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Sockeye Salmon Studies in Salmon Lake, Alaska: Limnology and Fishery Investigations Relative to a Nutrient Addition Program, 1994–2008

by

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July 2012

Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries

Symbols and Abbreviations

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat. or long.
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	"
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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SOCKEYE SALMON STUDIES IN SALMON LAKE; LIMNOLOGY AND FISHERY INVESTIGATIONS RELATIVE TO A NUTRIENT ADDITION PROGRAM, 1994–2008

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ABSTRACT

This study examined the efficacy of fertilization on enhanced production of sockeye salmon (*Oncorhynchus nerka*) of Salmon Lake, Alaska from 1994 to 2008. The fertilization was based on the assumption that productivity of sockeye salmon is based on foliate or trophic bottom-up process during their freshwater life-stage, and that lake fertilization would increase: 1) lake nutrients, especially total phosphorus (TP) and total nitrogen (TN), 2) phytoplankton biomass (chlorophyll *a*: Chl-*a*), 3) zooplankton biomass, and 4) weight and length of out-migrant smolt, which would increase smolt-adult marine survival and thus adult return. The lake has been monitored since 1994, and it was fertilized in 1997–2001, 2004, and 2007–2008. Consistent with the expectations, mean concentration of TP and TN during the fertilized period was significantly higher than those during pre-fertilized (1994–1996) and non-fertilized (2002, 2003, 2005, and 2006) periods ($P < 0.05$). Mean zooplankton biomass was higher during the fertilized period than the pre-fertilized period but lower than the non-fertilized period, although the differences were not significant. In contrast, mean weight and length of age-1 smolt was the lowest during fertilized periods, though the difference was not significant. As for trophic linkages, TN and TP were positively correlated with Chl-*a*, but Chl-*a* was not correlated with zooplankton biomass. On the other hand, zooplankton biomass was positively correlated with age-1 smolt weight and length. These results suggest that Salmon Lake sockeye salmon productivity is partially influenced by foliage-based or trophic bottom-up processes, except for the linkage between phytoplankton and zooplankton. However, efficacy of fertilization to enhance Salmon Lake smolt condition or adult returns remained unclear.

Key words: sockeye salmon, *Oncorhynchus nerka*, fertilization, *Bosmina*, *Daphnia*, *Cyclops*, limnology, Pilgrim River, Salmon Lake, Seward Peninsula, oligotrophic, trophic interactions, smolt

INTRODUCTION

Lake fertilization has been used in attempt to increase sockeye salmon returns in many lakes throughout British Columbia and Alaska (Bradford et al. 2000; Koenings and Kyle 1997; Mazumder and Edmundson 2002; Hyatt et al. 2004). The lake fertilization was designed to increase adult sockeye salmon returns by increasing the rate of nutrient transfer through bottom-up trophic linkage (carcasses → nutrients → phytoplankton → zooplankton → increased food consumption by fry → large smolt → increased marine survival → increased adult return (Hyatt et al. 2004). Lower trophic level productivity of sockeye salmon rearing lakes is typically limited by phosphorus, the major limiting factor of phytoplankton production (Koenings et al. 1987; Stockner 1987; Wetzel 2002), and many studies supported the above general bottom-up linkage, such as positive relationships between nutrient and algae, algae and zooplankton, and zooplankton and fish (e.g., Koenings and Kyle 1997; Hyatt et al. 2004). Additionally, Koenings and Burkett (1987) hypothesized that favorable fry rearing conditions would enhance fry growth, which would shift age composition of out-migrant smolt to younger age classes. Hyatt et al. (2004) reviewed 24 fertilization studies throughout North America and found that lake fertilization was associated with: 21 of 21 studies showed increased chlorophyll *a* concentrations, 16 of 16 showed increased zooplankton biomass and average smolt weight, 11 of 13 showed increased smolt biomass, 4 of 4 showed increased egg-to-smolt survival rates, and 3 of 3 showed increased smolt-to-adult survival.

In an effort to increase adult salmon returns an experimental fertilization program was implemented in Salmon Lake in Norton Sound Alaska. Salmon Lake is located in the Port Clarence District on the Seward Peninsula and supports one of the northern-most populations of sockeye salmon in North America (Figure 1). During the 1994–1996 pre-fertilization evaluation, Salmon Lake sockeye salmon production appeared to be rearing limited because of low concentration of phosphorous (1–3 µg L^{-1}), high N:P ratio (38–58:1), low chlorophyll *a* biomass (< 1 µg L^{-1}). Rearing limitation is further demonstrated by a low proportion of age-1 smolt (< 0.85) (Todd and Kyle 1997). These contrast to typically productive sockeye salmon rearing lakes which have higher nutrient and productivity indicators (phosphorus: 2-37 μgL^{-1}, N:P ratio: 20:1, chlorophyll *a* biomass: 1-18.72 $\mu g\ L^{-1}$; Todd and Kyle 1997), and age-1 smolt proportion >85%, (Koenings and Burkett 1987). Following the pre-fertilization evaluation, in 1996 the Norton Sound Salmon Regional Planning Team (NSSRPT) with the Alaska Department of Fish and Game (ADF&G), the Bureau of Land Management (BLM), and Norton Sound Economic Development Corporation (NSEDC) approved a 5 year nutrient enrichment and data collection program for Salmon Lake beginning in 1997. After the initial 5-year fertilization period, the lake was additionally fertilized in 2004, 2007 and 2008. This report presents the project results, and production of Salmon Lake sockeye salmon in relation to fertilization, limnological conditions, zooplankton biomass and adult return.

OBJECTIVES

The objectives of this study are to evaluate effects of fertilization on the Salmon Lake ecosystem and on sockeye salmon. Specifically, we tested following hypotheses: 1) fertilization would increase concentration/abundance/biomass of nutrients, phytoplankton, zooplankton, and smolt weight, length, and the proportion of fresh water age-1, and 2) there is a positive correlation between: nutrients and phytoplankton, phytoplankton and zooplankton, zooplankton and smolt and adult returns.

METHODS

STUDY SITE DESCRIPTION

Salmon Lake is located in the interior of the Seward Peninsula in northwest Alaska (Figure 1). Salmon Lake receives water from the Grand Central River and is the headwater of the Pilgrim River that flows into the Kuzitrin River, Imuruk Basin, and then into the Bering Sea. The lake consists of west (upper) and east (lower) basins (Figure 2). The west basin has a surface area of 3.38 km^2 and maximum depth 40 m; the east basin has a surface area of 4.19 km^2 and maximum depth of 20 m (Figure 2). Its water volume is $111.5 \times 10^{6}\ m^3$ with mean summer discharge volume of 14.3 $m^3\ s^{-1}$ (Todd and Kyle 1996, 1997). Water residence time is calculated to be 1.6 years (Todd and Kyle 1996, 1997). Salmon Lake is dimictic, thermally stratified in the summer, and isothermic in the spring and fall. From June to October, the epilimnion depth reaches 5 m, and the maximum summer epilimnetic and hypolimnetic temperatures reach 15°C and 4°C, respectively. In addition to sockeye salmon, Salmon Lake hosts coho salmon (*Oncorhynchus kisutch*), stickleback (*Pungitius pungitius*), round whitefish (*Prosopium cylindraceum*), least cisco (*Coregonus sardinella*), slimy sculpin (*Cottus cognatus*), Arctic grayling (*Thymallus arcticus*), Dolly Varden (*Salvelinus malma*), Arctic char (*S. alpinus*), and burbot (*Lota lota*) (DeCicco 1995). Salmon Lake macrozooplankton are taxonomically simple (Todd and Kyle 1997) consisting mainly of cladocerans: *Bosmina longirostris* and *Daphnia longiremis*, and the cyclopoid copepod *Cyclops columbianus*. Sockeye salmon escapement of Salmon Lake is monitored by aerial survey since 1963 and by weir at the Pilgrim River weir since 1997. An aerial count escapement goal was set in 2005 at 4,000–8,000. From 2000 to 2008, aerial sockeye salmon escapement counts ranged from 3,591 to 42,240 with average of 21,000, and weir counts ranged from 3,888 to 85,417 with an average escapement of 40,000 fish.

FERTILIZER APPLICATION

Following recommendation by Todd and Kyle (1997), two types of liquid fertilizers were applied to Salmon Lake: blended nitrogen (N) and phosphorus (P) fertilizer 20-5-0 (N-P-Potash) and N fertilizer 32-0-0. The blended N and P fertilizer was formulated from mixtures of pharmaceutical grade (white acid) P 32-0-0 (57.3%), N 8-24-0 (20.8%), and water (21.9%), and had a N:P ratio of 18-20:1 (by atoms) and weighed 10.4 lb per gallon. The N fertilizer was formulated from nitrate N (7.75%), ammonic N (7.75%), organic N as urea (16.5%), and water (68%), and had an N:P ratio of 32-0-0 and weighed 11.1 lb per gallon. This mixed fertilizer contained 250 mg L^{-1} of 19.7 kg ton^{-1} of P.

The fertilizer was applied to only the upper basin of Salmon Lake (Figure 2) where the majority of fry were found in preliminary studies (Todd and Kyle 1997). Fertilization typically started after the lake surface temperature exceeded $8^{o}C$ and continuing weekly through the growing season (Appendix A).

The amount of fertilizer changed through the years (Table 1). For the initial application, from 1997 to 2001, the amount of fertilizer was set to 40 tons or 788 kg of P. This was determined to be the necessary amount so that the N:P ratio exceeded 20:1 and so that the effects could be evaluated for an entire sockeye salmon life-cycle (Gary Todd ADF&G personal communication). In 2004, two years after the end of the initial application, fertilization was resumed and the amount of fertilizer applied was lowered to 27 tons or 532 kg of P. The amount of fertilizer applied was adjusted to incorporate the contribution of P from sockeye salmon escapement in the previous year. It was assumed that each adult spawner with an average weight of 2.2 kg contains 8 g of P of which 75% (6 g) would be released back into water (Larkin and Slaney 1997). The sockeye salmon escapement in 2003 was 42,700, so salmon carcasses were estimated to have added 256 kg of P in 2004 (Table 1). In 2007 and 2008, NSEDC applied 44 tons and 22 tons, respectively. However, the 2007–2008 fertilization, even including contribution from sockeye carcasses, did not reach the original fertilization target level of > 788 kg of P.

