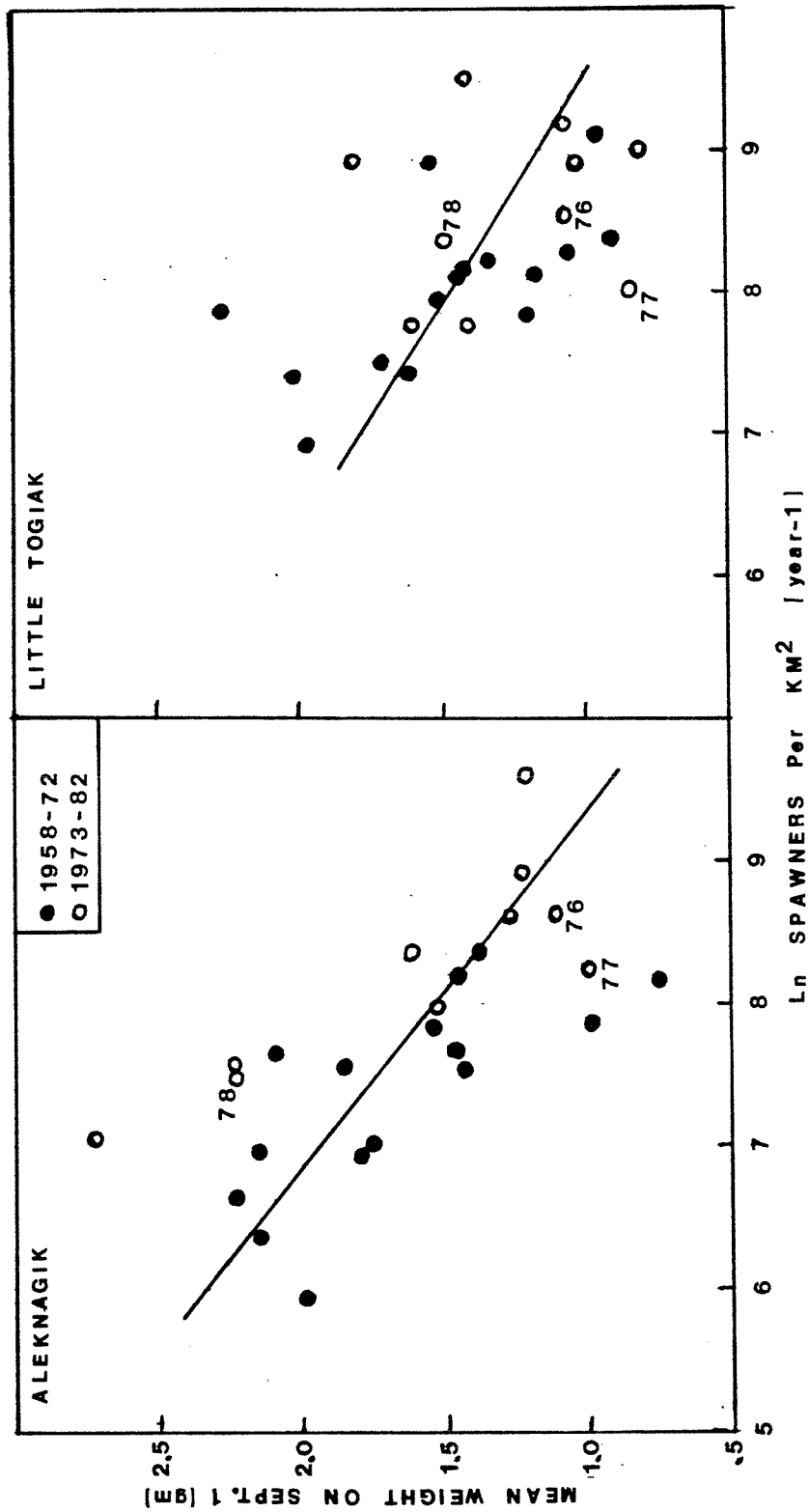


Fig. 12 Mean weight of sockeye fry on Sept. 1 plotted on the ln of parent spawner density for Lake Aleknagik and Little Togiak Lake.

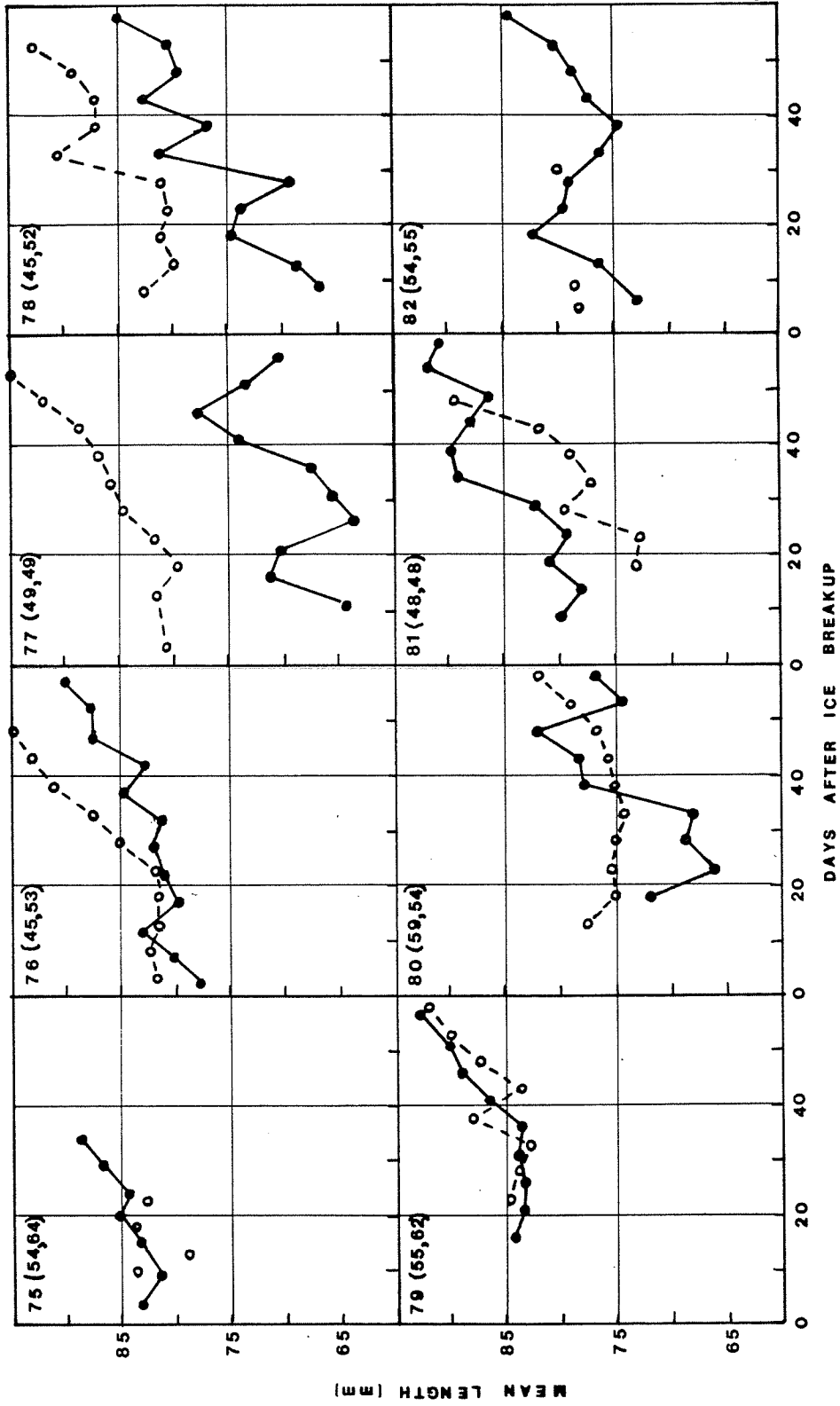


Fig. 13 Mean lengths of age I smolts during smolt migrations from Little Togiak Lake (open circles) and from the lake system at Aleknagik (closed circles), 1975-1982. Mean lengths of fry on Sept. 1 in the previous year for Little Togiak Lake and the lake system are given in parenthesis.

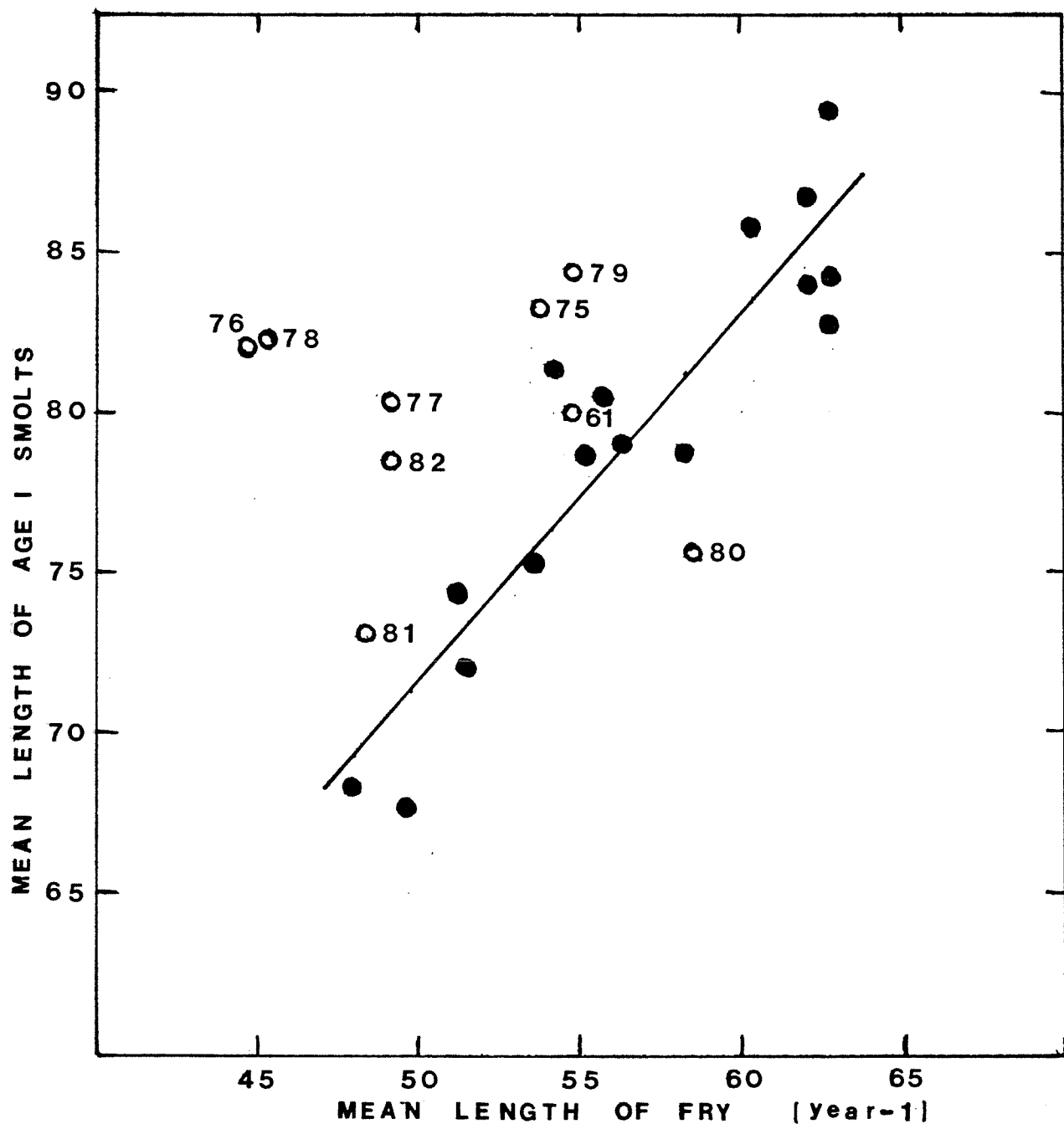


Fig. 14 Mean lengths of age I smolts during the first 10 days of migration from Little Togiak Lake (O) and Lake Aleknagik (●) plotted on the mean lengths of fry on September 1 in the previous year. Regression line fitted to the Aleknagik data only.

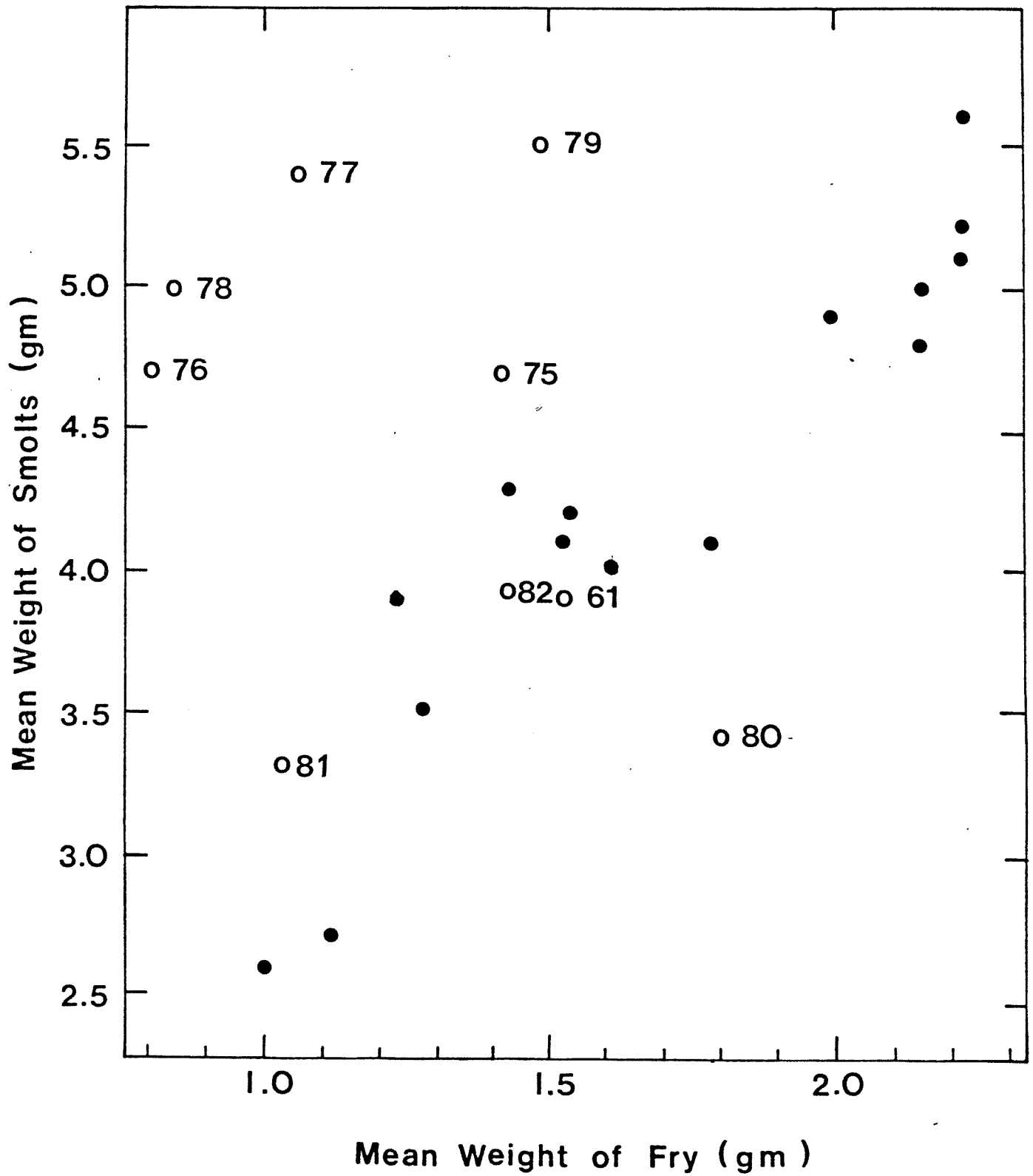


Fig. 15 Mean weight of age I smolts during the first 20 days of migration (year shown) vs. the mean weight of fry on September 1 of the previous year in Lake Aleknagik (●) and Little Togiak Lake (○).