DATA COLLECTION

Field sample collection sites

Field sampling and analytical methods followed standard protocols set by Koenings et al. (1987). Four sampling stations were established, two stations at each basin (Figure 2). Of the 4 stations, zooplankton samples were collected at all 4 sampling stations, whereas environmental and water samples were collected at stations 1 and 3 only. Further, water samples were collected both at the surface (1 m depth) and near the bottom (station 1:30 m, station 3:15 m). Water samples were collected with a 4 L *Van-Dorn*[1] water sampler, poured directly into carboys, then transported to and processed in the Nome laboratory within 24 hours. Zooplankton samples were collected using a conical tow net with a collection cup: 0.5 m (1994–2001) and 0.25 m (2001–2008) in diameter, mesh size 153 µm, and 3:1 length to diameter ratio. The tow net was drawn up vertically from within 1 m of the lake bottom to the surface at the speed of 0.5 m s^{-1}. After the tow, the net and collection cup were rinsed and poured into a 125 mL polyethylene bottle and stored in 10% buffered formalin solution (1994–2004) and in 50% ethanol solution (2005–2008). Sampling was conducted approximately every 3–4 weeks from June to October, shortly after the ice left the lake (Table 1).

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[1] Product names used in this report are included for scientific completeness but does not constitute product endorsement by Alaska Department of Fish and Game.

Lake physical environment analysis

Climatic conditions (approximate wind speed and direction, percent cloud cover or haze, and precipitation) and lake surface conditions (calm, choppy, or small whitecaps) were recorded at the beginning and end of each survey.

Temperature (°C) and dissolved oxygen content (mg L^{-1}) were measured using a *Yellow Spring Incorporated* (YSI) model 51B dissolved oxygen/temperature meter (1994–2006), and a YSI Model 85 ha ndheld dissolved oxygen, conductivity, salinity and temperature system (2007–2008). Measurements were read just under the surface; at depths of 1 through 5 meters at 1 meter intervals; and from 10 meters to the lake bottom at 5 meter intervals. Secchi disk depth was taken on the shaded side of the boat (away from sun) with a metered line and was the average of the depth the disk disappeared when slowly lowered and the depth it reappeared when pulled slowly back up.

Underwater irradiance (µmol) was measured using a submarine photometer (1994–2001: *International Light* model IL1400A; 2002–2008: *LI-COR* model LI-250) from the side of the boat facing the sun at the same depth intervals as temperature to the depth at which the reading was approximately 1% of the surface reading. From this reading, light extinction (attenuation) coefficient (K_d) and euphotic zone depth (EZD) were estimated. EZD is the depth where penetration of the subsurface Photosynthetically Active Radiation (PAR) is reduced to 1% of its maximum, the maximum depth of net primary production, and the extent of the littoral zone in lakes.

K_d was estimated by fitting a regression model (Edmundson et al. 2000).

$$\ln\left(\frac{I_0}{I_z}\right) = K_d Z$$

where I_z = irradiance (µmol s^{-1} m^{-2}) at each depth, I_o = irradiance at subsurface, and Z = depth (m).

From this, *EZD* was calculated as:

$$EZD = \frac{\ln(100)}{K_d}.$$

By multiplying *EZD* with lake surface area (*S*) (upper lake 3.38×10^6 m^2, lower lake 4.19×10^6 m^2) salmon lake's eutrophic volume (*EV*) was estimated as:

$$EV = EZD \cdot S.$$

Hypothetically, with 800–900 adult escapement per EV unit (10^6 m^3) , the average number of sockeye salmon fry rearing capacity is 110,000 spring and 33,000 fall fry, 23,000 smolt and 2,500 total adults per EV unit (Koenings and Burkett 1987; Koenings and Kyle 1997).

Limnology assessment

All samples were processed and analyzed following standard procedures (Koenings et al. 1987) at the ADF&G limnology laboratories in Soldotna (1994–2004) and in Kodiak (2005–2008). Of the 4 L water collected, 450 mL was refrigerated at 4°C for analyses of conductivity, PH, alkalinity, turbidity, 200 mL was frozen for analyses of total phosphorus (TP), total Kjeldahl nitrogen (TKN), and total nitrogen (TN), and 100 mL was acidified with 0.5 ml of 1:1 nitric acid solution for analyses of metals: calcium, magnesium, total iron, and reactive silicon. Further, 300 mL was filtered through a *Whatman* glass fiber filter (GFF) at 15 psi and frozen for analyses of filterable reactive phosphorus (FRP), total filterable phosphorus (TFP), nitrate + nitrite, total ammonia concentration, and color (Table 2).

Phytoplankton assessment

Abundance of phytoplankton was assessed by concentration of chlorophyll-*a* as proxy. For analyses of chlorophyll-*a* (Chl-*a*), phaeophytin, and particulate organic carbon, 1 L of water sample was filtered through a *Whatman* GFF, and 5 mL of a magnesium carbonate ($MgCO_3$) solution (10g L^{-1}) was added to the last 50 mL of the sample water to preserve the filtrate. The filter was ground with a *Teflon* pestle in 90% acetone to extract algal pigment. After being refrigerated at 4°C in the dark for 2 hours, the slurry was centrifuged and the supernatant was decanted and brought to volume with 90% acetone. The Chl-*a* concentration (corrected for inactive phaeophytin) was measured using a *Turner* model 112 fluorometer or Spectronic Genesis 5 Spectrophotometer.

Separate 125 mL water samples were preserved with 2 mL of Lugol's acetate to identify and enumerate phytoplankton. The samples were analyzed by *Eco-Logic Ltd.* of Canada (1994) and by University of Victoria, Canada (1995–2001).

Macro-zooplankton assessment

Zooplankton identification, enumeration and length measurements were performed using a binocular dissecting microscope (Koenings et. al 1987). A 1.0 mL subsample was taken with a Hansen-Stemple pipette and placed onto a Sedgewick-Rafter counting cell, and all organisms in five 0.01 cm^2 grids were counted. Three replicates were counted for each sample. Body lengths were measured to 0.01 mm from 10 individuals along a transect in each subsample. Computations of biomass also followed procedures from Koenings et al. (1987) using species-specific regression equations relating mean wet length to dry mass.

Fry abundance and size

To estimate the number and distribution of rearing sockeye salmon juveniles, hydroacoustic surveys were conducted yearly from 1995 to 2002 during September or October (See Appendix B for more details). All surveys were conducted at night because juvenile sockeye salmon are typically more dispersed in the water column during darkness, making fry more detectable by hydroacoustic gear. All transects were run perpendicular to the longitudinal lake basin axis, at approximately 2 m s^{-1}. In 1995 10 transects were surveyed: 7 in the west basin and 3 in the east basin. From 1996 to 2002 the number of transects were increased to 8 in the west basin and 6 in the east basin.

Smolt abundance and size

To examine smolt production, the abundance of out-migrant smolt was estimated on the Pilgrim River using a one-site mark-recapture method (Carlson et al. 1998; Appendix C). The smolt were captured using one or two inclined-plane traps. The captured smolt were dyed with Bismarck Brown Y solution and released in upriver 2–3 km from the trapping site. At the trapping site, the number of recaptured smolt was recorded for several days. When the recapture ceased, another mark–recapture experiment was conducted. This experiment was conducted throughout migration period. The age, weight, and length (AWL) of emigrating smolt were measured, and Fulton's condition factor (K) = $10^5W/L^3$ was computed (Guy and Brown 2007).

Adult salmon escapement

Salmon Lake-Pilgrim River sockeye salmon runs have been monitored since 1963 b y aerial survey. In 1995 and 1996 a *Rack Master* weir (metal pipes and pickets, and aluminum stringers) was installed at the outlet of the Salmon Lake. The weir was operated from 19 July to 22 August in 1995, and from 6 July to 19 August in 1996 (Todd and Kyle 1996, 1997). From 1997 to 2002, a counting tower was installed in the lower Pilgrim River and operated by Kawerak Inc. (Kohler and Knuefer 2001). In 2003 a r esistance board weir was installed near the tower sites and has been operated yearly by Kawerak Inc. (Waitman and Dunmall 2002; Dunmall 2003, 2004 ; Burkhart and Dunmall 2005; Kroeker and Dunmall 2006). Escapement in years without weir operations were reconstructed by converting aerial survey counts to weir count, using ratio regressions coefficient ($N_{weir} = \alpha N_{aerial}$) derived from paired aerial and weir count data.

Adult salmon return reconstruction

To examine relative contribution of the age-1 and age-2 out-migrant smolt on a dult return, the number *i-th* freshwater age adults that out-migrated in *t-th* year as a smolt ($N_{asi,t}$) was calculated as:

$$\hat{N}_{asi,t} = \sum_j (p_{i,j,t+j} N_{t+j}) ,$$

Where:

$p_{i,j,t+j}$ is the proportion of *i-th* freshwater age and *j-th* saltwater age adult retuning in *t+j-th* year. N_{t+j} is the total number of adults returning in *t+j-th* year.

Total number of adult cohort returning from the *t-th* outmigrant year is sum of the above for each *i-th* freshwater age.

$$\hat{N}_{as,t} = \sum_i \hat{N}_{asi,t} .$$

The proportion of *i-th* freshwater adult return is:

$$\hat{P}_{asi,t} = \frac{\hat{N}_{asi,t}}{\hat{N}_{ast}} .$$

Since the number returning *i-th* freshwater age adult from *t-th* year cohort ($N_{asi,t}$) is a fraction of the cohort of smolt that outmigrated in *t-th* year ($N_{smi,t}$)

$$\hat{N}_{as\,i,t} = s_{i,t}\hat{N}_{sm\,i,t} = s_{i,t}\,p_{s,i,t}\hat{N}_{sm,t}$$

Where:

$s_{i,t}$ is a marine survival rate of *i-th* freshwater age of *t-th* year cohort.

$N_{sm,i,t}$ is the number of *i-th* freshwater age smolt outmigrating in *t-th* year.

$N_{sm,t}$ is total the number of smolt outmigrating in *t-th* year.

$p_{s,i,t}$ is the proportion of *i-th* freshwater age smolt outmigrating in *t-th* year.

Hence, the proportion of *i-th* freshwater adult return is:

$$\hat{P}_{as\,i,t} = \frac{s_{i,t}\,p_{s,i,t}\hat{N}_{sm,t}}{\hat{N}_{sm,t}\sum_i s_{i,t}\,p_{s,i,t}} = \frac{s_{i,t}\,p_{s,i,t}}{\sum_i s_{i,t}\,p_{s,i,t}}.$$

Since greater than 99% of returning adult sockeye salmon comprise only freshwater age-1 and age-2, we ignore other age classes and,

$$\hat{P}_{as\,i,t} = \frac{s_{i,t}\,p_{s,i,t}}{s_{1,t}\,p_{s,1,t} + s_{2t}\,p_{s,2t}}.$$

From this, relative marine survival rate of age 2 freshwater over age 1 freshwater $s_{2,t}/s_{1,t}$ is calculated as:

$$\frac{s_{2t}}{s_{1,t}} = \left(\frac{p_{s,1,t}}{\hat{P}_{as,1,t}} - p_{s,1,t}\right)\Big/ p_{s,2t}.$$

DATA ANALYSIS

Based on the potential effects of fertilization on bottom-up mechanisms, we set the following hypotheses: 1) fertilization would increase concentration/abundance/biomass of nutrients, phytoplankton, zooplankton, and salmon juveniles, and 2) there is a positive correlation between concentration/abundance/biomass of lower trophic and upper trophic levels.