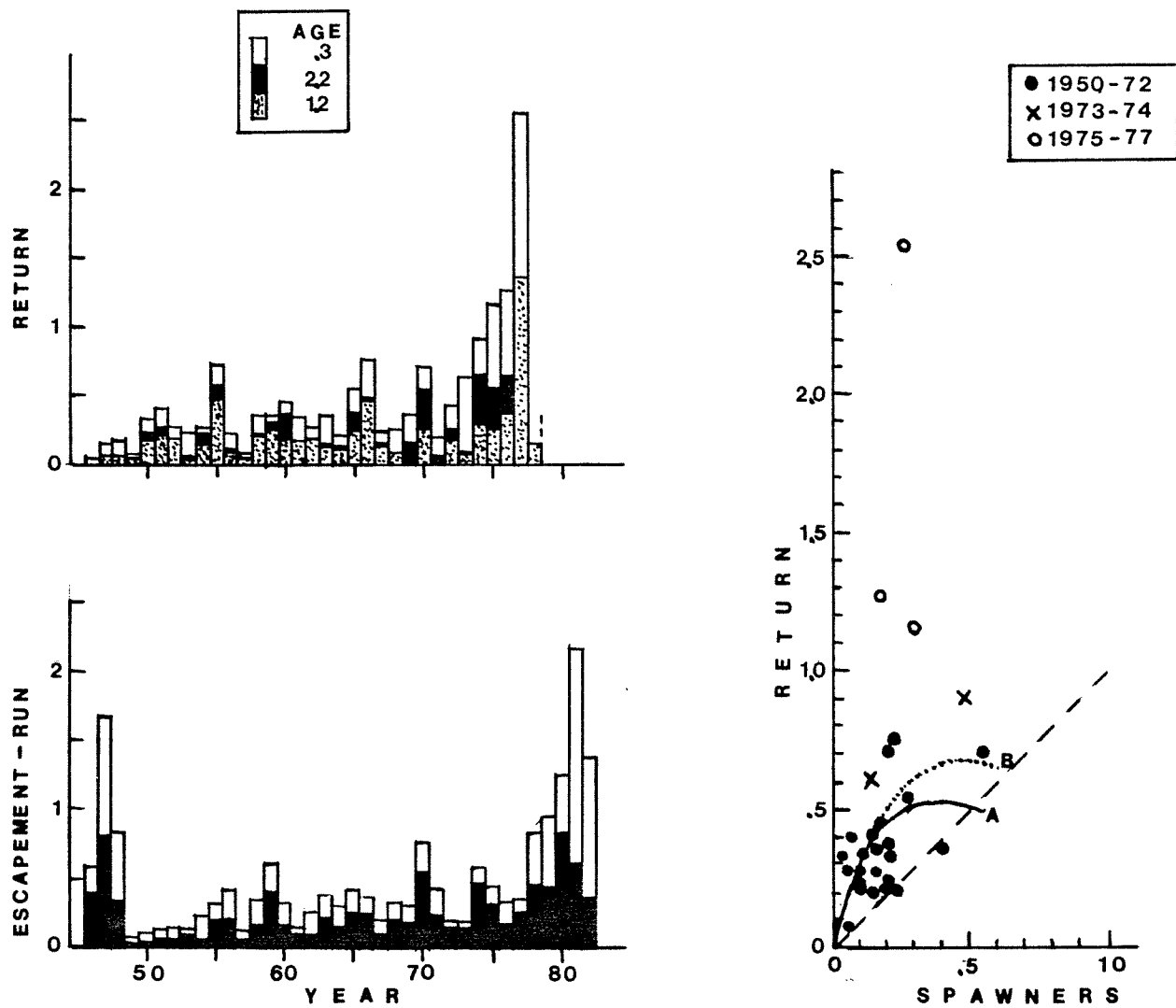


Fig. 16 Annual runs and escapements of sockeye salmon to Little Togiak Lake, adult returns from escapements, and spawner-return relationships; (A) fitted to data from 1950-74 brood years and (B) to data from 1950-77 brood years. Number of fish $\times 10^5$.

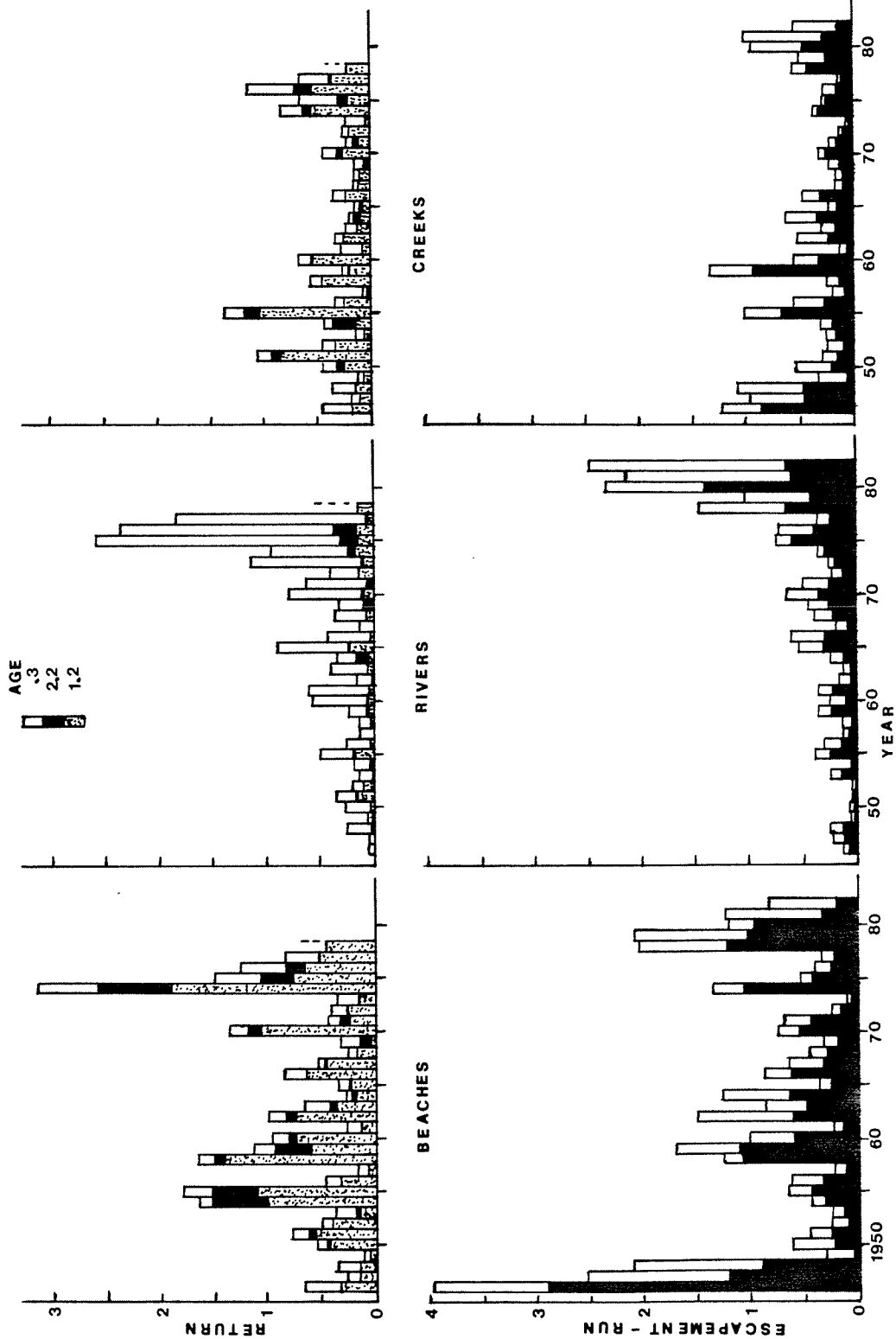


Fig. 17 Annual runs, escapements, and returns of sockeye salmon to the Wood River lake system by type of spawning area. Number of fish in millions.

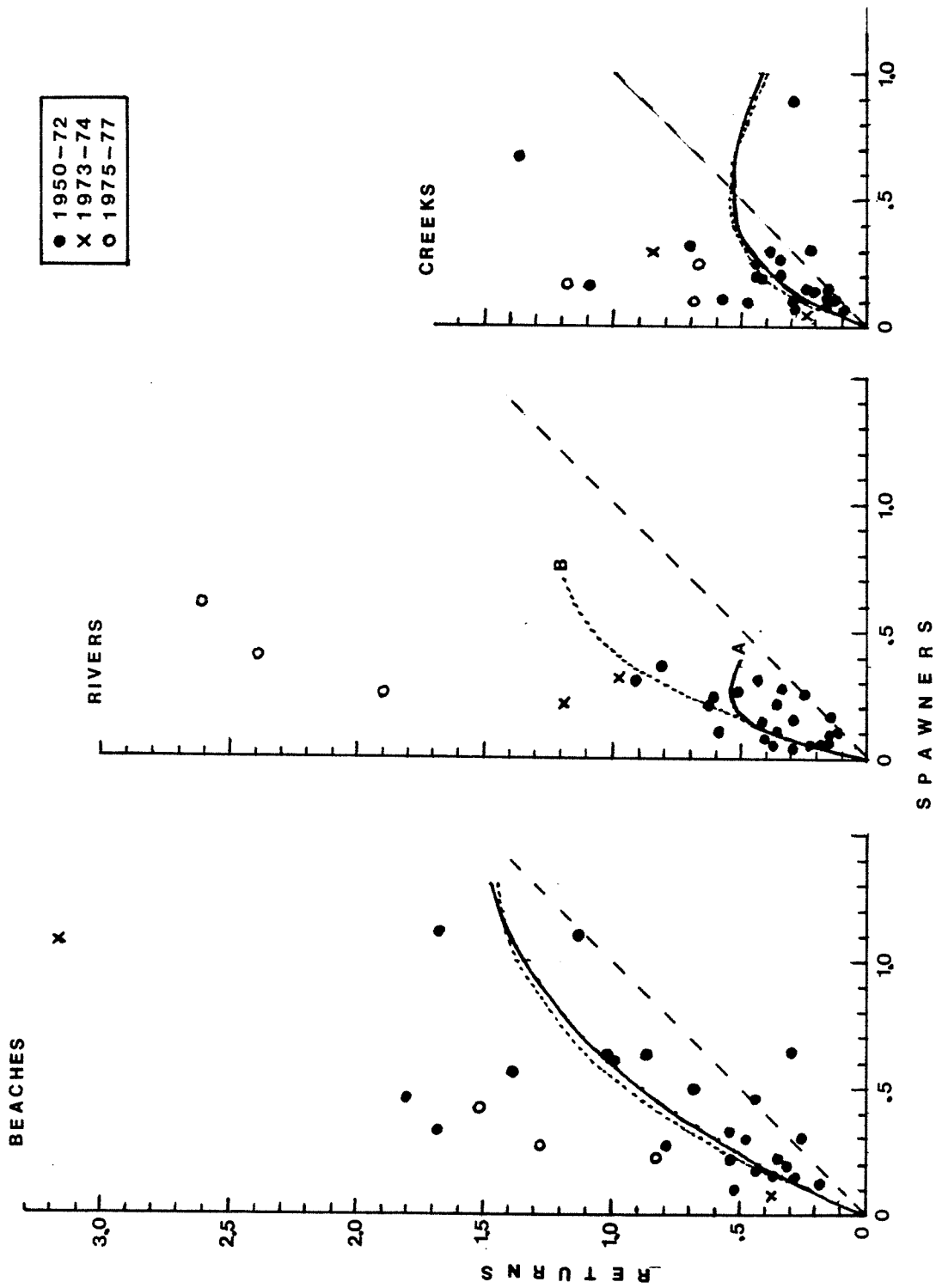


Fig. 18 Spawner-return relationships by type of spawning area in the Wood River lake system. Number of fish in millions. Curve (A) fitted to 1950-74 brood years and (B) to 1950-77 brood years.