Fertilizer was added during the periods when water temperature exceeded 8^{o}C, and after thermal stratification was established. Previous studies indicated that more than 80% of fry reside in the upper lake (Todd and Kyle 1996, 1997). Thus, we expected that the effects of fertilization would be the most noticeable at the surface of Salmon Lake. Analyses therefore concentrated on epilimnion data (depth 1 m) from the fertilized upper lake (stations 1 and 2).

Annual mean values (stations 1 and 2 combined) were calculated for each measured variable: total phosphorus, total nitrogen, Chl-*a* biomass, density, and length of *Daphnia*, *Bosmina*, and *Cyclops*, length and weight of age-1 smolt, and proportion of age-1 smolt.

For the first hypothesis, the 1994–2008 periods were classified into pre-fertilized (1994–1996), fertilized (1997–2001, 2004, 2007–2008) and non-fertilized (2002–2003, 2005–2006) periods, and one-way Wilcoxon Rank Sum test was used to examine differences among the three periods.

For the second hypothesis, simple linear correlation analyses were conducted. For the above analysis involving smolt (weight, length, age-1 proportion), we only examined fry that spent one year in the lake and became age-1 smolt. Data from age-1 smolt collected for the year of migration (e.g., 2001) was lagged backward one year so that they corresponded with their lake-rearing year (e.g., 2000).

RESULTS

LIMNOLOGY

At the upper lake, the seasonal EZD, light extinction coefficient (K_d), and Secchi depth ranged from 13.3 to 22.7 m, 0.203 to 0.348, and 5.2 to 10.5 m, respectively (Table 3). EZD declined from 1994 to 2002 (13.3), and increased back to 19.8 in 2008. A similar trend was observed at the lower lake, except that it became the lowest in 2005. Limnological measurements were within the range of oligotrophic lake characteristics (K_d: 0.03 – 1.0, Secchi: 5.4–28.3 m; Wetzel 2002). There was no significant difference in those measures among pre-fertilized, fertilized, and non-fertilized periods (Wilcoxon: $P > 0.05$). Based on EZD, euphotic volume unit (EV) was estimated to be 45–79 ($\times 10^6$) in the upper lake, and 51–101 ($\times 10^6$) in the lower lake.

The upper lake was isothermic early in the season, became thermally stratified during the summer, and then became isothermic later in the season, which is expected in dimictic lakes. The summer epilimnion depth ranged from 3 to 10 m and the metalimnion depth ranged from 10 to 20 m (Figure 3a). On the other hand, the lower lake had less consistent thermal stratification throughout the summer season (Figure 3b). Temperature showed an increasing trend from 1994 to 2008 (Table 3). There was a significant negative correlation between lake temperature and EZD in the upper lake ($R^2 = 0.32$, $P = 0.03$), but not in the lower lake ($R^2 = 0.02$, $P = 0.60$).

NUTRIENT CONTENT AND PRIMARY PRODUCTION

At the upper lake 1 m depth, TP and TN showed similar annual trends (Figure 4). Both increased during the pre-fertilized period (1994–1996). After the fertilization started in 1997, both peaked in 1997–1998, and declined for the rest of the fertilized period, which continued following the unfertilized period (2002–2003). In 2004, when fertilization resumed, both increased again; however, both declined thereafter, including during 2007 and 2008 fertilized periods. Similar to TP and TN, Chl-*a* increased during the pre-fertilized period (Figure 4). During the first fertilized period (1997–2001), Chl-*a* increased in the first year but then declined in the following 2 years to a level similar to the pre-fertilized period. For the next 2 years (2000–2001), Chl-*a* increased and reached the highest level (2.48–2.91 $\mu g\ L^{-1}$). The following 2 years of the non-fertilized period, it declined to the pre-fertilized level and remained low despite subsequent fertilization in 2004, 2007 and 2008 (0.64–1.00 μg L^{-1}).

Overall, mean TP, TN, and Chl-*a* were the highest during the fertilized period at the upper lake 1m depth; however the increase was not significant for Chl-*a* (Table 4). Mean TP during the fertilized period (7.22 g L^{-1}) was 2.85 times higher than the pre-fertilized (2.52 μg L^{-1}) and 1.85 times higher than the non-fertilized (3.89 μg L^{-1}) periods (χ^2 = 20.02, P < 0.0001). Mean TN during the fertilized period (113.73 μg L^{-1}) was 1.68 times higher than the pre-fertilized (61.63 μg L^{-1}) and 1.32 times higher than the non-fertilized (85.65 μg L^{-1}) periods (χ^2 = 8.2, P = 0.012). Mean Chl-*a* during the fertilized period (1.39 μg L^{-1}) was also 1.75 times higher than the pre-fertilized (0.80 μg L^{-1}) and 2.11 times higher than the non-fertilized (0.66 μg L^{-1}) periods. This lack of significant difference was largely due to high variability of the responses, in which standard deviation during the fertilized period was greater than the mean (Table 4).

At the upper lake 1 m depth, TP was positively correlated with total *P* input from both fertilizer and salmon carcasses in both upper lake (R^2 = 0.72 P= 0.002; Figure 5). Chl-*a* appeared to be positively correlated with TP and TN (Figure 5), which was significant for TP (R^2 = 0.32 P = 0.027), but not significant for TN (R^2 = 0.20 P = 0.09).

Comparing the above results at the upper lake depth 1 m with other 3 locations (i.e., upper lake depth 30 m, lower lake depth 1 m, and lower lake depth 15 m), similar annual trends (TP, TN, Chl-*a*) were observed in other sites, except for the upper lake 30 m depth (Figures 4, 5). On the other hand, annual trends of the upper lake at 30 m depth remained relatively constant. On average, the concentration of TP, TN, Chl-*a*, were similar among the 4 locations (Figure 4, Table 4); however, mean TP concentration at the upper lake 1 m depth during the fertilized periods (7.22 μg L^{-1}) was 30–50% higher than the other 3 locations (4.67–5.55 μg L^{-1}). The other noticeable difference was that composition of TN at the upper lake 30 m depth had higher proportion of nitrate: nitrite (30–50%) than other sites (~10%; Appendices D1–D4).

ZOOPLANKTON BIOMASS AND LENGTH

Zooplankton biomass varied during within the season, with CV ranging from 50% to 160% (Figure 4, upper lake). Trends of cladocerans, *Bosmina* and *Daphnia*, were similar. During the pre-fertilized period, 1994–1996, cladoceran biomass decreased. During the fertilized period, it continued declining for the first 3 years (1997–1999). Following 2 years of fertilized period (2000–2001) and a non-fertilized period in 2002, cladoceran biomass increased by two- to three-fold. For the next 4 years (2003–2006) cladoceran biomass declined to the pre-fertilized level. Following 2 years of a fertilized period, it increased in 2007 by ten-fold, but declined to the level of the pre-fertilized period in 2008. Annual dynamics of *Cyclops* were slightly different from those of *Bosmina* and *Daphnia*. *Cyclops* biomass increased during the pre-fertilized period, reaching the highest biomass in 1996. During the fertilized period, it showed a similar pattern to that of *Bosmina* and *Daphnia*; however, it continued to increase through the next non-fertilized period (2002–2003) and the fertilized period in 2004. Following the 2 non-fertilized (2005–2006) and 2 fertilized (2007–2008) years, *Cyclops* showed similar dynamics as that of *Bosmina* and *Daphnia*.

Length of zooplankton did not change considerably and did not show apparent patterns associated with fertilization or Chl-*a* (Figure 4). Length of *Cyclops* and *Daphnia* showed similar patterns, declining from 1994 to 1999, increasing in 2000, and declining from 2000 to 2008. Length of *Bosmina* remained constant, ranging 0.34 to 0.37 mm. Composition of zooplankton among the 3 species remained: *Cyclops* dominated, except in 2002 and 2007 (Figure 6).

Responses of zooplankton to fertilization were highly varied and inconsistent among species (Table 4). There was no statistically significant difference in zooplankton biomass, length, or composition. This was again largely due to high variations among years and sites. Neither biomass nor length of zooplankton was correlated with Chl-*a* (Figure 7). On the other hand, zooplankton biomass was positively correlated with light extinction coefficient (K_d; R^2 = 0.48, P = 0.005) and marginally with water temperature (R^2 = 0.23, P = 0.07).

Similar results were also observed at the lower lake (Figures 4, 6; Table 4), except that biomass of zooplankton at the lower lake was about 50% of the upper lake. However zooplankton biomass and length were not correlated with K_d, or water temperature at the lower lake (Figure 6).

FRY ABUNDANCE

Fry abundance was available only from 1995 to 1998, and total fry abundance estimates in those years ranged from 962,324 to 2,262,554 (Appendix B). We were unable to locate hydroaccoustic data for 1999–2002. Based on the townet species compositions, the majority of counts are sockeye salmon fry. However, because of low sample sizes, it was not possible to separate these abundances by species.

SMOLT LENGTH, WEIGHT, PROPORTION

Smolt length and weight varied, similar to zooplankton biomass (Figure 7). For instance, low age-1 smolt weight and length during 1998 through 2000 correspond to a period of low zooplankton biomass (1997–1999), and the decline of smolt weight and length from 2003 to 2007 and the increase in 2008 also correspond to a decline of zooplankton biomass (2002–2006) and increase in 2007. Smolt age proportions varied widely among years (Figure 8). During the pre-fertilized years, smolt composition was dominated by age-1. During the fertilized years 1997-2001, age-2 became dominant, which was contrary to the prediction. Following non-fertilized years, age-1 became dominant, but during 2005 through 2006 non-fertilized years (2006–2007 out-migrant smolt) age-2 dominated. On average, proportion of age-1 smolt was 86% during the pre-fertilized, 53% during the fertilized, and 40% during the non-fertilized years (Figure 8).

Overall, mean length and weight of age-1 smolt (75.55 mm, 3.2 g) during the fertilized periods were significantly the lowest (P < 0.0001) (Table 4; Figure 9). On the other hand, weight of age-2 smolt were highest during the fertilized period, but their length was highest during the pre-fertilized period (P < 0.0001). Average age-1 smolt length was lower than that of age-2 even without fertilization (Figure 9; Table 4). Trends of Fulton's condition factor were stable throughout years (Figure 9). Fulton's condition factor of age-2 tended to be lower than that of age-1. Among the three periods, the condition factor was significantly the lowest during the fertilized period for age-1 (P < 0.0001), but were not different for age-2 (Figure 9; Table 4). Contrary to expectations, proportion of age-1 was the highest during the pre-fertilization period (86%) than that during the fertilized period (52%); however, the difference was not significant (P = 0.19; Table 4).

Length and weight of age-1 smolt were positively correlated with previous year's zooplankton biomass (R^2 = 0.51, P = 0.009; R^2 = 0.61, P = 0.003; Figure 10). Similarly, length and weight of age-2 smolt were positively correlated with previous year's zooplankton biomass (R^2 = 0.47, P = 0.014; R^2 = 0.39, P = 0.031), but were not correlated with previous two year's zooplankton biomass (Figure 10). No significant correlation was found between Fulton's K and other factors.

Proportion of age-1 smolt was not correlated with previous year's zooplankton biomass, but showed an asymptotic trend, where age-1 proportion became constant > 70% once the zooplankton biomass exceeded 400 mg m^{-2} (Figure 10). Proportion of age-1 was also positively correlated with the length of age-1 ($R^2 = 0.45$, $P = 0.007$).

SMOLT ABUNDANCE

Mark–recapture estimates of emigrating smolt abundance ranged from 61,306 (1999) to 1,049,800 (2005), with average counts of 306,607 (Appendix C). Except for 2003, the CV of the estimate remained less than 20%. Despite high precision, accuracy of the estimates was in doubt, largely due to technical difficulties in operating mark-recapture experiments (Dan Reed, Sport Fish Biologist, ADF&G, Anchorage; personal communication). Smolt counts were positively correlated with previous year's escapement counts ($R^2 = 0.53$, $P = 0.002$), which suggests that accuracy of smolt estimates is somewhat reasonable. Based on the upper lake EV, the maximum upper lake smolt production range is 1,034,000–1,815,000.

ADULT RETURN

From 1994 to 2010, returns of Salmon Lake sockeye salmon fluctuated widely. Escapement peaked in 2004 (85,417), and decreased in subsequent years (Table 5). In 2009 and 2010, escapement collapsed to 953 and 1654, respectively, approximately 3% of the 2004 return. Age composition of the adult return was dominated by age 2.2 or 2.3, except for 2008 when the return was dominated by age 1.3 (Table 6). Reconstructed proportions of adult returns showed that the majority of adult returns were dominated by freshwater age-2 fish, except in 2004 (Figure 11). Comparing these proportions with those of smolt (Figure 9 vs. Figure 12), the proportion of freshwater age-2 was higher in adult returns than in out-migrant smolt. Relative marine survival rate of freshwater age-2 during 2002 through 2007 period were 1.97, 3.98, 3.51, 3.06, 4.92, and 1.24, respectively, or 3.04 on average.

DISCUSSION

Lake fertilization was based on the concept that the productivity of sockeye salmon can be limited by productivity of lower trophic levels (Mazumder and Edmundson 2002; Stockner 1987). Through trophic links, nutrient additions are intended to increase phytoplankton biomass, zooplankton biomass, and growth of fry and smolt, resulting in larger, younger smolt (age-1) migrating out to the ocean (Koenings and Burkett 1987). Since larger smolt have higher marine survival rates (Koenings et al. 1993; Henderson and Cass 1991; Quinn 2005), it was expected that lake fertilization would ultimately increase the number of returning salmon. While effectiveness of lake fertilization depends on ecosystem characteristics of the lake and fertilizer application processes, lake fertilization will generally increase nutrient concentration, Chl-*a*, zooplankton biomass, fry density, age-1 smolt weight, and smolt abundance and biomass, though its effect on increasing the number of returning salmon remains unclear (Hyatt et al. 2004).

The effectiveness of fertilization of Salmon Lake in increasing sockeye salmon returns is unclear and results do not consistently support the above bottom up trophic transfer expectations. While some positive correlations from nutrient input to Chl-*a* were present, the link between Chl-*a* and zooplankton was absent. Simultaneously, some correlations from zooplankton to smolt size and to proportion of age-1 out-migrating were present. These provide supportive evidence for the bottom up processes and the effects of fertilization in Salmon Lake ecosystem. Simultaneously, at each level, the links were highly variable. In the following, we discuss each linkage.

Nutrient input to phytoplankton

In Salmon Lake, fertilizer was applied only to the upper lake during the period of growing season and thermal stratification (Figure 3a), under the premise that the nutrient would remain on the surface and be taken up by phytoplankton. Consistently, average total phosphorus (TP) during the fertilized years was about three times higher than that of pre-fertilized and twice as high as during the non-fertilized period at the upper lake surface, whereas the increase was not dramatic or not significant in the other three locations (Table 4). Further, TP was positively correlated with phosphorus inputs from both fertilizer and carcasses, though correlation was marginally significant at the lower lake (Figure 5). This suggests that the majority of nutrients stay in the upper lake surface, and that marine derived nutrients from salmon carcasses contribute to the lake nutrient budget (e.g., Schmidt et al. 1998; Naiman et al. 2002). Further, similarity of annual trend of TP among the upper lake 1 m depth, the lower lake 1 m depth, and the lower lake 15 m depth, but not at the upper lake 30 m depth (Figure 4), suggest epilimnetic water movement from the upper lake to the lower lake. The lack of difference in TP between surface and bottom at the lower lake is probably due to the lack of thermal stratification in the lower lake (Figure 3b), where lake water is mixing throughout the season.

For nitrogen (TN), even though its concentration was significantly higher during the fertilized period, its increase was about 70% of pre-fertilized and 20% of non-fertilized at the upper lake surface (Table 4). This is probably because nitrogen input from the fertilizer is small, compared with amount of nitrogen in the lake (Table 1). Also, nitrogen concentrations and annual variations were similar in all locations (upper lake, lower lake, surface, and bottom). These data suggest that the major source of nitrogen is not from fertilizer but other sources.

Regardless of the origin of the sources, there was a general positive association between nutrient concentration and Chl-*a*, which is consistent with the concept of bottom-up control of lake trophic structure (Figure 5). In Salmon Lake the positive correlation was only significant for TP, which is also consistent with other studies that demonstrate that sockeye salmon productivity in Alaska lakes may be limited by *P* (e.g., Schmidt et al. 1998; Naiman et al. 2002). However the relationship was not consistent. For instance, despite TP concentration being similar in 1999 and 2001 (5.32 and 6.10), Chl-*a* concentration was low in 1999 (0.5 $\mu g\ L^{-1}$) but the highest recorded in 2001 (2.91 $\mu g\ L^{-1}$) (Figure 4). Furthermore, the annual variation patterns of Chl-*a* were similar among the four sampling locations, showing increase in 1997, 2000, and 2001, and decline in 1998 and 1999. These data suggest that Chl-*a* concentration is also influenced by other factors such as the physical environment and zooplankton predation.

Phytoplankton to zooplankton

Based on the weak association between TP and Chl-*a*, it is not surprising that zooplankton biomass was not correlated with Chl-*a*, and that mean zooplankton biomass did not significantly increase during the fertilized period (Table 4; Figure 7). This is consistent with findings (Wetzel 2001) that food limitation and food competition have not been demonstrated to strongly affect natural zooplankton populations, but is inconsistent with findings (Hyatt 2004) that lake fertilization generally increased zooplankton biomass. These are not contradictory but rather indicative of the fact that zooplankton biomass is influenced by a multitude of factors, including water temperature, and grazing pressure by predatory fish (Wetzel 2002). It is likely that strength of each factor differs among lakes, or even within a lake among different time periods and conditions. For instance, in Salmon Lake, zooplankton biomass in the lower lake is about half the biomass in the upper lake, despite that both lakes had similar Chl-*a* concentration level (Figures 4 and 7). Furthermore, because the majority of salmon fry reside in the upper lake (Todd and Kyle 1996, 1997), low zooplankton biomass at the lower lake cannot be explained by grazing pressure of fishes. In the upper lake, zooplankton biomass was positively correlated with K_d, a measure of water clarity (higher K_d indicates low water clarity), but no correlations were found in the lower lake (Figure 7). These indicate that different factors could be affecting zooplankton biomass between the two lakes; however, similarity of the annual biomass trends between the two lakes (Figure 4) also suggests that zooplankton biomass of the both lakes are affected by common unidentified factors. These conflicting relationships illustrate difficulties of attributing to one primary factor for explaining observed zooplankton biomass and dynamic.

Zooplankton to smolt

Factors affecting smolt growth and size are highly complex, involving multiple factors such as food availability, water temperature, length of growing season, intra and interspecific competition, etc. (e.g., Kyle et al. 1988; Burgner 1987; Edmundson and Mazumder 2001). It is likely that the relative strength of each factor would differ among lake systems and with annual variation within an individual lake, and that these interactions would result in varied responses. For instance, while fertilization would increase availability of zooplankton, this positive effect may be nullified by high fry density or low water temperature. In this study, length and weight of smolt were significantly and positively correlated with zooplankton biomass (Figure 9), suggesting that availability of food is a significant factor. Also, for freshwater age-2 smolt, their length and weight were positively correlated with zooplankton biomass, not in their first year lake residency but their second year residency. This indicates that size of freshwater age-2 smolt is largely influenced by availability of food during their second year of growth. The age-2 smolts are fry that did not attain sufficient growth during their first year but remain in the lake for an additional year (or more) to attain sufficient size before out-migrating (Quinn et al. 2009).

Despite some evidence that smolt length and weight were influenced by zooplankton biomass and that zooplankton biomass was generally higher during the fertilized period, average length and weight of smolt was lowest during the fertilized period (Table 4), contrary to the prediction (Hyatt et al. 2004). However, it is unclear whether this reduction is caused by fertilization.

It has been hypothesized that increased fry growth due to fertilization would shift smolt outmigration toward younger age, and thus increasing the proportion of age-1 out-migrating smolt (Koenings and Burkett 1987). However, evidence supporting this hypothesis is scant. We were also not able to find studies examining changes of smolt age composition in association with lake fertilization, except for Kyle (1994) reporting an increase of age-1 smolt after fertilization in Leisure and Packers lakes. Further, in their review of lake fertilization studies, Hyatt et al. (2004) did not include change of smolt age composition as predicted outcome of the lake fertilization. On the other hand, a growing number of studies have shown that age at smoltification is influenced by many factors, including genetics and environmental conditions (Quinn et al. 2009). For instance, even though both Illiamna and Aleknagik lakes had similar range of fry length (45–70 mm), only fry at Iliiamna lake showed positive correlation between their length and percentage of age-1 smolt, whereas at Aleknagik Lake the percentage of age-1 smolt remained above 85% regardless of fry length (Quinn et al. 2009). Hence, it is more likely that age at smoltification is population and lake specific (Quinn et al. 2009), which cannot be generalized as a predictable outcome of lake fertilization.