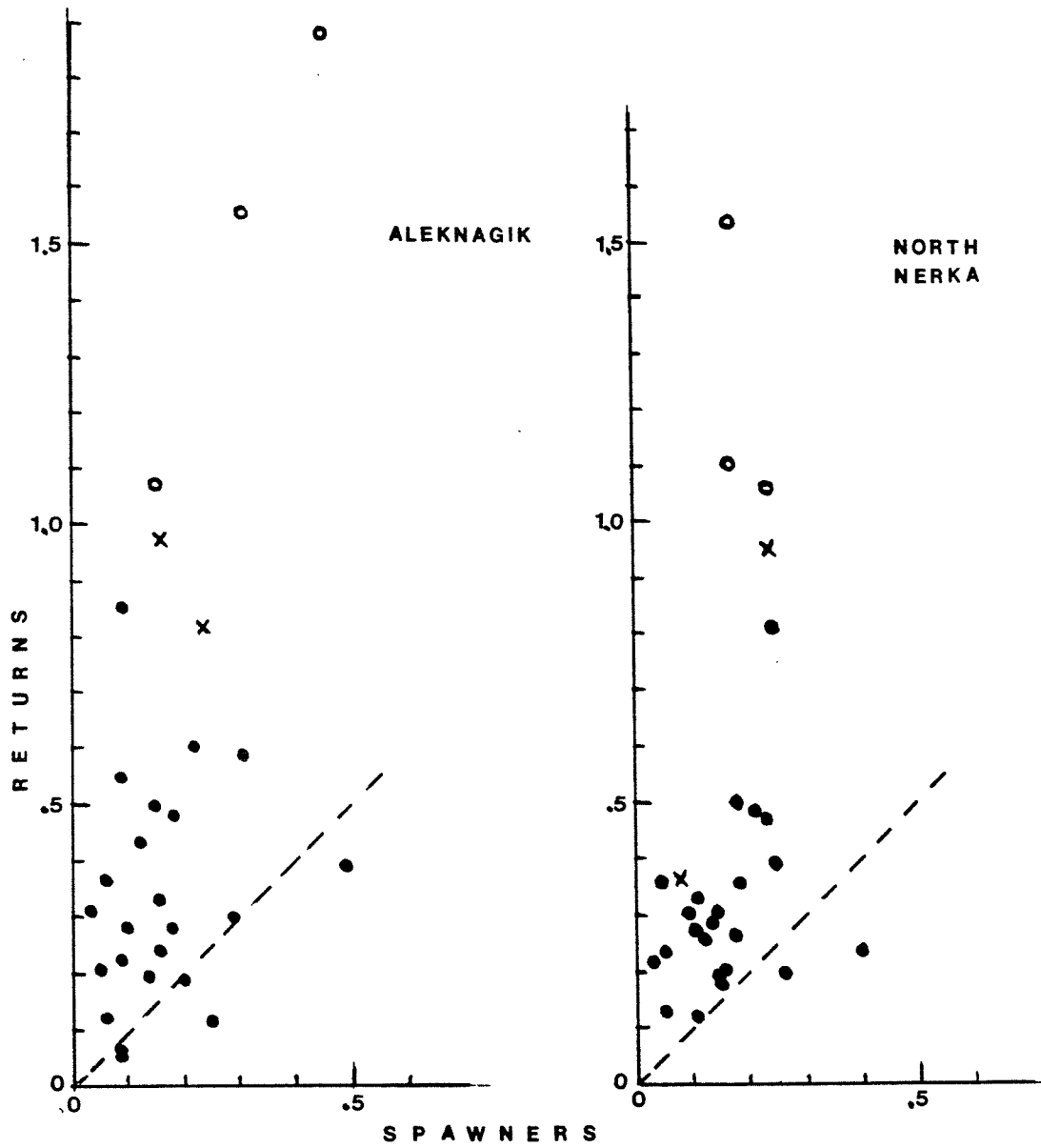


Fig. 19 Spawner-return plots for sockeye salmon from Lake Aleknagik and the north arm of Lake Nerka. Number of fish in millions.

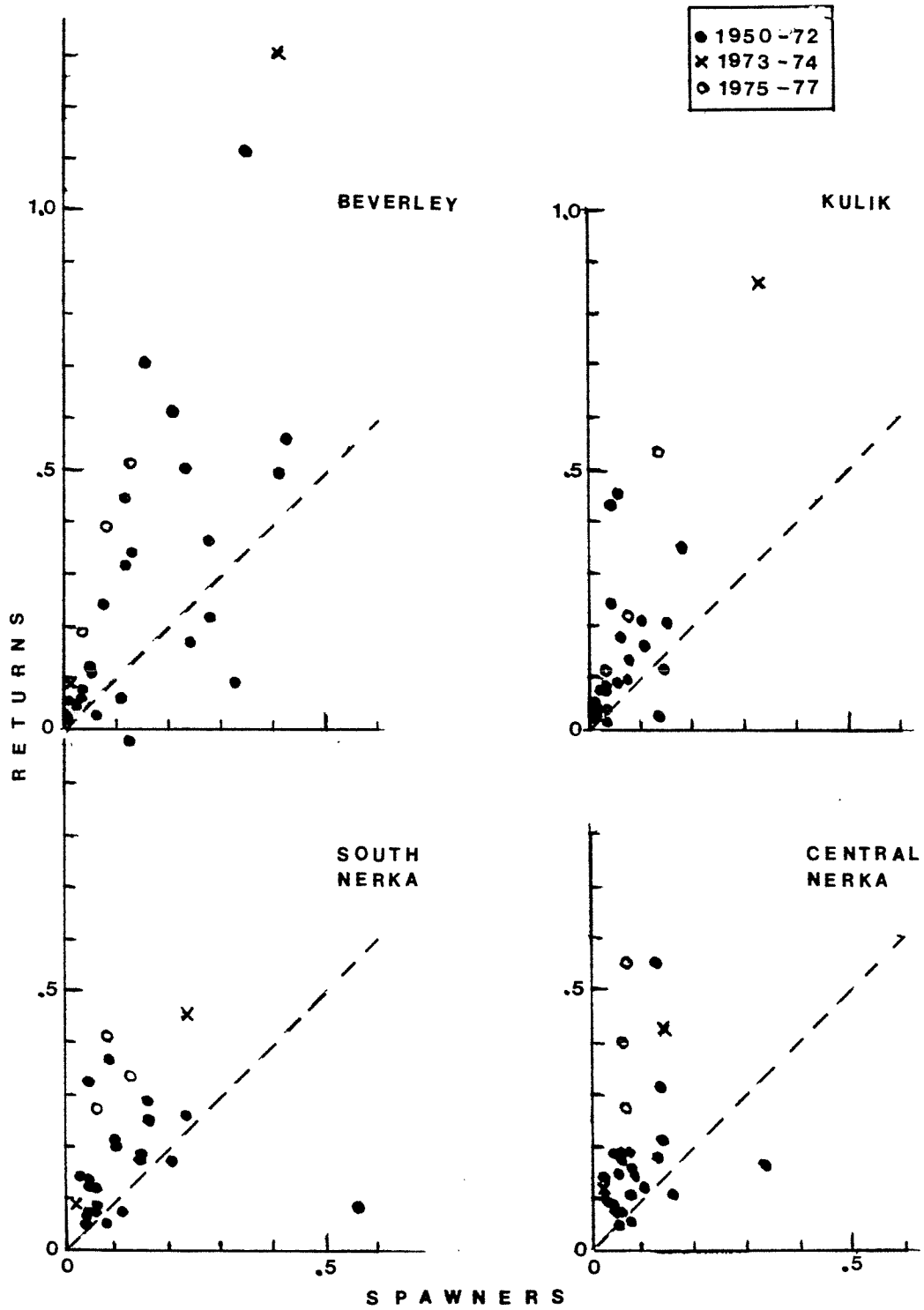


Fig. 20 Spawner-return plots for sockeye salmon from four lakes in the Wood River system. Number of fish in millions.

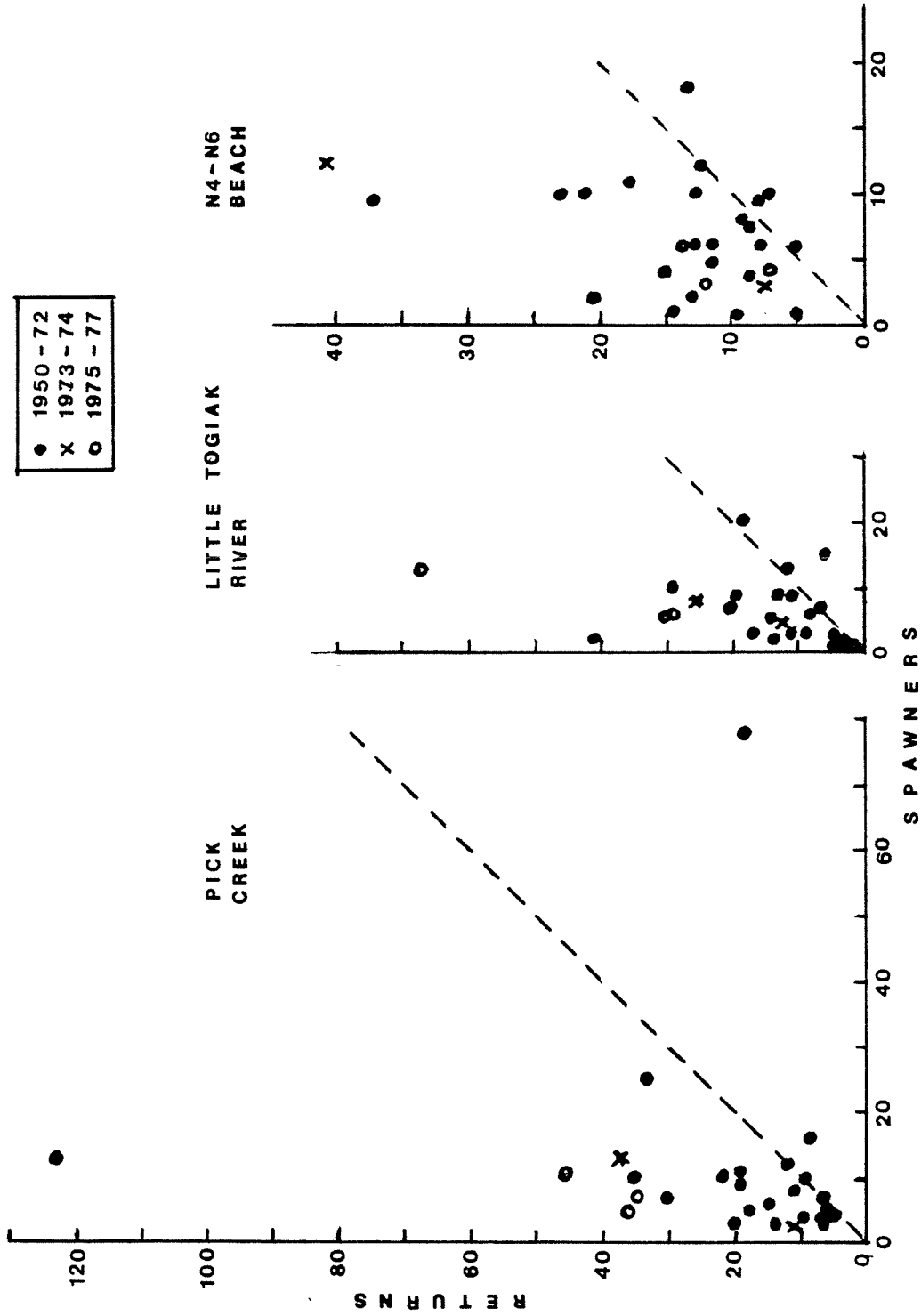


Fig. 21 Spawner-return plots for three spawning areas in central Lake Nerka. Number of fish in thousands.

Table 1. Dates of ice breakup and the average surface temperatures at insect traps in Little Togiak Lake by 5-day periods, 1973-1982.

		1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Breakup:		6/8	5/27	6/15	6/17	6/13	6/2	5/24	5/27	5/28	6/12
June	3	0.0	--	0.0	0.0	0.0	--	--	--	--	--
	8	0.0	--	0.0	0.0	0.0	--	--	--	--	--
	13	--	--	0.0	0.0	1.5	6.9	--	4.8	--	--
	18	3.2	8.6	4.0	1.0	6.0	7.2	8.2	6.2	10.0	--
	23	--	--	4.3	5.0	8.8	7.9	9.1	6.4	10.9	5.0
	28	8.2	11.6	5.7	8.4	10.7	8.2	9.3	7.8	12.0	5.2
July	3	10.7	15.9	6.2	7.9	9.2	7.5	11.3	7.8	10.4	5.4
	8	10.3	14.7	9.7	10.4	10.1	8.3	10.4	8.3	12.0	6.8
	13	10.2	12.8	11.4	11.6	12.1	10.3	10.6	10.1	12.7	9.2
	18	11.5	12.3	11.5	13.0	11.9	10.0	13.7	12.9	13.5	9.2
	23	13.1	15.7	13.0	11.7	12.3	11.1	12.4	15.0	14.0	9.9
	28	11.5	15.2	13.5	12.0	12.2	14.3	13.8	13.6	14.6	10.8
Aug	2	13.5	13.6	13.7	13.7	11.2	17.6	14.1	13.6	14.3	11.5
	7	13.0	13.9	14.6	12.6	11.4	17.4	14.0	13.3	15.2	11.8
	12	13.1	14.4	14.9	13.1	11.3	15.4	13.3	12.5	--	12.2
	17	13.0	14.7	13.7	12.4	11.3	14.7	11.3	11.6	--	12.2
	22	12.2	13.8	13.8	13.5	13.2	14.5	11.8	11.1	--	11.9
	27	10.2	13.1	12.9	13.0	14.2	14.6	12.1	12.1	12.2	12.2
Sept	1	10.0	13.2	11.5	11.2	13.8	14.0	10.9	11.6	--	--
	6	9.5	13.0	--	11.6	12.6	12.4	10.2	10.6	--	--
	11	9.4	12.3	10.5	10.4	12.2	11.7	--	--	--	--
	16	--	11.4	10.2	9.9	--	11.2	--	--	--	--
	21	--	10.1	9.9	8.1	--	--	--	--	--	--
	26	--	--	9.4	--	--	--	--	--	--	--

Table 2. Dates of ice breakup and the average surface temperatures at insect traps in Lake Aleknagik by five-day periods, 1969-1982.