In this study, we did not find evidence of fertilization increasing proportion of age-1 smolt, though the proportion of age-1 smolt differed among the 3 periods: 86% during the pre-fertilized period, 52% during the fertilized period, and 41% during the un-fertilized period. The proportion of age-1 smolt was positively correlated with the length of age-1 smolt (Figure 12). Further, the proportion showed asymptotic trends with zooplankton biomass where proportion of age-1 smolt nears > 80% when zooplankton biomass surpasses 400 mg m^{-2} (Figure 12). These suggest that faster growing (and thus larger) fry tend to out-migrate at age-1 and that there appears to be a threshold lake rearing conditions, beyond which the age-1 become the dominant out-migrant in Salmon Lake.

Smolt to adult return

While we were able to track the effects of fertilization from nutrients to smolt size (weight, length) and proportion of age-1 smolt, we were unable to examine its effects on the number of fry, smolt or returning adult salmon. Attempts were made to estimate fry density and age using hydroacoustics from 1995 to 2002 (Appendix B). However, the surveys had difficulties in accurately and reliably detecting and counting fish. Furthermore, even when counting was successful, it was difficult to apportion the count by species because we were not able to catch sufficient number of fish.

A major obstacle in estimating out-migrating smolt abundance was that timing of smolt emigration coincides with the spring lake and river ice break-up (Appendix C). Large ice debris floating downstream makes it difficult and hazardous to enumerate smolt abundance using standard methods such as a screw-trap, inclined plane trap, hydroacoustics, or meeting assumption of the mark–recapture experiment.

Adult sockeye salmon escapement was monitored by aerial survey before 1999 (Menard et al. 2011). Since 1999 returning salmon have been successfully counted at the Pilgrim River tower and weir, but the record was too short to assess the effects of fertilization on return and the correlation between the aerial surveys and the weir surveys was too low to reconstruct historical escapements. With continued monitoring it will become possible to examine effects of fertilization on adult return.

However, even if all abundance and return data had been accurately collected, it would be very difficult to link the effects of fertilization and reduced rearing limitation on adult salmon returns (Hyatt et al. 2004). In theory, given the similar number of spawners (escapement) and lake physical characteristics, the number of returning salmon should be higher for cohorts in a fertilized lake than for an unfertilized (control) lake. However, *in situ*, finding a control lake is very difficult. Further, marine environmental changes also have significant effects on salmon returns (e.g., Ruggerone et al. 2007), which are probably stronger than the effects of fertilization. Consequently, annual returning sockeye salmon abundance would show similar patterns in both fertilized and non-fertilized lakes (Hyatt et al. 2004). This was observed when sockeye salmon runs increased simultaneously over several years in both Salmon Lake (fertilized) and Glacier Lake (non-fertilized; Menard et al. 2011). It may be unlikely to provide definite empirical proof of fertilization increasing salmon return.

Still, Hyatt et al. (2004) supported lake fertilization because of the absence of studies reporting negative impacts on smolt marine survival and thus salmon return. However, comparison of the marine survival rate revealed that age-2 out-migrant smolt had higher (about twice) survival rate than the age-1 smolt of the same out-migrant year, which is similar to estimates in other sockeye salmon lakes (e.g., Koenings et al. 1993; Quinn 2005; Quinn et al. 2009). This suggests that, given the same number of smolt out-migrating, a cohort dominated by age-1 smolt would have lower adult return than that dominated by age-2 smolt. Hence, if fertilization enhances the age-1 smolt migration (Koenings and Burkett 1987), it could result in reducing the adult return. This potential negative effect has not been studied and may be worthy of further exploration.

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TABLES AND FIGURES

Table 1.–Tons of fertilizer mixture added to Salmon Lake, the amount of N and P by weight (kg) in the fertilizer mixture, estimated P weight from previous year's spawner, and limnology sampling dates.

		N		P		Salmon P	Sampling Days									
Year	Tons	(kg)	(kg amu^{-1})	(kg)	(kg amu^{-1})	(kg)[a]	June		July		August		September		October	
1994	0	0	0	0	0	33					8/4			9/28		
1995	0	0	0	0	0	58		6/27	7/13	7/23		8/15		9/27		
1996	0	0	0	0	0	13		6/23	7/12		8/4		9/3			
1997	40 [b]	109	7.8	788	25.4	65			7/8	7/29		8/23		9/18		
1998	40	109	7.8	788	25.4	94			7/5		8/6	8/27		9/21		
1999	40	109	7.8	788	25.4	83		6/28	7/10		8/6	8/30		9/26		
2000	40	109	7.8	788	25.4	28		6/28	7/10		8/6		9/8	9/30		
2001	40	109	7.8	788	25.4	73			7/11	7/31			9/10		10/6	
2002	0	0	0	0	0	111		6/27		7/29		8/22			10/9	
2003	0	0	0	0	0	23				7/24		8/13	9/4			
2004	27	74	5.2	532	17.2	256	6/10		7/9		8/5		9/2			
2005	0	0	0	0	0	512	6/12			7/14		8/25		9/30		
2006	0	0	0	0	0	339			7/1		8/3		9/1			10/25
2007	16	44	3.1	315	3.1	313		6/25		7/17	8/7	8/21		9/27		
2008	8	22	1.6	158	1.6	240			7/8		8/13		9/11			

Note: Shaded cells indicate years that fertilizer was applied.

[a] Calculated as previous year's escapement × 6 g of P per fish.

[b] An additional 6 barrels of nitrogen fertilizer, 32-0, was added.

Table 2.–Summary of water sample analyses methods.

Elements	Water treatment	Analytical Method
Conductivity	1	YSI conductance meter
pH	1	Orion model 420A pH meter
Alkalinity	1	Acid (0.02 N H_2SO_4) titration to pH 4.5 units
Turbidity	1	HF model 00B meter
Total phosphorus (TP)	2	Molybdenum blue/ascorbic acid reduction procedure after acid-persulfate digestion
Total Kjeldahl nitrogen (TKN)	2	Measured as ammonia following acid-block digestion
Calcium	3	EDTA (0.01 N) titrations
Magnesium	3	EDTA (0.01 N) titrations
Iron	3	Reduction of ferric iron with hydroxylamine during hydrochloric acid digestion
Reactive silicon	3	Ascorbic acid reduction to molybdenum blue procedure
Filterable reactive phosphorus (FRP)	4	Modified molybdenum blue/ascorbic acid reduction procedure
Total filterable phosphorus (TFP)	4	Acid-persulfate digestion procedure
Nitrate + nitrite	4	after nitrate was reduced to nitrite with cupric sulfate.
Ammonia	4	Phenyl hypochlorite method
Color	4	Spectrophotometric absorbance at 400 nanometers (nm) then converting to equivalent platinum cobalt (Pt) units

Note: See Koenings et al. (1987) for further details.
1: Unfiltered refrigerated.
2: Unfiltered frozen.
3: Unfiltered and acidified with 0.5 ml nitric acid.
4: Filtered with Watman GFF.

Table 3.–Seasonal means and CV from station 1 of euphotic zone depth (EZD), light extinction coefficient (K_d), and Secchi disk depth for 1994–2008.

	Upper Lake				Lower Lake			
Year	EZD	K_d	Secchi	Temp[a]	EZD	K_d	Secchi	Temp
1994 [b]	22.7	0.203	10.5	9.8	24.2	0.191	10.3	11.4
1995	22.4	0.209	9.3	8.7	18.5	0.258	7.8	8.1
1996 [c]	19.5	0.256	8.0	11.3	17.0	0.292	8.1	12.1
1997	20.7	0.223	7.3	11.3	20.4	0.233	6.8	12.2
1998	23.3	0.205	6.5	9.5	20.6	0.236	6.3	10.3
1999	20.3	0.229	7.4	9.8	20.5	0.231	6.6	11.6
2000 [d]	17.9	0.263	5.2	10.3	14.6	0.330	5.2	11.6
2001	17.3	0.268	7.6	12.4	17.1	0.270	7.4	12.4
2002	13.3	0.348	7.3	12.4	14.9	0.309	7.3	12.4
2003	18.5	0.252	9.5	8.9	18.5	0.253	7.8	9.4
2004	16.2	0.286	10.3	10.2	16.2	0.292	9.5	12.1
2005	19.0	0.285	7.4	9.0	12.4	0.385	6.4	10.3
2006	17.8	0.273	7.0	10.2	14.7	0.322	7.0	11.0
2007 [e]	16.0	0.292	6.7	12.9	15.4	0.303	6.0	13.9
2008	19.8	0.239	6.8	11.9	17.3	0.268	8.3	11.2

Note: Shaded cells indicate years that fertilizer was applied.

[a] Midseason (day 189-220) surface to 20 m depth average.

[b] In 1994 the samples were taken on one day.

[c] On 6/23/96 secchi disk depth was not recorded at station 3.

[d] On 8/6/00 light measurements were not taken at station 3.

[e] Light measurements were not always taken at station 2.

Table 4.–Mean and (Standard deviation) of nutrients, chlorophyll-a, zooplankton, and smolt, among pre-fertilized, fertilized, and non-fertilized periods.

Upper Lake	Pre-fertilized	Fertilized	Non-fertilized	Statistical significance
Nutrients (mg L^{-1})				
Depth 1 m				
Total-P	2.52 (1.01)	7.22 (4.28)	3.89 (1.03)	$\chi 2 = 20.02$, $P < 0.0001$
Total-N	61.63 (21.74)	104.69 (46.02)	86.65 (42.58)	$\chi 2 = 8.22$, $P = 0.016$
Chlorophyll-*a*	0.80 (0.50)	1.39 (1.41)	0.66 (0.35)	$\chi 2 = 3.82$, $P = 0.150$
Depth 30 m				
Total-P	3.19 (2.11)	4.67 (3.82)	4.67 (3.81)	$\chi 2 = 3.60$, $P = 0.165$
Total-N	64.26 (23.01)	95.41 (32.00)	107.96 (50.20)	$\chi 2 = 10.67$, $P = 0.005$
Chlorophyll-*a*	1.17 (0.41)	0.92 (0.61)	0.64 (0.33)	$\chi 2 = 8.31$, $P = 0.016$
Zooplankton				
Biomass (mg m^{-2})				
Bosmina	44.47 (47.61)	122.11 (204.65)	102.64 (169.26)	$\chi 2 = 0.58$, $P = 0.750$
Daphnia	39.23 (37.26)	77.46 (124.53)	110.85 (149.27)	$\chi 2 = 2.34$, $P = 0.311$
Cyclops	360.89 (287.55)	253.04 (211.32)	293.20 (198.09)	$\chi 2 = 3.22$, $P = 0.200$
Length (mm)				
Bosmina	0.35 (0.03)	0.36 (0.04)	0.34 (0.07)	$\chi 2 = 1.23$, $P = 0.541$
Daphnia	0.66 (0.06)	0.64 (0.13)	0.66 (0.09)	$\chi 2 = 0.97$, $P = 0.617$
Cyclops	0.79 (0.11)	0.69 (0.11)	0.66 (0.09)	$\chi 2 = 13.62$, $P = 0.001$
Lower Lake				
Nutrients (mg L^{-1})				
Depth 1 m				
Total-P	3.32 (1.31)	5.29 (2.28)	4.89 (1.35)	$\chi 2 = 8.13$, $P = 0.017$
Total-N	55.41 (11.75)	81.02 (40.86)	96.49 (38.71)	$\chi 2 = 10.90$, $P = 0.004$
Chlorophyll-*a*	0.89 (0.52)	0.92 (0.61)	0.85 (0.41)	$\chi 2 = 0.00$, $P = 0.999$
Depth 15 m				
Total-P	3.36 (0.98)	5.55 (1.56)	5.31 (0.86)	$\chi 2 = 15.57$, $P = 0.0004$
Total-N	60.97 (17.63)	87.21 (40.63)	88.39 (31.91)	$\chi 2 = 8.09$, $P = 0.018$
Chlorophyll-*a*	1.46 (0.60)	1.37 (0.67)	1.12 (0.51)	$\chi 2 = 1.92$, $P = 0.383$

-continued-

Table 4.–Page 2 of 2.

Upper Lake	Pre-fertilized	Fertilized	Non-fertilized	Statistical significance
Zooplankton				
Biomass (mg m^{-2})				
Bosmina	33.97 (38.35)	53.85 (87.64)	55.00 (110.15)	χ2 = 1.23, P = 0.540
Daphnia	16.80 (26.16)	33.20 (42.89)	103.35 (130.59)	χ2 = 2.54, P = 0.281
Cyclops	133.69 (116.40)	139.67 (124.26)	279.41 (197.81)	χ2 = 0.18, P = 0.912
Length (mm)				
Bosmina	0.34 (0.03)	0.34 (0.04)	0.34 (0.10)	χ2 = 0.683, P = 0.711
Daphnia	0.66 (0.11)	0.60 (0.16)	0.64 (0.08)	χ2 = 1.72, P = 0.423
Cyclops	0.70 (0.15)	0.59 (0.11)	0.66 (0.10)	χ2 = 11.36, P = 0.004
Out-migrating Smolts				
Weight (g)				
Age1	3.42 (0.60)	3.17 (0.74)	3.94 (0.77)	χ2 = 413.7, P < 0.0001
Age2	5.56 (1.05)	5.76 (2.50)	4.74 (1.35)	χ2 = 76.22, P < 0.0001
Length (mm)				
Age1	76.62 (3.55)	75.05 (5.10)	79.31 (5.07)	χ2 = 468.6, P < 0.0001
Age2	92.37 (6.16)	91.37 (10.86)	86.73 (6.77)	χ2 = 43.55, P < 0.0001
Fulton's K				
Age1	0.75 (0.51)	0.74 (0.10)	0.78 (0.06)	χ2 = 125.1, P < 0.0001
Age2	0.70 (0.09)	0.71 (0.10)	0.71 (0.09)	χ2 = 5.31, P = 0.07
Proportion of Age 1	0.86 (0.13)	0.52 (0.27)	0.41 (0.43)	χ2 = 3.35, P =0.19

Table 5.–Escapement counts of sockeye salmon at Pilgrim River and harvest from 1994 to 2010.

Year	Operating Period	Sockeye Counts	Port Clarence subsistence Harvest
1994	Aerial expansion	9,602	1,979
1995	July 19- Aug 22	2,170	4,481
1996	July 7- Aug 20	10,845	4,558
1997	July 12 - Aug 21	15,619[a]	3,177
1998	Aerial expansion	13,885	1,665
1999	July 13 - Aug 06	4,650	2,392
2000	July 05 - Aug 18	12,141	2,851
2001	Aerial expansion	18,460	3,692
2002	July 04 - Aug 04	3,888	3,732
2003	June 21 - Sept 14	42,729	4,495
2004	June 21 - Sept 14	85,417	8,288
2005	June 24 - Sept 05	55,951	8,492
2006	June 30 - Sept 09	52,323	9,940
2007	June 29 - Sept 10	43,432	9,484
2008	June 25 - Sept 01	20,452	5,069
2009	June 26 - Aug 31	953	1,643
2010	June 24 - Sept 01	1,654	824

[a] Chum and sockeye salmon escapements were combined due to species identification problems during 1997.

Table 6.–Returning adult age composition 1997–2010.

		Age											
Year	*n*	0.2	0.3	1.2	1.3	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3
1997	81	0	0	0.01	0.17	0	0	0.12	0.67	0	0	0	0.02
1998	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
1999	413	0	0	0	0.01	0	0	0.03	0.91	0	0	0.01	0.02
2000	281	0	0	0	0.16	0	0	0.02	0.82	0	0	0	0
2001	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2002	198	0	0	0.01	0.02	0	0	0.74	0.18	0.01	0.01	0.03	0
2003	264	0	0	0.03	0.05	0	0	0.59	0.31	0.01	0	0	0
2004	606	0	0	0.06	0.16	0	0	0.44	0.34	0	0	0	0
2005	705	0	0	0.06	0.13	0	0	0.45	0.35	0	0	0	0
2006	390	0	0	0.19	0.28	0	0	0.1	0.43	0	0	0	0
2007	354	0	0	0.04	0.73	0	0	0.05	0.18	0	0	0	0
2008	332	0	0	0	0.48	0.01	0	0.01	0.5	0	0	0	0
2009	159	0	0	0.01	0.18	0.48	0	0.01	0.14	0.19	0	0	0
2010	405	0	0	0.06	0.03	0	0	0.07	0.82	0.01	0	0	0

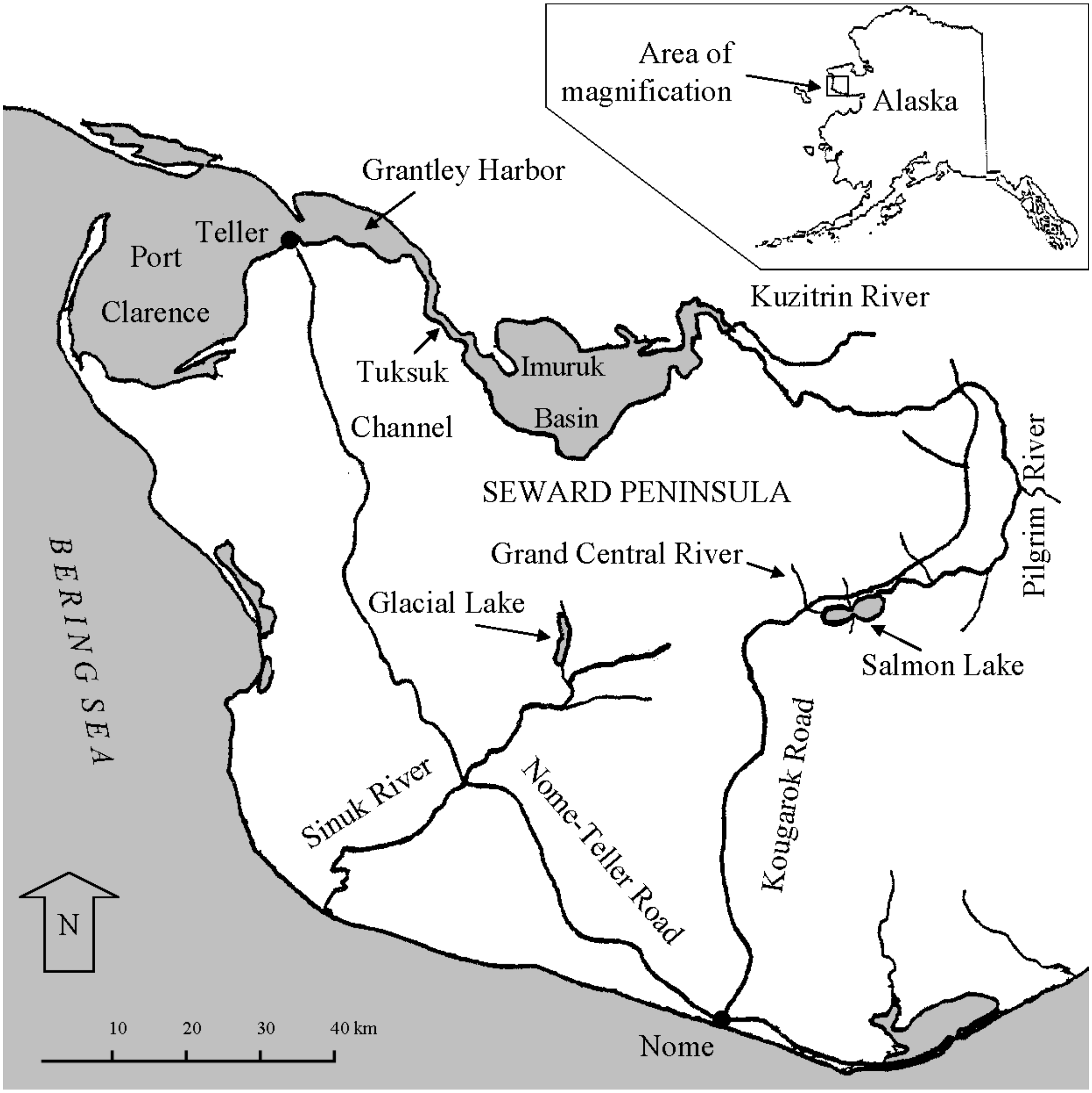

Figure 1.–Map of the Seward Peninsula and various waterways.

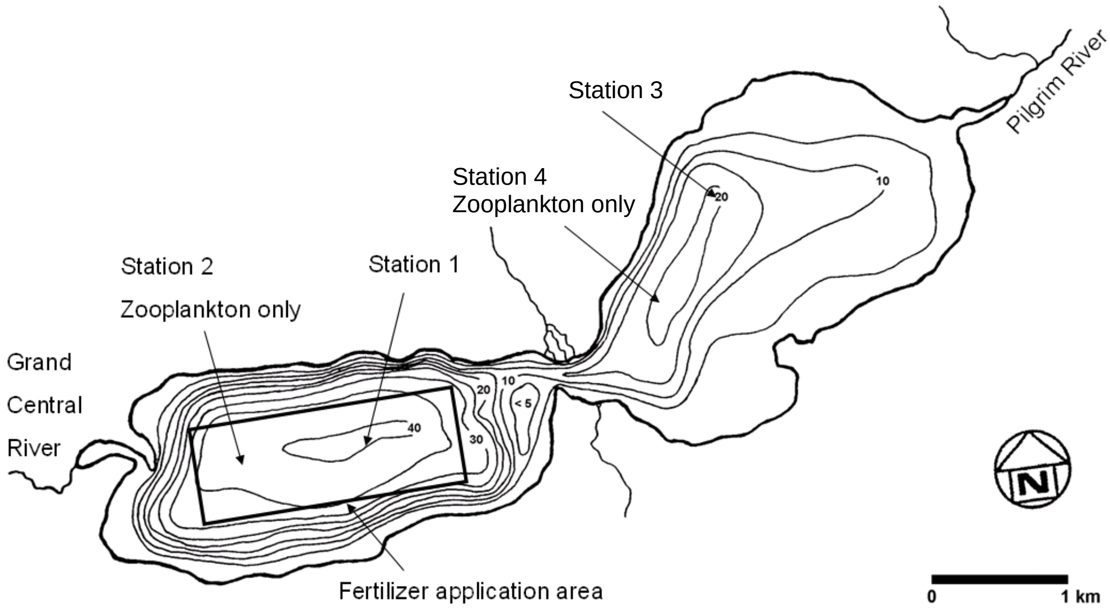

Figure 2.–Bathymetric map of Salmon Lake with limnology sampling stations and fertilizer application area.