	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
Breakup:	6/2	5/23	6/16	6/8	6/2	5/22	6/8	6/10	6/1	5/22	5/16	5/17	5/23	6/5
June 1-5	(2.0)*	(8.5)	0	0	3.3	7.3	0	0	2.4	8.1	(9.4)	--	--	0
6-10	(3.9)	9.2	0	1.3	4.9	8.2	0.7	0.5	5.0	8.2	8.9	--	--	--
11-15	(5.5)	6.6	0	3.9	6.0	7.7	4.3	5.6	6.1	8.3	9.4	--	--	5.8
16-20	(5.5)	7.3	2.8	4.1	6.8	8.7	5.8	6.2	8.5	(8.6)	9.5	--	12.6	9.1
21-25	8.2	8.9	5.6	4.6	8.1	10.1	5.4	8.5	10.8	(8.6)	9.6	--	12.8	8.0
26-30	(10.2)	10.6	8.2	5.8	8.7	15.2	6.0	10.2	9.8	10.4	8.5	--	13.0	7.5
July 1-5	13.3	12.8	10.0	8.8	9.2	14.4	7.7	8.8	8.6	9.9	11.6	--	13.9	8.1
6-10	10.4	12.5	12.1	13.0	11.8	14.1	10.7	11.7	9.7	10.1	(12.1)	--	13.8	10.0
11-15	12.9	8.9	10.9	10.8	10.6	12.7	11.5	12.8	9.3	11.8	(12.6)	--	13.0	11.0
16-20	11.2	11.4	8.5	9.2	12.3	11.7	10.9	12.7	11.1	10.9	(13.3)	14.3	12.6	10.3
21-25	11.0	10.6	8.1	12.2	11.6	13.9	11.9	12.0	12.5	12.1	13.3	17.2	11.7	10.3
26-30	11.5	10.6	8.7	13.3	9.4	14.1	13.6	11.6	10.7	14.5	14.8	14.9	14.3	9.9
Aug 31-4	12.4	11.8	10.1	12.7	11.5	16.4	15.0	14.3	11.2	17.5	15.2	13.3	14.7	11.1
5-9	12.7	11.7	10.5	14.0	10.6	14.5	16.3	13.7	11.8	16.8	14.0	(12.9)	15.2	13.3
10-14	12.7	13.1	12.1	14.0	11.9	14.2	14.3	14.1	11.9	15.0	(13.0)	12.4	--	12.1
15-19	(13.0)	(12.8)	11.0	12.5	13.5	(14.5)	14.3	13.2	11.7	14.5	(11.3)	11.7	13.2	12.3
20-24	(12.0)	(13.0)	9.9	(12.3)	(13.0)	(14.5)	15.4	13.4	12.5	14.4	(12.3)	12.0	--	12.4
25-29	(11.0)	(11.5)	(9.8)	(12.0)	(12.5)	14.7	14.7	11.2	13.2	14.0	15.2	12.4	--	11.3
Sept 30-3	(10.5)	(11.0)	(9.7)	(10.5)	(11.5)	14.6	13.6	11.3	14.2	13.6	12.2	11.5	13.5	11.5
4-8			9.5			14.0	10.8	10.5	12.7	11.6	(11.3)	10.9		11.7
9-13			9.7			13.9	10.3		12.1	12.0				
14-18							9.7							

*Estimates of missing observations from other locations are given in parentheses.

Table 4. Average daily catches of chironomids at stations 1, 3, and 4 in Little Togiak Lake by 5-day periods, 1973-1982. Asterisk indicates period in which ice breakup occurred.

Period mid-date	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
May 24							*			
29		*					--	*	*	
June 3		--				*	--	--	--	
8	*	--				--	--	--	--	
13	0	3	*		*	7	--	5	--	*
18	2	3	0	*	2	4	3	4	3	--
23	1	5	4	1	4	4	2	3	3	4
28	9	5	3	2	2	4	3	3	1	4
July 3	11	4	2	2	2	3	3	2	1	4
8	16	5	3	4	3	2	5	2	1	3
13	14	7	2	2	2	13	22	7	1	3
18	11	6	4	8	2	9	11	21	6	5
23	13	6	9	16	8	4	16	5	3	4
28	9	4	8	16	13	31	14	27	2	17
Aug 2	8	5	5	19	23	62	3	28	3	20
7	7	4	10	8	23	29	2	19	4	33
12	23	3	6	8	18	28	4	14	11	68
17	6	5	5	6	14	19	5	12	10	32
22	21	6	3	5	22	9	5	6	8	6
27	14	12	1	6	15	8	2	5	4	5
Sept 1	13	6	1	4	11	5	0	7	--	--
6	8	3	1	3	7	5	--	0	--	--
11	7	6	1	2	2	2	--	--	--	--
16	4	2	1	1	--	1	--	--	--	--
21	2	1	0	--	--	--	--	--	--	--
Ave. catch 6/21-9/3										
Sta. 1	18	13	8	8	9	7	10	5	5	10
2	2	3	3	3	3	3	4	4	--	--
3	2	1	1	5	9	27	1	13	3	17
4	16	4	3	8	14	12	9	15	4	15
5	--	--	4	5	9	7	5	2	5	12

Table 5. Average daily catches of chironomids at three stations in Lake Aleknagik by five-day periods, 1969-1982. Asterisk indicates period in which ice breakup occurred.

Period mid-date	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
May 19		*				*				*		*		
24														*
29														
June 3	*				*				*	13				*
8		70		*	6	34	*		3	7	2			
13		53			8	15	46	6	50	6	14			
18	8	10	5*	2	12	7	94	35	168	5	7			7
23	10	7	6	7	12	7	42	10	5	5	18			5
28	6	6	7	4	12	5	11	4	2	8	8			2
July 3	3	8	13	3	11	8	4	4	1	12	8			3
8	4	12	19	7	23	12	4	4	1	15	3			8
13	2	21	15	11	26	28	3	3	1	14	17			12
18	7	24	12	13	27	16	2	5	4	36	21	5		5
23	50	40	10	13	23	19	7	13	13	19	31	10		11
28	59	39	14	45	56	17	46	35	35	31	32	11		8
Aug 2	2	77	15	27	76	7	73	24	23	39	26	7		10
7	67	17	40	86	80	3	43	15	15	23	24	4		23
12	28	13	54	52	34	3	22	9	19	27	15	2		37
17			70	9	33	3	13	8	13	19	7	2		23
22			28			2	12	8	13	5	4	1		7
27						3	11	1	5	10	4	1		3
Sept 1						5	8	1	9	10	2	1		3
6			4			6	9	1	6	11		1		
11			29				6		5	13				
16							4			9				

Table 6. Comparative limnological measurements made in Little Togiak Lake and Lake Aleknagik. Means during June 20 to September 1, 1973-1982.

Year	Chlorophyll a, 0-20 m (mg/m^2)				Water temperature, 0-20 m			
	6/20-7/15		7/16-9/1		6/20-7/15		7/16-9/1	
	Alek	L.T.	Alek	L.T.	Alek	L.T.	Alek	L.T.
1973	34.0	32.4	26.1	22.5	5.5	5.7	9.5	10.1
74	32.5	27.5	17.0	24.1	8.3	8.9	12.5	11.6
75	26.0	37.1	23.3	32.5	5.7	5.8	10.3	9.8
76	26.5	30.2	21.4	29.7	6.2	5.4	9.5	9.4
77	37.5	39.5	30.4	59.6	6.6	6.5	11.1	10.3
78	21.0	36.2	22.8	27.6	8.3	7.2	11.8	10.8
79	26.0	24.9	27.9	20.6	8.6	8.5	12.8	11.6
80	31.5	35.1	36.1	21.4	7.2	6.8	10.2	9.9
81	33.0	35.0	24.2	25.7	9.5	9.1	12.0	11.2
82	42.5	49.2	32.8	44.0	5.9	5.7	8.6	8.9

Year	No. zooplankton ($1,000's/\text{m}^2$)				Volume of zooplankton (ml/m^2)			
	6/20-7/15		7/16-9/1		6/20-7/15		7/16-9/1	
	Alek	L.T.	Alek	L.T.	Alek	L.T.	Alek	L.T.
1973	172	246	281	459	75	59	163	103
74	222	261	291	344	118	72	130	102
75	86	60	252	288	48	25	114	76
76	167	113	151	391	72	39	72	85
77	76	68	177	254	33	24	83	54
78	148	208	149	511	56	43	67	99
79	126	439	183	417	56	90	63	94
80	77	138	176	275	34	33	72	61
81	246	333	187	436	103	84	62	81
82	175	87	233	230	48	23	96	43

Year	Surface temperature (inshore)				Emergent chironomid catch/day			
	6/16-7/15		7/16-9/1		6/16-7/15		7/16-9/1	
	Alek	L.T.	Alek	L.T.	Alek	L.T.	Alek	L.T.
1973	9.2	8.0	11.8	12.3	16	9	44	12
74	12.5	12.3	14.3	14.1	11	5	8	6
75	7.8	6.9	14.0	13.5	26	2	25	6
76	9.7	7.4	12.9	12.8	10	2	13	10
77	9.5	9.5	11.8	12.1	30	3	16	15
78	9.9	8.2	14.4	14.4	10	5	23	22
79	10.6	9.8	13.6	12.9	10	6	18	7
80	--	7.8	13.5	12.9	--	4	5	15
81	13.2	11.3	13.7	14.0	6	2	14	6
82	8.9	5.8	11.4	11.3	2	3	22	21

Table 6, cont'd

Year	Date of ice breakup		Mean daily solar radiation (gm cal cm)		Mean lake level (cm) for L. Nerka	
	Alek.	L.T.	6/16-7/15	7/16-9/1	6/16-7/15	7/16-9/1
1973	6/2	6/8	463	280	157	86
74	5/22	5/27	547	322	111	59
75	6/8	6/15	341	337	150	83
76	6/10	6/17	445	307	126	90
77	6/1	6/13	468	290	204	170
78	5/22	6/2	327	335	130	98
79	5/16	5/24	463	319	136	116
80	5/17	5/27	331	362	154	102
81	5/23	5/28	436	291	112	83
82	6/5-6	6/12	321	294	176	103

Year	Secchi depth (m)			
	6/20-7/15		7/16-9/1	
	Alek	L.T.	Alek	L.T.
1973	9.7	7.9	10.4	10.4
74	7.8	9.4	8.0	11.3
75	7.2	7.8	10.1	10.1
76	8.8	10.0	10.1	9.9
77	7.6	6.6	8.1	5.6
78	8.0	8.2	10.3	7.9
79	8.0	9.6	7.1	8.6
80	8.0	8.4	7.0	11.8
81	9.0	7.0	9.1	7.8
82	5.4	4.7	7.2	5.8

Table 7. Mean townet catches and lengths on September 1 of juvenile sockeye salmon in Little Togiak Lake according to abundance of parent spawners and sampling area.

Escapement (thousands)	Brood year	Age 0 (year + 1)						Age 1 (year + 2)									
		Geometric mean catch			Mean length (mm)			Geometric mean catch			Mean length (mm)						
		A	B	C	Mean ¹	A	B	C	Mean ²	A	B	C	Mean ¹	A	B	C	Mean ²
6	1957	65	40	18	38	59	61	61	60	3	1	1	1	107	105	104	106
10	62	38	304	44	120	61	60	63	61	8	4	0	3	97	96	94	97
10	67	127	48	36	66	60	54	58	56	2	0	1	1	99	105	95	98
11	61	19	33	15	21	59	57	57	57	0	5	1	2	105	100	102	100
14	72	4	10	5	6	56	56	57	56	1	0	1	1	85	87	82	84
14	73	47	49	29	40	51	55	54	54	6	2	1	3	79	77	90	80
15	64	130	57	142	113	48	53	53	51	11	7	4	7	80	92	88	86
16	58	550	110	93	228	63	62	66	63	8	1	0	3	95	100	99	96
17	60	266	160	145	184	53	55	57	55	14	10	3	8	90	92	87	90
18	76	8	77	7	28	45	45	47	45	1	1	2	1	96	91	92	92
20	56	--	--	--	--	--	--	--	--	2	0	1	1	102	96	93	97
20	68	3	3	3	3	44	53	56	51	3	0	0	1	91	--	--	91
20	69	353	57	6	120	54	61	59	54	4	2	2	2	87	91	88	88
21	63	14	90	11	36	49	54	57	54	10	4	8	7	86	85	88	87
22	66	102	99	8	62	51	54	55	53	15	1	1	5	87	90	90	87
24	71	0	7	44	21	--	47	49	49	2	15	5	7	82	85	86	85
26	77	11	44	22	25	51	53	59	55	1	2	1	2	90	96	98	96
27	65	32	11	7	15	44	45	49	45	4	9	1	4	86	86	91	87
30	75	29	39	28	32	51	47	50	49	9	7	3	6	79	84	87	83
40	59	278	60	99	138	57	53	53	55	13	17	26	26	86	90	87	88
44	79	35	39	13	27	47	49	50	48	2	2	7	4	77	93	85	85
45	78	53	238	124	138	53	60	58	59	8	3	1	4	80	78	--	79
48	74	26	21	24	24	45	45	43	45	3	3	4	3	88	88	90	89
55	70	18	9	5	10	47	48	50	47	7	53	102	60	76	79	77	77
60	81	88	52	94	80	47	49	51	49	--	--	--	--	--	--	--	--
81	80	37	30	80	53	49	48	57	54	8	10	32	19	74	71	77	75

¹Weighted by surface area, i.e. $(\bar{C}_A \times 1.7) + (\bar{C}_B \times 1.8) + (\bar{C}_C \times 2.5) \div 6$.

²Weighted by surface area times mean catch.

Table 10. Statistics from stomach samples of Arctic char collected by hook and line from Little Togiak River during 30 days following ice breakup, 1972-1982.

	1972	1973	1974	1975	1976	1977	1978	1979	1980 ²	1981	1982
Samples collected in the day:											
Number examined	--	49	--	18	49	206	170	50	122	101	96
Mean length (mm)	--	470	--	449	435	399	443	431	457	411	447
Percent containing smolts	--	67	--	50	61	21	42	38	80	27	54
Mean number of smolts	--	4.9	--	3.3	3.1	0.5	1.6	1.6	6.5	1.4	5.8
Samples collected at night:											
Number examined	82	72	64	53	47	119	146	128	156	23	20
Mean length (mm)	446	429	429	404	400	411	431	441	461	434	467
Percent containing smolts	60	29	39	31	51	11	42	20	82	48	80
Mean number of smolts	4.5	1.6	1.6	1.3	1.2	0.3	1.4	1.0	11.7	1.4	6.6
Sockeye escapement to Little Togiak Lake in year-2 (thousands)											
Number of smolts migrating (hundreds)	55	24	14	14	48	30	18	26	45	44	81
Mean length of smolts in migration (mm)	--	--	--	--	1,438	3,036	4,582	3,588	9,813	267	--
Lake level (cm)	--	83	90	84	84	88	84	85	76	75	80
	177	161	121	150	122	206	133	164	172	135	179
Total number of char removed	463	208	283	71 ¹	113 ¹	574	587	344	87	181	116
Total number of char measured	729	208	263	71	113	574	587	344	512	181	116
Mean length (mm)	444	444	435	415	427	388	432	427	456	408	450

¹Char were also removed by the Alaska Department of Fish and Game; however, the total number removed in each of these years was less than 200.