(a)

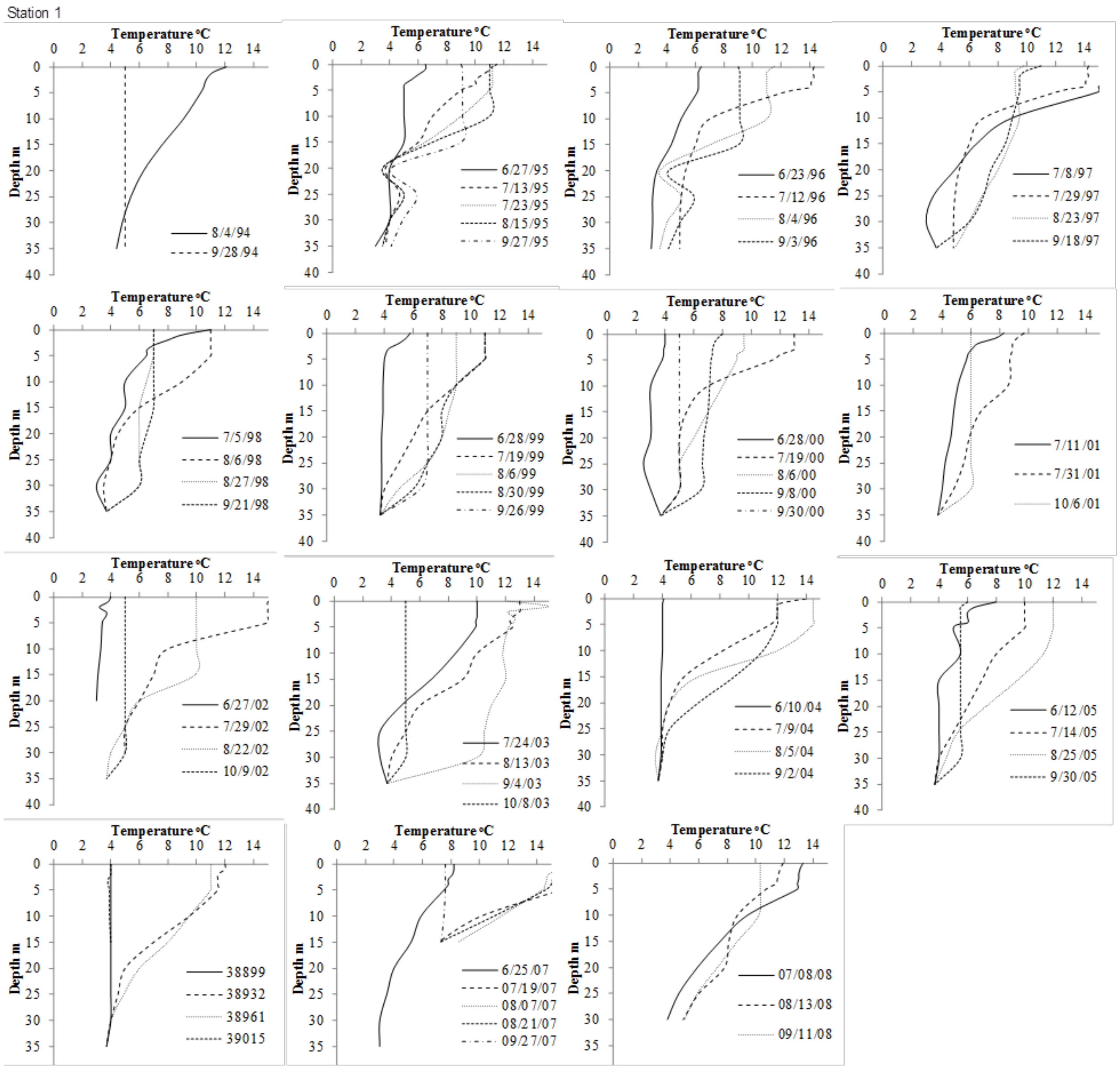

Figure 3.–Seasonal temperature (˚C) and depth profiles at upper lake station 1 (a) and station 3 (b) for study years from 1995 through 2008.

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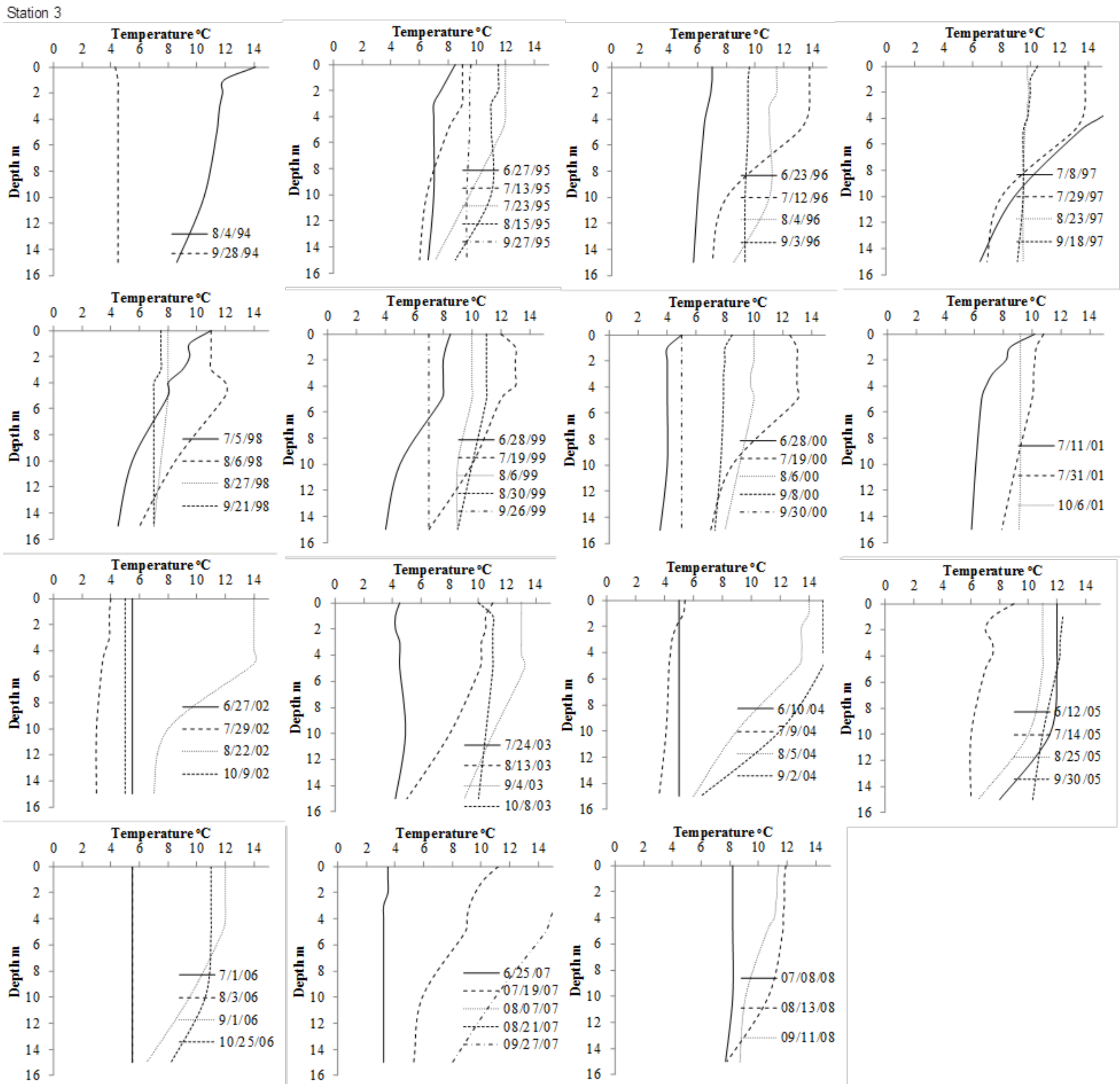
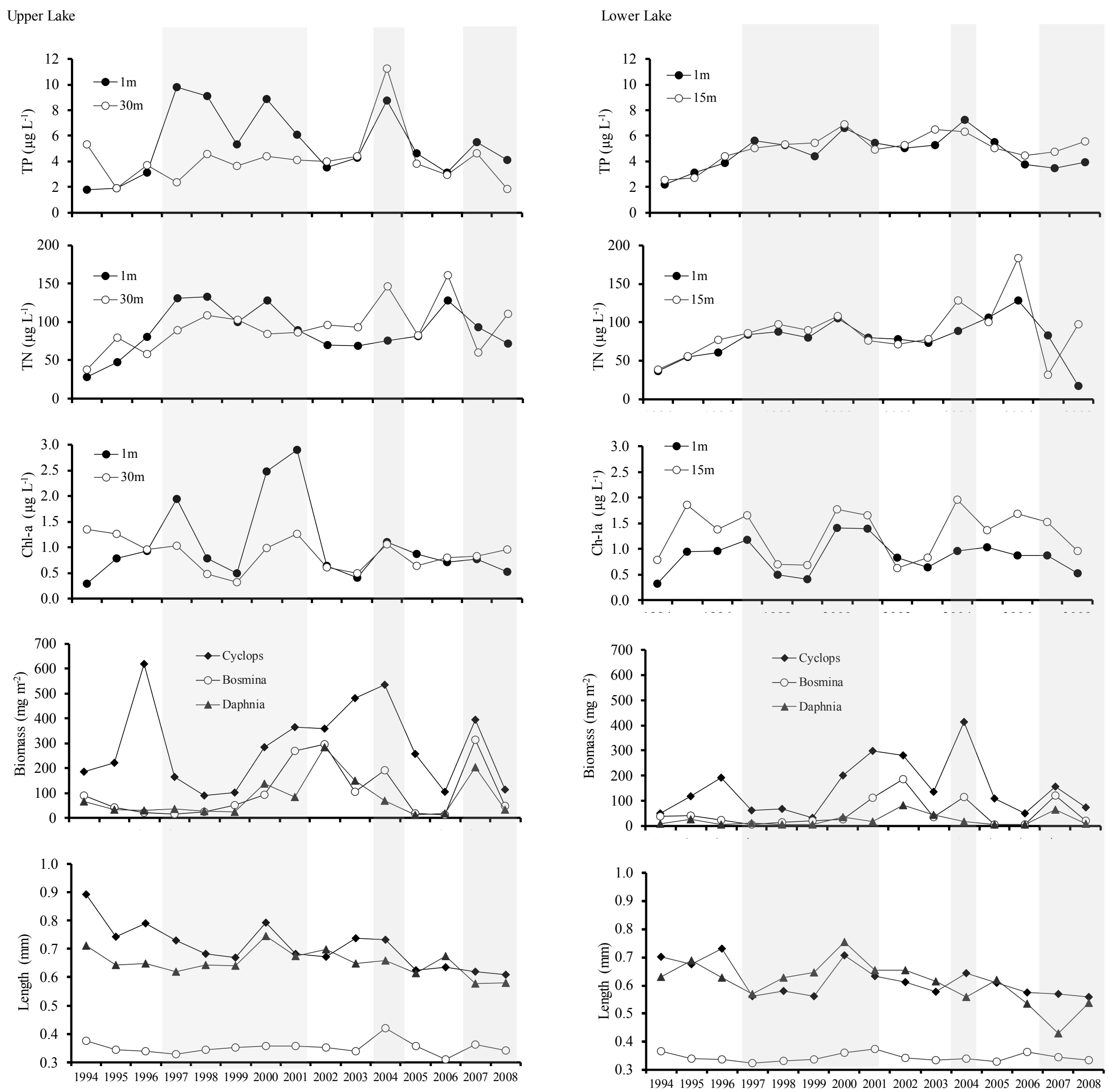
Figure 3.–Part 2 of 2.