²Sixty-nine percent of char were captured by 5 to 15 minute drift gillnet sets.

Table 11. Sockeye salmon escapements, smolt production, and returns for the Wood River lake system (numbers in millions) and Little Togiak Lake (numbers in thousands).

Brood year	Escape-ment	No. of smolts		Smolts/spawners	Mean length		Adult returns			Survival (%)		
		Age I	Age II		Age I	Age II	1.2	1.3	2.2	2.3	Age I	Age II
Wood River Lake System^a												
1973	0.33	27.95	4.80	99	83	95	0.19	1.12	0.06	0.03	5	2
74	1.71	101.40	12.55	67	84	98	2.85	1.56	0.40	0.05	4	4
75	1.27	60.75	8.40	54	71	90	1.53	1.85	0.38	0.65	6	12
76	0.82	46.60	5.13	63	79	100	2.14	2.26	0.51	0.26	9	15
77	0.56	60.84	1.99	112	90	95	0.95	2.73	0.05	--	6	--
78	2.27	46.30	33.20	35	78	96	0.85	--	--	--	--	--
79	1.71	64.33	(4)	40	88	98	--	--	--	--	--	--
80	2.97	(33)	--	--	79	--	--	--	--	--	--	--
Little Togiak Lake												
1958	16	--	16	--	--	113	20	13	2	+	--	13
59	40	650	--	--	79	--	24	5	7	+	4	--
73	14	--	20	--	84	101	7	48	1	5	--	16
74	48	167	144	6	85	101	29	25	35	1	32	25
75	30	366	62	14	84	105	27	56	29	5	23	55
76	18	479	4+	27	84	104	37	50	26	8	19b	--
77	26	129+	12	5+	85	100	135	119	0	--	--	--
78	45	1021	5+	23	75	99	12	--	--	--	--	--
79	44	67+	--	--	83	95	--	--	--	--	--	--
80	81	--	--	--	79	--	--	--	--	--	--	--

^aModified from: Bucher, Wesley. 1982. 1981, Wood River Sockeye Salmon Smolt Studies. In 1981 Bristol Bay Sockeye Salmon Smolt Studies, D.C. Huttunen, ed. ADF&G Tech. Data Report No. 73.

^bFive thousand age 1.4 return included.

Table 12. Runs, escapements, and returns (in thousands) of sockeye salmon to Little Togiak Lake, 1946-1982.

Brood year	Run	Escape- ment	Return				Total	R/E
			1.2	2.2	1.3	2.3		
1946	57	40	*	0	5	0	5	0.1
47	168	80	5	1	7	*	13	0.2
48	82	35	5	1	10	*	16	0.5
49	6	1	4	*	4	*	8	8.0
50	10	3	19	3	8	3	33	11.0
51	11	6	20	8	12	*	40	6.7
52	13	5	19	*	8	0	27	5.4
53	14	10	3	3	16	1	23	2.3
54	23	16	14	9	2	2	27	1.7
55	31	20	49	10	10	2	71	3.6
56	42	20	9	1	11	0	21	1.1
57	12	6	3	*	5	0	8	1.3
58	33	16	20	2	13	*	35	2.2
59	61	40	24	7	5	*	36	0.9
60	31	17	18	16	8	3	45	2.6
61	17	11	18	1	15	*	34	3.1
62	25	10	18	*	9	0	27	2.7
63	39	21	11	2	21	0	34	1.6
64	30	15	10	3	5	2	20	1.3
65	42	27	23	15	15	1	54	2.0
66	37	22	45	2	28	1	76	3.5
67	20	10	11	2	8	2	23	2.3
68	33	20	9	0	15	*	24	1.2
69	31	20	2	15	19	1	37	1.8
70	77	55	26	30	13	3	72	1.3
71	42	24	1	5	5	9	21**	0.9
72	20	14	8	6	12	5	41	2.9
73	19	14	7	1	48	5	61	4.4
74	60	48	29	35	25	1	90	1.9
75	45	30	27	29	56	5	117	3.9
76	31	18	37	26	50	8	126**	7.0
77	34	26	135	0	119	(0)	254	9.8
78	83	45	12					
79	92	44						
80	124	81						
81	216	60						
82	139	36						

*Less than 500. **Includes returns of age 1.4.

Table 15. Runs, escapements, and returns (in thousands) for river spawners in the Wood River lake system, 1946-82.

Brood year	Run	Escape- ment	Return				Total	R/E
			1.2	2.2	1.3	2.3		
1946	125	87	5	*	33	*	39	0.4
47	235	112	8	*	29	3	40	0.4
48	257	110	25	1	221	0	247	2.2
49	61	9	33	0	27	0	60	6.7
50	84	23	30	2	239	20	291	12.7
51	46	24	157	17	166	18	358	14.9
52	54	21	101	1	105	*	207	9.9
53	258	164	10	17	89	18	134	0.8
54	57	35	26	26	134	8	194	5.5
55	398	258	191	21	205	90	507	2.0
56	304	142	23	2	253	1	279	2.0
57	134	83	6	0	129	*	135	1.6
58	132	58	52	2	85	*	139	2.4
59	369	250	45	24	142	21	232	0.9
60	257	105	87	17	444	41	589	5.6
61	351	237	51	3	539	26	619	2.6
62	182	54	23	2	135	5	165	3.1
63	132	63	50	3	344	2	399	6.3
64	253	112	50	116	122	58	346	3.1
65	533	301	210	19	546	125	900	3.0
66	606	298	36	1	363	20	420	1.4
67	213	99	13	0	96	0	109	1.1
68	402	235	94	1	262	0	357	1.5
69	450	275	2	71	201	50	324	1.2
70	659	352	99	19	653	42	813	2.3
71	502	242	18	65	458	67	608	2.5
72	210	138	145	4	255	0	404	2.9
73	265	212	56	4	1074	49	1183	5.6
74	371	310	187	47	718	33	985	3.2
75	740	606	185	122	1798	497	2602	4.3
76	710	399	178	182	1385	635	2380	6.0
77	382	252	81	9	1728	(40)	1858	7.4
78	1479	650	153					
79	1023	435						
80	2336	1504						
81	2145	608						
82	2525	643						

Table 16. Deviations from predicted returns of sockeye salmon to creeks and beaches in the Wood River lake system and to Little Togiak Lake.

Brood year	Creeks				Beaches				Little Togiak			
	Return		Deviation		Return		Deviation		Return		Deviation	
	Obs.(R)	Pred.(R)	$\hat{R}-\hat{R}$	%	Obs.(R)	Pred.(R)	$\hat{R}-\hat{R}$	%	Obs.(R)	Pred.(R)	$\hat{R}-\hat{R}$	%
Geom.means												
1950-72	310	313	133*	43*	581	580	155*	27*	34	35	12*	35*
1973	241	100	141	141	302	141	161	114	62	36	26	72
1974	842	463	379	82	3103	1346	1757	131	90	53	37	70
1975	662	413	249	60	1387	711	676	95	116	51	65	127
1976	1175	316	859	272	1148	488	660	135	127	42	85	202
1977	688	213	475	223	575	393	182	46	254	49	205	418

*Mean of deviations, ignoring sign.

APPENDIX

APPENDIX

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Effects of Fertilization of Little Togiak Lake on the Food Supply and Growth of Sockeye Salmon

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Abstract

Juvenile sockeye salmon (*Oncorhynchus nerka*) in the Wood River lake system exhibit density-dependent growth and are among the smallest smolts produced in Bristol Bay. We hypothesized that an increase in growth would be followed by an increase in survival and hence an increase in the abundance of returning adults. Little Togiak Lake (6 km²) was annually treated with various amounts of diammonium phosphate (220 to 1,780 kg) during the summers of 1974 to 1978 and the effects on phytoplankton, zooplankton, chironomids, and fish growth were monitored. In each year that phosphates were applied, the biomass of phytoplankton increased within a few days and the increase was approximately proportional to the density applied. Significant increases in abundance of zooplankton and chironomids during June to September were observed in some, but not all years; however, following each year of fertilization, the smolts that migrated from Little Togiak Lake were larger than those from the other lakes in the system, indicating that growth was enhanced by fertilization.

Introduction

The commercial fishery for sockeye salmon (*Oncorhynchus nerka*) in the Nushagak District of Bristol Bay developed in the late 1880s. Following the build-up of the fishery, there was a 20-year period when the annual catches averaged 5 million fish and then a 30-year period when the catches averaged 3 million fish. Since 1949, the catches have averaged about 1 million. Comparable declines in catches did not occur in the other fishing districts in Bristol Bay and the decline in the Nushagak catches appears to have been caused by a decline in the productivity (return per spawner) of the Wood River stock, which in the most recent period has produced the majority of fish in the Nushagak District. The level of escapements to the Wood River lake system during the three periods of the fishery did not change significantly, although there has been considerable annual variation (Mathisen, 1971).

The Fisheries Research Institute began investigations of the sockeye salmon in the Wood River lakes in 1946. By the end of the 1960s, it was evident that: 1) smolts migrating from Wood River in recent years were the smallest in Bristol Bay and were smaller than smolts that migrated from Wood River in the early 1900s; 2) growth of juvenile sockeye was density-dependent; 3) the standing stock of zooplankton (their principal food) was inversely related to the abundance of juveniles; 4) primary productivity was low and did not vary greatly from year to year; and 5) phosphorus was the most likely nutrient that limited primary production (Burgner, 1964; Burgner, et al., 1969; Gadau, 1966; and Rogers, 1968, 1973 and 1977). Therefore, in 1970 we fertilized a small bay (0.6 km²) in Lake Aleknagik (Figure 1) with a commercial diammonium phosphate fertilizer to determine if primary and secondary productivity could be increased. The standing crop of phytoplankton increased in 1970 and the abundance of zooplankton and chironomids increased in 1971 (Rogers, et al., 1973).

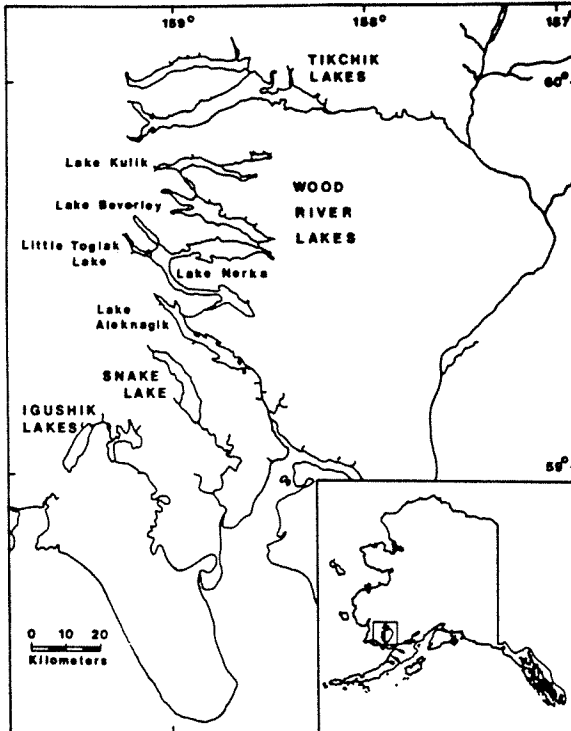


Figure 1. Lakes of the Nushagak District of Bristol Bay.

Little Togiak Lake was chosen for experimental fertilization because it is small (6 km²), has a history of high fish density and poor growth of juvenile sockeye salmon, and the abundance and size of smolts and the abundance of returning adults could be measured easily. Intensive limnological measurements were begun in 1973 and variable amounts of fertilizer were added to the lake during the summers of 1974 to 1978. A final evaluation of the effects on the production of sockeye salmon will not be made until 1982. This report is a summary of the results to date. Detailed methods and results are given in B. Rogers (1979), D. Rogers (1979) and Hardy (1979).

Methods

Since the experimental fertilization of Little Togiak Lake was conducted under natural, and thus uncontrolled environmental conditions, it was important that we had several long-term measurements of environmental parameters so the effects of fertilization could be separated from natural annual variation. Although intensive sampling in Little Togiak Lake did not begin until 1973 for some parameters, such as chlorophyll *a* and zooplankton densities, we had annual measurements in Lake Aleknagik since 1963. Annual estimates of the growth and relative abundance of sockeye salmon juveniles and threespine stickleback (*Gasterosteus aculeatus*) were available for each of the Wood River lakes since 1958. Annual estimates of the abundance of sockeye salmon spawners and spawner-return statistics were available for each lake since 1946 and annual weather data have been collected for the region since 1919.

Our methods for measuring the effects of fertilization were to compare measurements between 1) fertilized and unfertilized areas of Little Togiak within a year, 2) fertilized and unfertilized years in Little Togiak, and 3) Little Togiak and Lake Aleknagik (and to some extent other lakes) in normal years compared to years of fertilizing. The lakes are usually

icefree from early June to mid-November but field observations were largely restricted to the period from mid-June to mid-September because most of the workers were university students who had to return for classes each autumn.

Some morphometric data and statistics on the adult sockeye salmon populations in Little Togiak and Lake Aleknagik are given in Table 1. Little Togiak is a narrow lake and it has two basins, a shallow upper basin (1.7 km²) with a maximum depth of only 25 m and a deeper lower basin with a maximum depth of 83 m. Lake Aleknagik has a single basin. Alder predominates along the shore of Little Togiak and spruce trees are absent, whereas spruce, birch, and alder surround most of Lake Aleknagik. The littoral zone is rather restricted in Little Togiak with typically steep gradients and a rock or gravel bottom. In contrast, Lake Aleknagik contains some rather extensive, shallow bays with mud bottom. The relative production of sockeye salmon is similar for the two lakes; however, the populations in Lake Aleknagik are exploited at a slightly higher rate (mean rate of exploitation 1950 to 1976 was 45 percent vs. 41 percent) because it has a higher proportion of older and larger fish and the gillnet fishery is selective for these larger fish.

Physical Parameters

Solar radiation was measured daily with a Belfort pyrheliometer and lake level was measured at Lake Nerka near the outlet of Little Togiak Lake. Surface temperatures were measured almost daily. The following measurements were made weekly in Little Togiak Lake and monthly in Lake Aleknagik, unless otherwise noted. Temperature-depth profiles were made at three stations on each lake. Secchi depth was measured at six stations, and when fertilizer was being applied, the measurements were made every two or three days. Conductivity was measured at 5 and 15 m at two stations on each lake. Nitrate-nitrogen, NH₃ + organic nitrogen, and total soluble phosphorus were measured at 5, 15, and 20 m at two stations in Little Togiak Lake and one station in Lake Nerka just before and after periods of fertilization in 1976 to 1978.

Biological Parameters

The concentration of chlorophyll *a* was determined from 2-liter water samples collected in Van Dorn bottles from 1, 3, 5, 7, 10, 15, 20, 30, and 45 m at two stations on each lake. Water

Table 1. Morphometric data for Little Togiak Lake (59°03'N, 159°09'W) and Lake Aleknagik (59°20'N, 158°48'W), and statistics on their sockeye salmon populations (1950-1976).

	Little Togiak	Aleknagik
Elevation (m)	23	10
Lake area (km ²)	6	83
Mean depth (m)	29	44
Maximum depth (m)	83	110
Drainage (km ²)	86	3,108
Annual discharge (m ³ x 10 ⁶)	102	4,139
Sockeye escapement (thousands)		
Minimum	3	31
Mean	20	183
Maximum	55	493
Average age composition of spawners (%):		
1.2	50	33
1.3	35	56
2.2	12	6
2.3	3	5
Return per spawner:		
Geometric mean	2.3	2.1
Minimum	0.9	0.4
Maximum	11.0	10.1

was filtered through an AA Millipore filter (0.8 μ , 45 mm diameter) which was later dissolved in 90 percent acetone. Absorbances were measured on a Bausch & Lomb Spectronic 20 Spectrophotometer with a 1 cm path length. Calculations of chlorophyll *a* densities were made using formulas by Parsons and Strickland (1963). Phytoplankton species composition, numbers, and cell volumes were also calculated in 1976 and 1977.

The relative abundance and settled volume of zooplankton were determined from vertical hauls by a 1/2-m net with a mesh size of 234 μ . Hauls were made from 60 m or near the bottom at shallower stations. The net did not sample nauplii or most rotifers (only *Asplanchna* sp. was usually caught); however, the mesh size retained the sizes of organisms typically eaten by the pelagic fish.

The relative abundance of emergent chironomids was determined from catches in conical, clear plastic traps similar to those described by Sublette and Dendy (1959). These were suspended 1 m off the bottom at a depth of about 3 m. Five traps were located in Little Togiak Lake and three in the lower end of Lake Aleknagik. The catches were counted every two or three days during the summer. Chironomid larvae, and other benthic organisms, were sampled with an Ekman dredge (225 cm² opening) at each end of Little Togiak Lake from depths of 3, 5, 7, and 10 m. Samples were taken at additional deeper stations in 1974, but the density of benthic organisms was low at sites deeper than 20 m. Sampling was usually conducted every other week between 20 June and 10 September.

The relative abundances and sizes of fish in the littoral zone were estimated from weekly beach seine hauls during late June to early August. Six stations were sampled in Little Togiak and ten in Lake Aleknagik. Juvenile sockeye and most of the threespine stickleback move offshore during late July. The fish were then sampled with a ternet during mid-August to early September. Nine hauls of five minute duration were made on two nights in Little Togiak Lake and 12 hauls were made in Lake Aleknagik on one night each year. Stomach contents of fish sampled in Little Togiak Lake were examined in 1975 and 1976 to determine the composition and amount of food eaten.

The abundance, length, and weight of sockeye salmon smolts migrating from Little Togiak Lake were estimated from fyke net catches in Little Togiak River. The opening between the wings of the net was from 1/6 to 1/8 of the width of the river, depending on the flow. The net with a live box was fished almost continuously during June and July, and daily samples of 25 to 50 fish were collected to determine the age composition and size of the smolts. The Alaska Department of Fish and Game sampled the smolt migration from the lake system at the outlet of Lake Aleknagik and provided us with their data.

Arctic char (*Salvelinus alpinus*), which concentrate around the interconnecting rivers of the lake system in June and July to feed on migrating smolts, are the most abundant predators on juvenile sockeye in the lake system. We have sampled char in Little Togiak River by hook and line since 1972 to determine the number and occurrence of smolts in their stomachs.

Yearly, the Alaska Department of Fish and Game (ADF&G) utilized counting towers on Wood River to estimate the escapements of adult salmon into the lake system and aerial surveys to estimate the abundance of adult salmon in each of the lakes (by Mr. Mike Nelson). Since 1975, we have also counted the salmon as they migrated into Little Togiak Lake. These counts were made for 30 minutes out of each daylight hour and were later expanded to estimate the total escapement. The age composition in the escapement to Little Togiak Lake was determined from otoliths collected on the spawning grounds, and the runs (catch plus escapement) by age group to the lake were estimated from the ratios of run to escapement for the Wood River lake system.

Fertilization

A commercial diammonium phosphate fertilizer was used in 1974 and 1975 and a technical grade of diammonium phosphate was used in 1976 through 1978. Fertilizer was

dissolved in a drum and then sprayed on the surface of the lake from a moving boat. For purposes of sampling and the application of fertilizer, the lake was divided into three areas. Area A was the upper basin (1.7 km²), and fertilizer was applied over the upper half of this basin in 1974 and 1975 and over the entire basin in 1976 (Figure 2 and Table 2). Area B was the middle portion of the lake (1.8 km²), and it was fertilized in 1976 to 1978. Area C was the lower portion of the lake (2.5 km²), and it was fertilized in the same years; however, fertilizer was not applied near the lake outlet to minimize loss through the river. The amounts of phosphorus added to the lake were comparable to amounts contained in the salmon carcasses (Table 3). However, since most of the salmon decompose after mid-September and the decomposition is rather slow in the lake, nutrients from salmon carcasses probably did not affect primary production during the summer, but may have affected production in the fall or following spring.

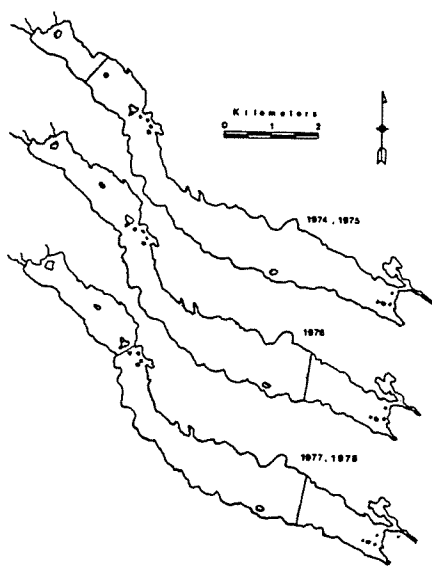


Figure 2. Areas fertilized (shaded) in Little Togiak Lake.

Results

Physical Parameters

During the years of our experiment there were some rather drastic variations in the environment that have made it difficult to interpret the biological effects of fertilization. Winter temperatures can affect the survival of eggs in the gravel, while spring and summer weather determines the length of the growing season and influences the growth rate of the fish. There were exceptionally cold winters (November to March) in Bristol Bay from 1969-70 through 1975-76; but the winter of 1976-77 was the mildest on record since 1919 (the Wood River lakes did not freeze over until March). The following winters of 1977-78 and 1978-79 were much milder than normal. Air temperatures in April and May largely determine when ice breakup occurs on the lakes. The date of ice breakup was about normal in 1973, one to two weeks late in 1975, 1976, and 1977, and one to two weeks early in 1974, 1978, and 1979.

Water temperatures during the summer in the upper 20 m were warmest in 1974; however,

Table 2. Schedules of applications of diammonium phosphate to Little Togiak Lake, 1974-1978.

Year	Date	Amount added (kg) by lake area			Total	Density of applications (kg/km ²)
		A	B	C		
1974	8/13	123			123	246
	14	88			88	176
	17	88			88	176
	18	80			80	160
	22	71			71	142
	23	106			106	212
	28	48			48	96
	29	57			57	114
Total/mean		661			661	165
1975	8/13	88			88	88
	17	66			66	66
	20	66			66	66
Total/mean		220			220	73
1976	7/12	133	89		222	85
	13	45	89	89	223	89
	14		44	178	222	92
	18	133	89		222	85
	19	89	89	44	222	89
	21			223	223	149
Total/mean		400	400	534	1,334	98
1977	7/13		312		312	173
	14			356	356	237
	20		222	89	311	111
	21		89	89	178	94
	22			177	177	118
Total/mean			623	711	1,334	147
1978	7/12			178	178	118
	13		178		178	99
	17			178	178	118
	18		178		178	99
	24			178	178	118
	25		178		178	99
	31			178	178	118
	8/1		178		178	99
	7		178		178	99
	8			178	178	118
Total/mean			890	890	1,780	109

the highest surface temperatures occurred in 1978 and the temperature in the entire water column was highest in 1979 (Figure 3). A thermocline develops in August usually between 10 and 15 m, but in 1979 the thermocline was near 20 m. Each year, water temperatures were about one degree warmer in Lake Aleknagik than in Little Togiak Lake.

Lake level declines during the winter to a low in mid-April and increases rapidly in May to a peak in late June as a result of the melting snow pack. Fluctuations during the remainder of the summer are caused by precipitation, which is usually highest in August and September. Lake level was exceptionally high during the summer of 1977 (Figure 3).

When fertilizer was applied in late August of 1974 and 1975, water temperatures were higher, but solar radiation and lake level were lower than when fertilizer was applied in late

Table 3. Amounts of phosphorus and nitrogen added to Little Togiak Lake annually from 1972 to 1979 in salmon carcasses in the fall and in diammonium phosphate fertilizer.

Year	Salmon escapement	Amount (kg) in salmon carcasses ¹		Fertilizer added (kg)		Dates
		P	N	P	N	
1972	14,000	126	1,222	0	0	
1973	14,000	149	1,445	0	0	
1974	48,000	413	4,017	155	140	August 13-29
1975	30,000	261	2,540	52	47	August 13-20
1976	18,000	150	1,460	313	283	July 12-21
1977	26,000	247	2,397	313	283	July 13-22
1978	45,000	384	3,731	418	377	July 12—August 8
1979	44,000	375	3,648	0	0	

¹Assumes a weight of 4.5 lb (2.04 kg) for age .2 and 6.8 lb (3.08 kg) for age .3, and that a salmon contains 0.36% P and 3.5% N (Donaldson, 1967; Nelson and Edmondson, 1955).

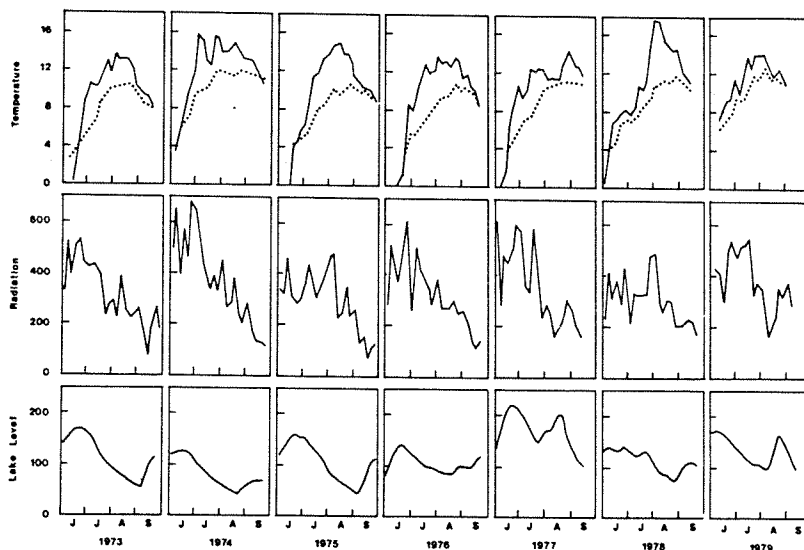


Figure 3. Average water temperature (C) at the surface (solid line) and 0-20 m (dotted line), and 5-day means of daily solar radiation (gm cal/cm²); and relative lake level (cm) during summers of 1973-1979.

July from 1976 to 1978 (Figure 3). In every year, except 1978, there were relatively heavy rains and overcast skies soon after the applications.

Conductivity did not vary greatly during the summer, except in 1977 when some rather extreme fluctuations occurred in Little Togiak Lake and to a lesser extent in Lake Aleknagik (Figure 4). These fluctuations were not closely correlated with fluctuations in other measurements except that the low values in July corresponded to exceptionally low concentrations of nitrogen whereas the high values in late August followed a heavy rainfall.

Variation in Secchi depth generally corresponded to variation in chlorophyll concentration except for the low values in late September 1973 and late August to early September 1979 (Figure 4). Runoff from rain caused a milky-white color on those occasions rather than the usual blue or green water color. In early August 1977, runoff plus a high phytoplankton density caused a milky-green color. When fertilizer was applied to only the upper basin of the lake (1974-75) Secchi depth decreased there but not in the lower basin. Secchi depth decreased from 11.5 m to 4 m within a few days after the addition of fertilizer to the upper basin in 1974.

Phosphorus concentrations averaged 10 to 14 $\mu\text{g/l}$ prior to fertilization in 1976, 1977 and

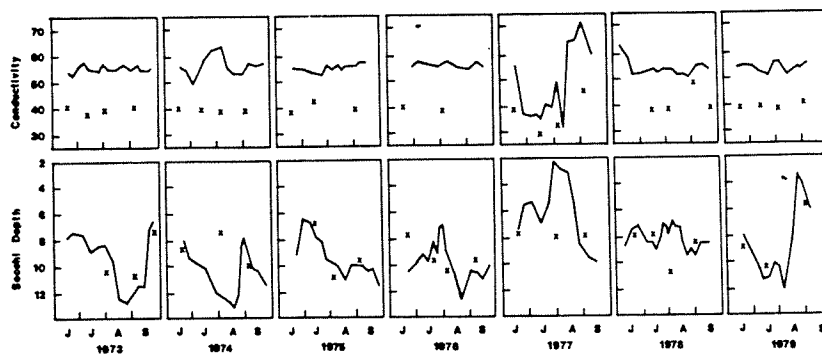


Figure 4. Conductivity (micromhos/cm) and Secchi depth (m) in Little Togiak Lake and Lake Aleknagik (x) during the summers of 1973-1979.

1978. The concentrations increased twofold in 1976 and 1978, and threefold in 1977 following fertilization. Total nitrogen did not change significantly in 1977 after fertilization. Mean values ranged from 111 to 163 $\mu\text{g/l}$. Total nitrogen declined from 236 before fertilization to 188 $\mu\text{g/l}$ after fertilization in 1976 and from 400 to 270 $\mu\text{g/l}$ in 1978. Nitrogen to phosphorus atomic ratios were usually greater than 20:1 except following the fertilization in 1977 when a low average ratio of 9:1 occurred in early August.

Phytoplankton

Primary production was not measured during our experiment in Little Togiak Lake for budgetary reasons. However, the rate of carbon-fixation was measured annually in Lake Aleknagik during the 1960s and in one year in Little Togiak Lake. No significant difference in the rates was observed between the lakes. In Lake Aleknagik, primary production was quite low below 20 m and usually zero below 30 m. Maximum rates of production nearly always occurred between 3 and 10 m and midday production rates for the upper 20 m averaged 14, 13, 12 and 15 $\text{mgC/m}^2/\text{h}$ in late June, mid-July, early August and early September, respectively. In our experiment, we relied on changes in chlorophyll *a* and measurements of zooplankton standing stock to evaluate the effect of fertilization on primary production.

Chlorophyll *a* increased in each year of fertilization, usually in the upper 10 m, and the amount of increase was approximately proportional to the density of phosphorus added and the amount of zooplankton present (Figure 5). In 1974 and 1975, chlorophyll increased only in the upper basin where the fertilizer was applied; however, in 1977 and 1978, when fertilizer was applied only in the lower basin, there were greater increases in the upper basin. This was probably caused by the movement of warm surface water toward the upper end of the lake and the lower density of zooplankton there. Most of the water comes into the lake at the west end from melting snow and the prevailing winds are easterly.

After the beginning of fertilization in August 1974 the chlorophyll concentration was significantly higher in Little Togiak Lake than in Lake Aleknagik until 1979 when fertilization was discontinued (Figure 6). The peak in chlorophyll concentration during late June to early July was related to the estimated amount of phosphorus in salmon carcasses in the previous fall. Excluding observations in 1979 (when the peak obviously occurred prior to our first measurements), but including observations in 1980, the correlation was .88 ($n = 7$). There was thus some evidence that nutrients from salmon carcasses have a positive effect on primary production during the early growth period of the progeny.

The phytoplankton communities were dominated by diatoms throughout the summers of 1976 and 1977. The greatest increase in numbers after fertilization occurred in the order

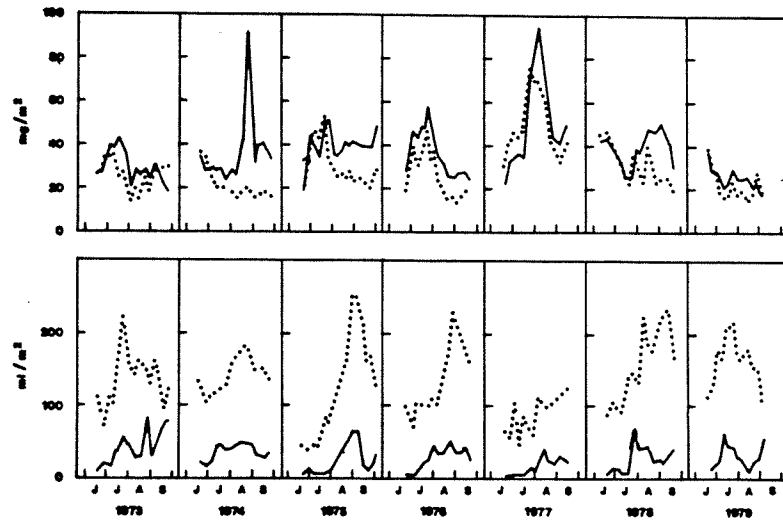


Figure 5. Amounts of chlorophyll a 0-20 m (top) and volumes of zooplankton (bottom) in the upper basin (solid line) and lower basin (dotted line) of Little Togiak Lake during summer 1973-1979.

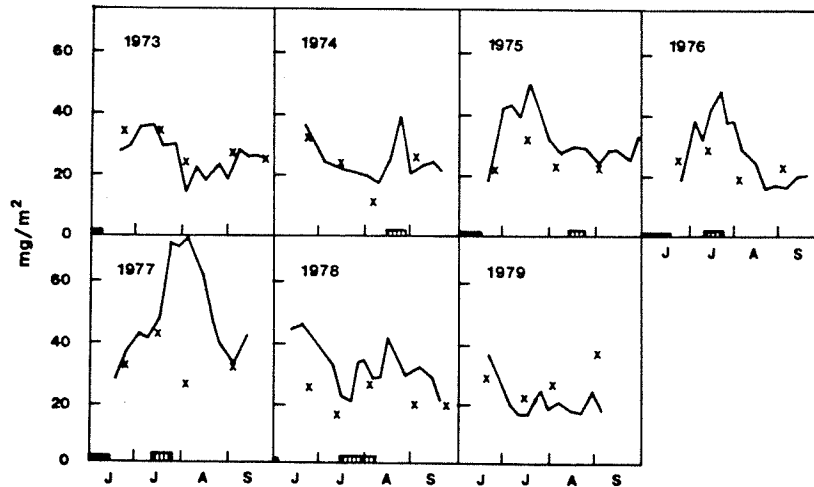


Figure 6. Amount of chlorophyll a (mg/m^2) in the upper 20 m in Little Togiak Lake and Lake Aleknagik (X), 1973-1979. The solid bars indicate ice cover on Little Togiak Lake and the hatched bars indicate when fertilizer was applied.

Centrales in 1976, and in Pennales in 1977. There were increases in cell volumes of both orders in 1976, but only in the Pennales in 1977. *Asterionella formosa*, which contributed 23 percent of the total cell volume in 1976 and 80 percent in 1977, was the species most affected by fertilization. Following fertilization in 1977, 96.5 percent of the phytoplankton standing crop was *A. formosa*. *Cyclotella ocellata* was the next principal species affected by fertilization and in both years there were significant increases in the volume of this species following fertilization. Blue-green algae were absent in 1976, but *Anabaena* and *Chroococcus* did appear after fertilization in 1977.

Zooplankton

The volume of zooplankton early in the summer was generally higher in Lake Aleknagik

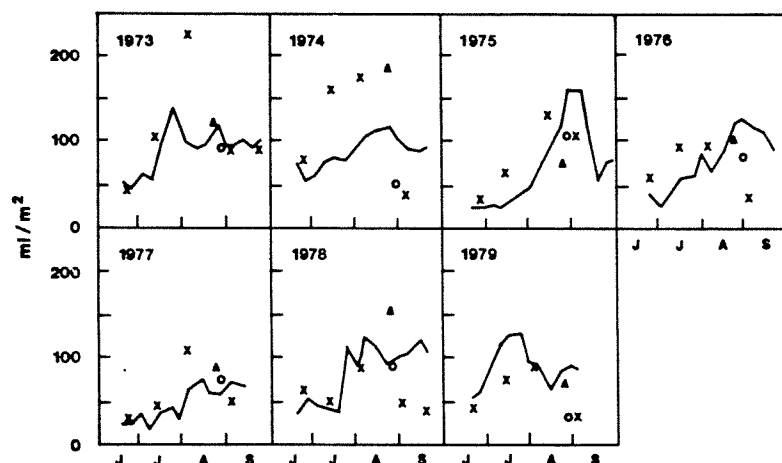


Figure 7. Settled volume of zooplankton (ml/m²) in Little Togiak Lake at weekly intervals and in lakes Aleknagik (X), Nerka (O), and Beverley and Kulik (▲).

than in Little Togiak Lake, except in 1979; late in the summer, the volume of zooplankton in Little Togiak Lake tended to be higher (Figure 7). The abundance of sockeye fry and threespine stickleback, which feed upon several species of zooplankton, was low in both lakes during 1973 and 1974, but high between 1975 and 1979. Even so, settled volumes of zooplankton were quite high during late August of 1975, and relative to the density of predators in the lake, again in late August of 1976. However, these high volumes were caused in part by relatively high densities of the large cladoceran *Holopedium gibberum* which was not commonly eaten by either fish species. *Holopedium* was scarce in 1973 and 1974, relatively abundant in late August of 1975 and 1976 (30,000 and 20,000/m², respectively) and then was nearly absent from Little Togiak Lake between 1977 and 1979.

We could not fully evaluate the effect of fertilization on the zooplankton community because our sampling terminated in September. This was often at a time when some species, such as *Diaptomus gracilis*, *Eurytemora yukonensis*, and *Daphnia longiremis* were increasing in abundance (Figure 8). Only the seasonal occurrence of *Eubosmina longispina* was typically within our sampling period. The densities of *Cyclops columbianus*, which can live longer than a year, were similar in the two lakes prior to fertilization; but it was generally more abundant in Little Togiak Lake after fertilization and there were exceptionally high densities in July 1979. Calanoid copepods were unusually numerous in September 1978, *Eubosmina* in July 1978 and 1979, and *Daphnia* in August 1976 and 1978, even though fish densities were high from 1975 to 1979. The abundances of all zooplankters were low in 1977. Between 1974 and 1978, the rotifer *Asplanchna* sp. was relatively scarce with maximum abundances of only 20,000 to 55,000/m². However, in late July 1979, *Asplanchna* became very abundant, reaching densities of 187,000/m². At that time it was next to *Cyclops* in abundance.

Benthos

Chironomids can be a major source of food for juvenile sockeye salmon and threespine stickleback in June and July when the abundance of zooplankton is usually low. Average catches of emergent chironomids were consistently greater in Lake Aleknagik than in Little Togiak Lake (Figure 9), which is probably because Lake Aleknagik has more suitable habitat for chironomid production than does Little Togiak Lake. Catches in Lake Aleknagik during 1974 and perhaps in 1979 were low partly because sampling did not begin soon after ice

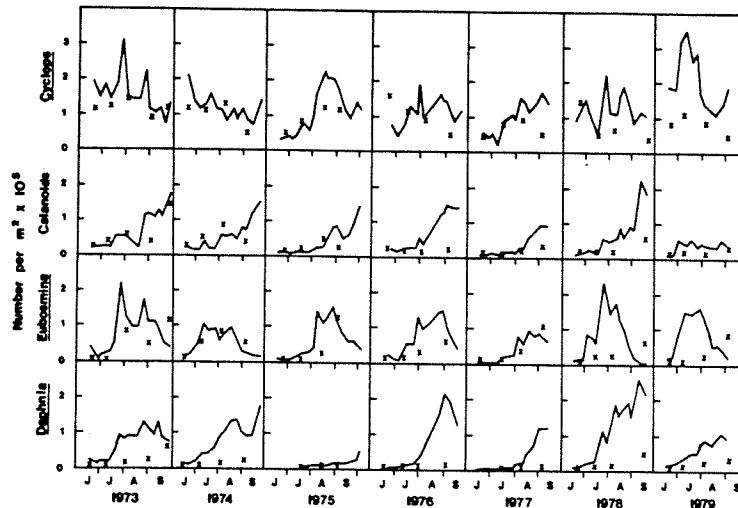


Figure 8. Summer abundance of zooplankters in Little Togiak Lake and Lake Aleknagik (X), 1973-1979.

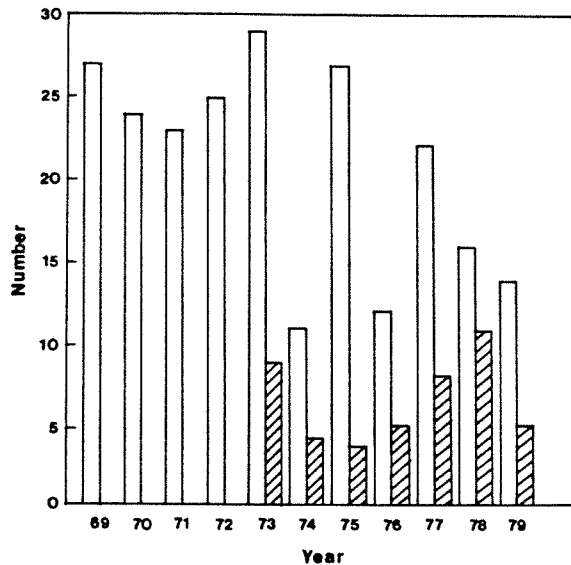


Figure 9. Average daily catches of emergent chironomids during the summer in Lake Aleknagik (1969-1979) and Little Togiak Lake (1973-1979).

breakup as in other years. In Little Togiak Lake, the highest emergence rates occurred during early August, whereas catches during June and early July were usually quite low (2 to 3 per trap per day). By contrast, there was often a high emergence rate in Lake Aleknagik soon after the ice was out in early June and then another peak emergence in late July. Neither the seasonal occurrence nor the average catch of chironomids in Little Togiak Lake were apparently affected by fertilization; however, fish abundance and presumably predation on chironomids were also higher after fertilization.

The relative abundance of chironomid larvae in benthic samples from Little Togiak Lake declined in August 1975 and then increased in 1978, but mean values for 1978 and 1979 were not significantly different from those in 1974 and 1975 (Figure 10). Differences in the relative

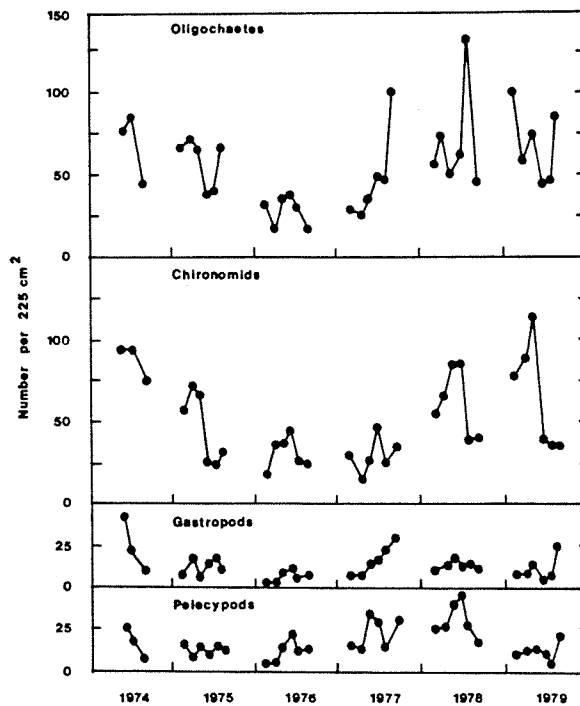


Figure 10. Relative abundances of benthic organisms in Little Togiak Lake. Each point is the geometric mean of eight observations. Early August to early September in 1974 and late June to early September in other years.

annual abundance of oligochaetes were similar to chironomids and the composition of benthic animals did not change significantly from 1974 through 1979. During 1977 and 1978, pea clams were more numerous than in prior years, but they were not abundant in 1979.

Fish Abundance and Growth

In both lakes, the average annual beach seine catches of sockeye salmon fry and threespine stickleback were lower in 1973 and 1974 than in 1975 to 1979. The increases in sockeye catches after 1974 correspond to increases in parent escapements to both lakes. Catches of threespine stickleback were relatively low throughout the lake system from 1972 through 1974 following exceptionally cold summers in 1971 and 1972. They began to increase in abundance during 1975. Catches of other species did not change significantly during the seven years. Beach seine catches for most species were higher in Lake Aleknagik than in Little Togiak Lake. Averages of the annual geometric mean catches were 102 and 92 sockeye salmon fry, 92 and 59 threespine stickleback, 17 and ten sculpin (*Cottus cognatus*), and ten and five ninespine stickleback (*Pungitius pungitius*), respectively. However, catches of Arctic char fry were significantly higher in Little Togiak Lake—19 compared with five in Lake Aleknagik.

The growth rates (mm/day between 20 June and 1 September) of sockeye salmon fry were higher in Lake Aleknagik, except in 1977 (.25 to .27) and 1979 (.28 to .39). The fry were longer on 1 September in Lake Aleknagik each year except 1979. Growth rates of age I threespine stickleback did not differ significantly between the lakes, but they were significantly longer in Lake Aleknagik. Growth rates of threespine stickleback and Arctic char were lower in both lakes during 1975 to 1979 when fish populations were denser than in 1973 and 1974.

Zooplankton abundance during the early summer and hence the amount of food in the fish

stomachs was lowest in the upper basin of Little Togiak Lake, where most of the sockeye spawn. Later in the summer, after the sockeye fry and threespine stickleback had moved offshore, there was little difference in the level of feeding between fish in the two basins of the lake. Stomachs of sockeye fry and threespine stickleback collected offshore throughout the lake during August usually contained 60 to 90 percent *Eubosmina*. Although *Cyclops* was more abundant in the zooplankton hauls, it occurs deeper in the water column than the cladocerans and probably is not as available to the fish. In August 1976, when *Daphnia* increased in the zooplankton, there was a corresponding increase in the stomachs of sockeye fry and threespine stickleback. However, fertilization did not greatly affect the growth of sockeye salmon fry up to 1 September, except perhaps in 1978 and 1979 (Figure 11). The average weights of fry in those years were heavier than expected from the density of parent spawners, but still within the range of variation from past years.

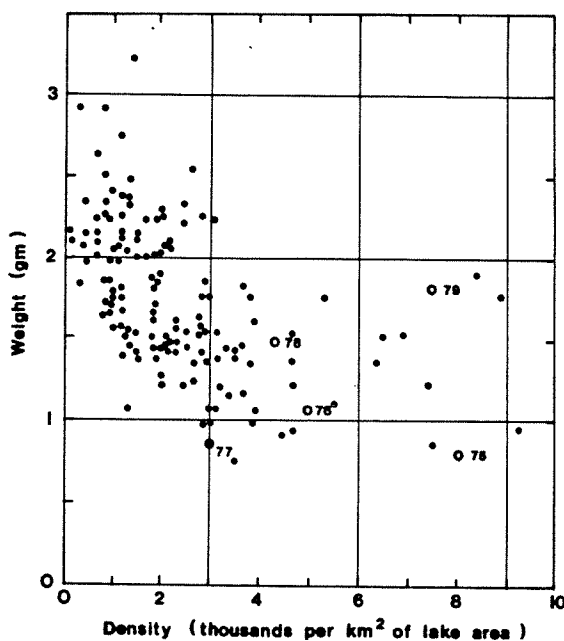


Figure 11. Mean weights of sockeye salmon fry on 1 September (1958-1979) in each of the Wood River lakes vs. the relative density of parent spawners (prior year). Observations from Little Togiak Lake following fertilization are indicated (o).

The mean lengths of age I smolts from Little Togiak Lake were comparable to those from the lake system prior to fertilization; however, the sampling was limited except in 1961 (Figure 12). After fertilization, smolts from Little Togiak Lake were significantly longer than smolts from the other lakes in 1977 and 1978.

Smolt migration from each lake in the system begins soon after each lake is clear of ice, and this happens progressively later from the lowest lake (Aleknagik) to the upper lake (Kulik), which is clear of ice about two weeks later than Lake Aleknagik. Therefore, the first smolts to migrate out of the system are almost entirely from Lake Aleknagik.

The mean weights of age I smolts early in the migrations from Lake Aleknagik were plotted against the mean weights of fry in Lake Aleknagik on 1 September in the previous year (Figure 13). If we assume that the correlation in the Lake Aleknagik data also applies to Little Togiak data then there were exceptional increases in weight from fry to smolts in Little Togiak following the fertilization. The observation for 1976 (the year of migration) is

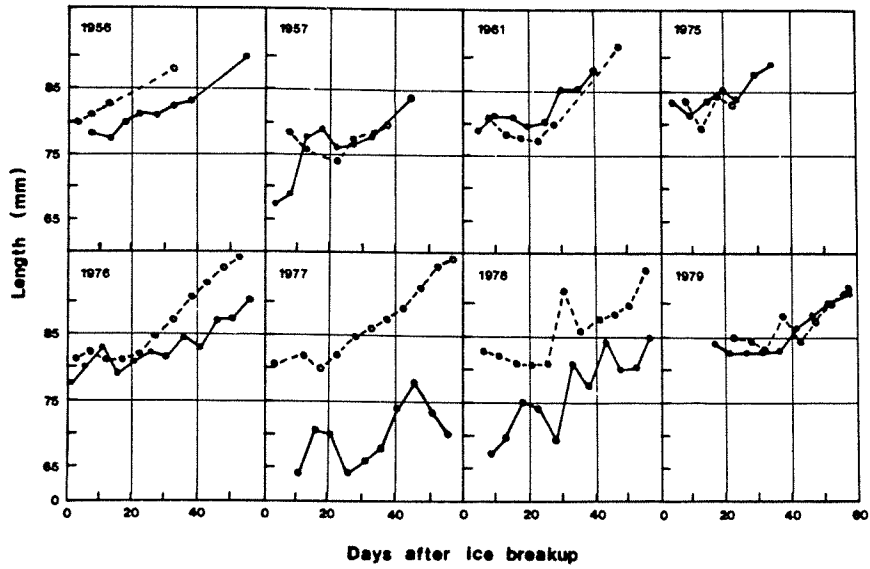


Figure 12. Mean lengths of age I smolts in migrations from Little Togiak (o) and the Wood River lakes at the outlet of Lake Aleknagik (*).

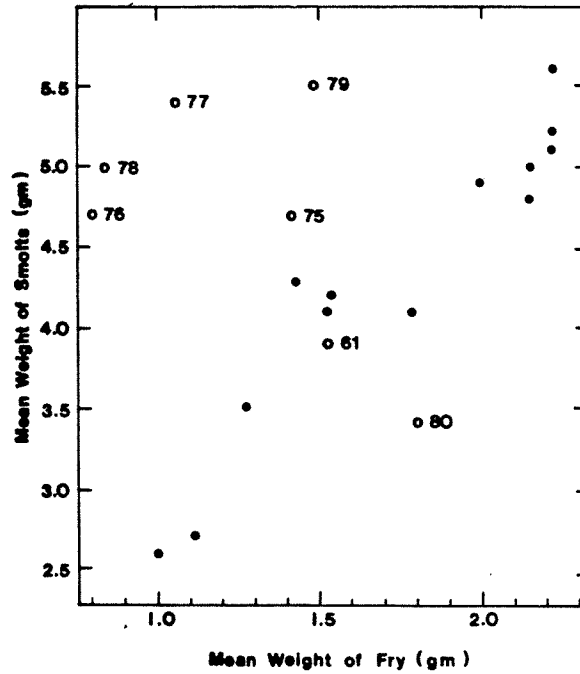


Figure 13. Mean weight of age I smolts during the first 20 days of migration (year shown) vs. the mean weight of fry on 1 September of the previous year in Lake Aleknagik (*) and Little Togiak Lake (o).

misleading because nearly as many age II smolts migrated in 1977 as age I smolts in 1976. The lake was not fertilized in 1979 and although the fry had exceptionally good growth up to 1 September, their growth during September/October was apparently very poor because the smolts that migrated in 1980 were the smallest ever observed from Little Togiak Lake.

The number of smolts in the migration from Little Togiak Lake were estimated during five years. Sampling began too late in 1979 to obtain a reliable estimate. The estimates (in thousands) were: 666 in 1961, 187 in 1976, 510 (28 percent age II) in 1977, 541 in 1978, and 1,033 in 1980. Thus, the largest migrations contained the smallest smolts.

The purpose of fertilization is to increase the survival of juveniles by either reducing mortality from malnutrition (starvation) or reducing mortality from predation, on the assumption that this mortality is a function of size or health of the juvenile salmon. Predation by Arctic char on sockeye salmon smolts in Little Togiak River apparently decreased following fertilization of the lake (Table 4). The number of smolts in char stomachs is partly a function of the size of the char; however from 1977 to 1979, the average numbers of smolts in char stomachs were low relative to the average length of the char sampled in those years. Of course predation by Arctic char in Little Togiak River is probably a minor source of mortality between juveniles in the lake and returning adult salmon, two to three years later.

Table 4. Statistics from stomach samples of Arctic char collected by hook and line from Little Togiak River during 30 days following ice breakup, 1972-1979.

	1972	1973	1974	1975	1976	1977	1978	1979
Samples collected in the day:								
Number examined	—	49	—	18	49	206	170	50
Mean length (mm)	—	470	—	449	435	399	443	431
Percent containing smolts	—	67	—	50	61	21	42	38
Mean number of smolts	—	4.9	—	3.3	3.1	0.5	1.6	1.6
Samples collected at night:								
Number examined	82	72	64	53	47	119	146	128
Mean length (mm)	446	429	429	404	400	411	431	441
Percent containing smolts	60	29	39	31	51	11	42	20
Mean number of smolts	4.5	1.6	1.6	1.3	1.2	0.3	1.4	1.0
Sockeye escapement to Little Togiak Lake in year-2 (thousands)								
	55	24	14	14	48	30	18	26
Mean length of smolts in migration (mm)								
	—	83	90	84	84	88	84	85
Lake level (cm)								
	177	161	121	150	122	206	133	164
Total number of char removed								
	463	208	283	71 ¹	113 ¹	574	587	344
Total number of char measured								
	729	208	263	71	113	574	587	344
Mean length (mm)								
	444	444	435	415	427	388	432	427

¹Char were also removed by the Alaska Department of Fish and Game; however, the total number removed in each of these years was less than 200.

Adult Returns

The most difficult effects of fertilization to evaluate and yet the most important are the effects on the marine survival of sockeye salmon and the number of returning adults. Positive effects on primary and secondary productivity and the growth of juvenile sockeye salmon were demonstrated in the Bare Lake and Great Central Lake experiments (Nelson and Edmondson, 1955; LeBrasseur, et al., 1978). Effects on primary production were also demonstrated in four other British Columbia lakes in experiments currently in progress (Stockner, et al., 1980). However, effects on the adult returns to Bare Lake were not fully evaluated (Nelson, 1959) and the effects on the adult returns to Great Central Lake were difficult to ascertain because the runs also increased in an adjacent unfertilized lake and there was an increasing trend in the runs prior to fertilization.

The initial adult returns from juveniles in Little Togiak Lake when it was first fertilized came in 1977; however, first returns from the whole-lake fertilization came in 1979 and the final returns will not come until 1982. The runs to Little Togiak Lake were exceptionally large from 1978 to 1980 but so were the runs to the entire lake system (Figure 14). The runs or catches of all species of salmon in Bristol Bay and indeed most of Alaska have been large in

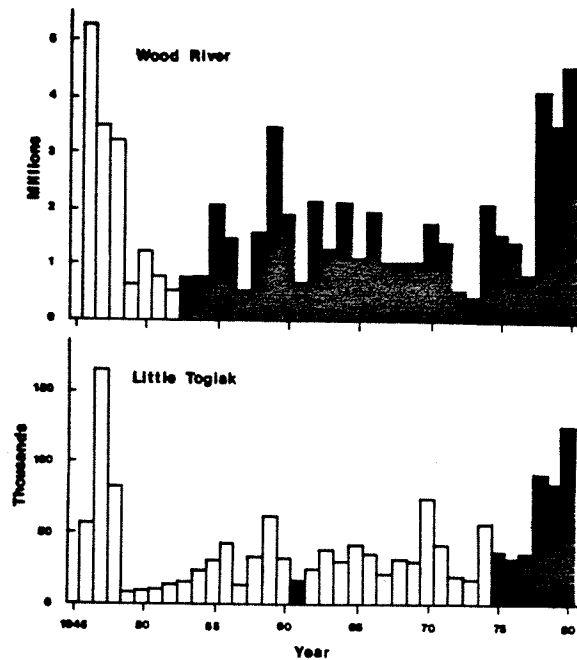


Figure 14. Annual runs of sockeye salmon (catch plus escapement) to the Wood River lake system and Little Togiak Lake. Open bars when escapements estimated by aerial survey and solid bars when estimated by counts on the river.

these recent years. So relative to the area-wide increase, the initial returns of adult sockeye salmon from the fertilization of Little Togiak Lake were not exceptional.

Summary

Little Togiak Lake was fertilized with diammonium phosphate to enhance the growth and survival of juvenile sockeye salmon, and thus increase the abundance of returning adult salmon. Fertilization increased primary production and increases in secondary production (food for juvenile sockeye) were observed in some cases but not in others. Growth of fish during the early summer was not significantly increased except perhaps in 1979 (the year following the last fertilization) when there was an exceptionally high density of *Cyclops*. The apparent growth from juveniles on 1 September to smolts the following spring was greatly increased after fertilization. Presumably the abundances of *Daphnia* and perhaps calanoid copepods were increased in the fall; however, direct observations were seldom made after mid-September. The age I sockeye salmon smolts were larger relative to the abundance of parent spawners, their size as fry, and the size of other smolts in the lake system. However, they were not larger than the largest smolts observed at Wood River in past years when abundance was low. The fertilization thus produced smolts that were above average in size during years in which they normally would have been well below average in size. Whether this larger size will result in higher marine survival and more returning adults has yet to be determined, since the early returns of adult salmon to Little Togiak Lake have not been exceptionally large relative to the returns to the other lakes in the system.

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