(b)





Note: Shading indicates fertilized years.

Figure 4.–Total phosphorus (TP, µg L^{-1}), total nitrogen (TN, µg L^{-1}), chlorophyll-a concentration (Chl-a, mg m^{-2}), *Cyclops*, *Bosmina* and *Daphnia* biomass (mg m^{-2}) and length (mm) from 1995 through 2008.

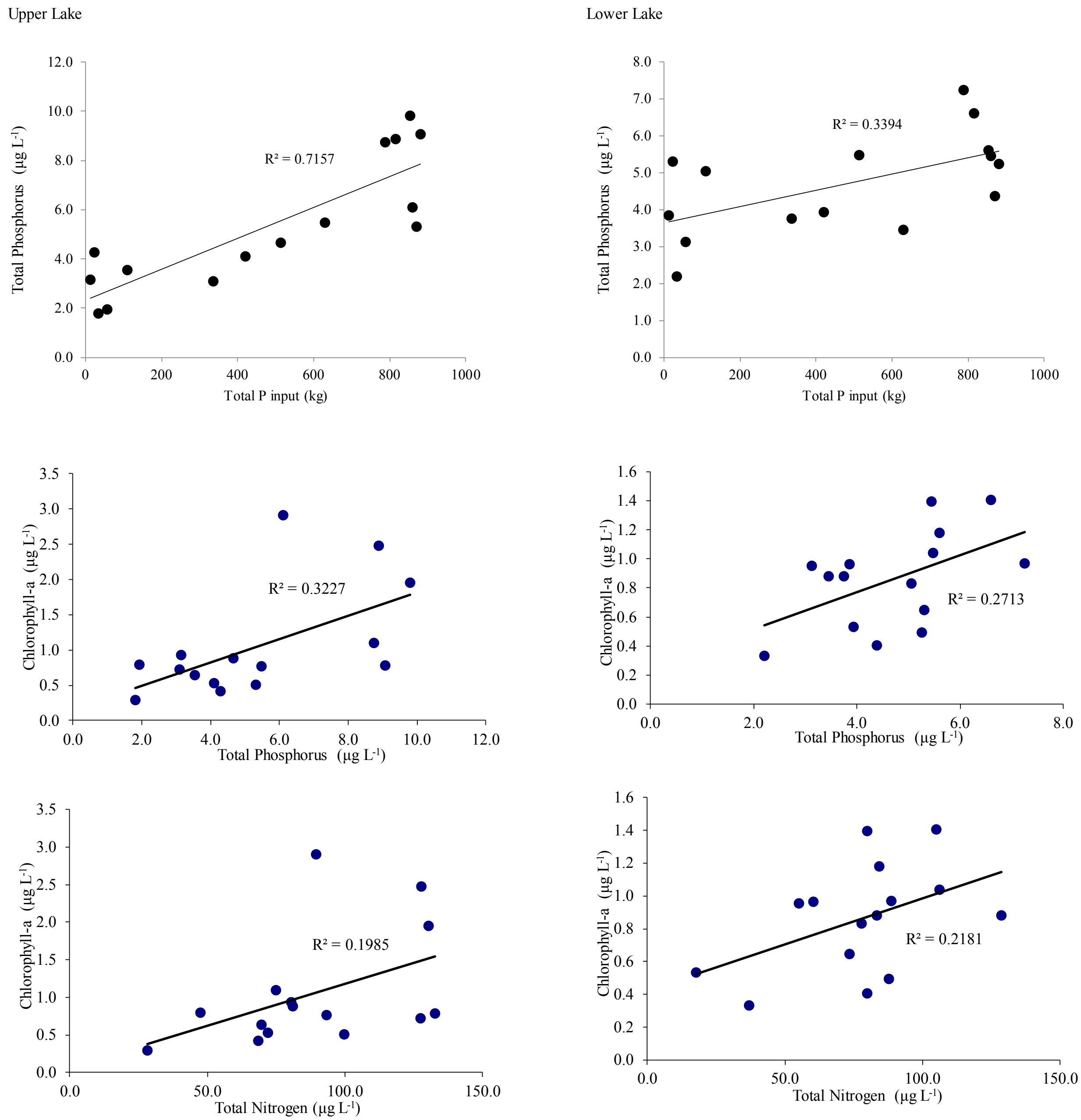
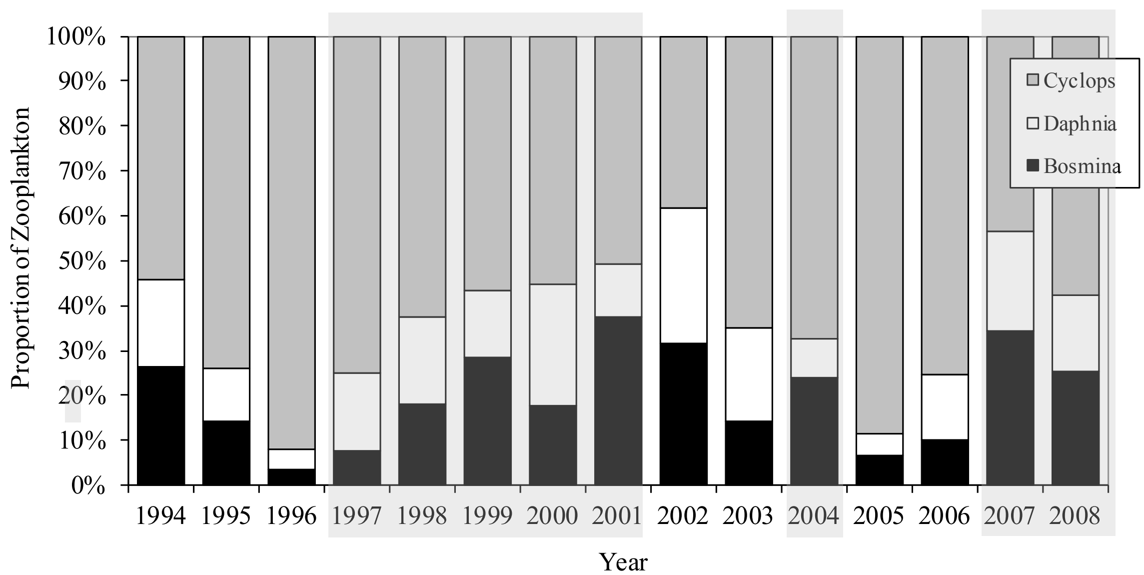
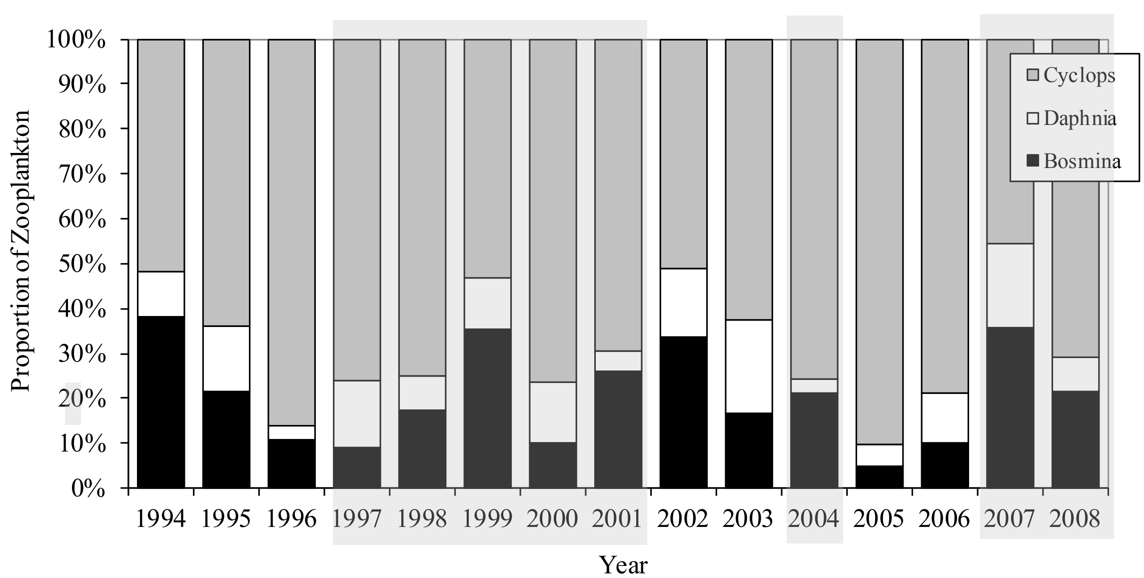


Figure 5.–Correlations between total P input and total phosphorus, total phosphorus and chlorophyll-*a*, and total nitrogen and chlorophyll-*a*.

Upper Lake

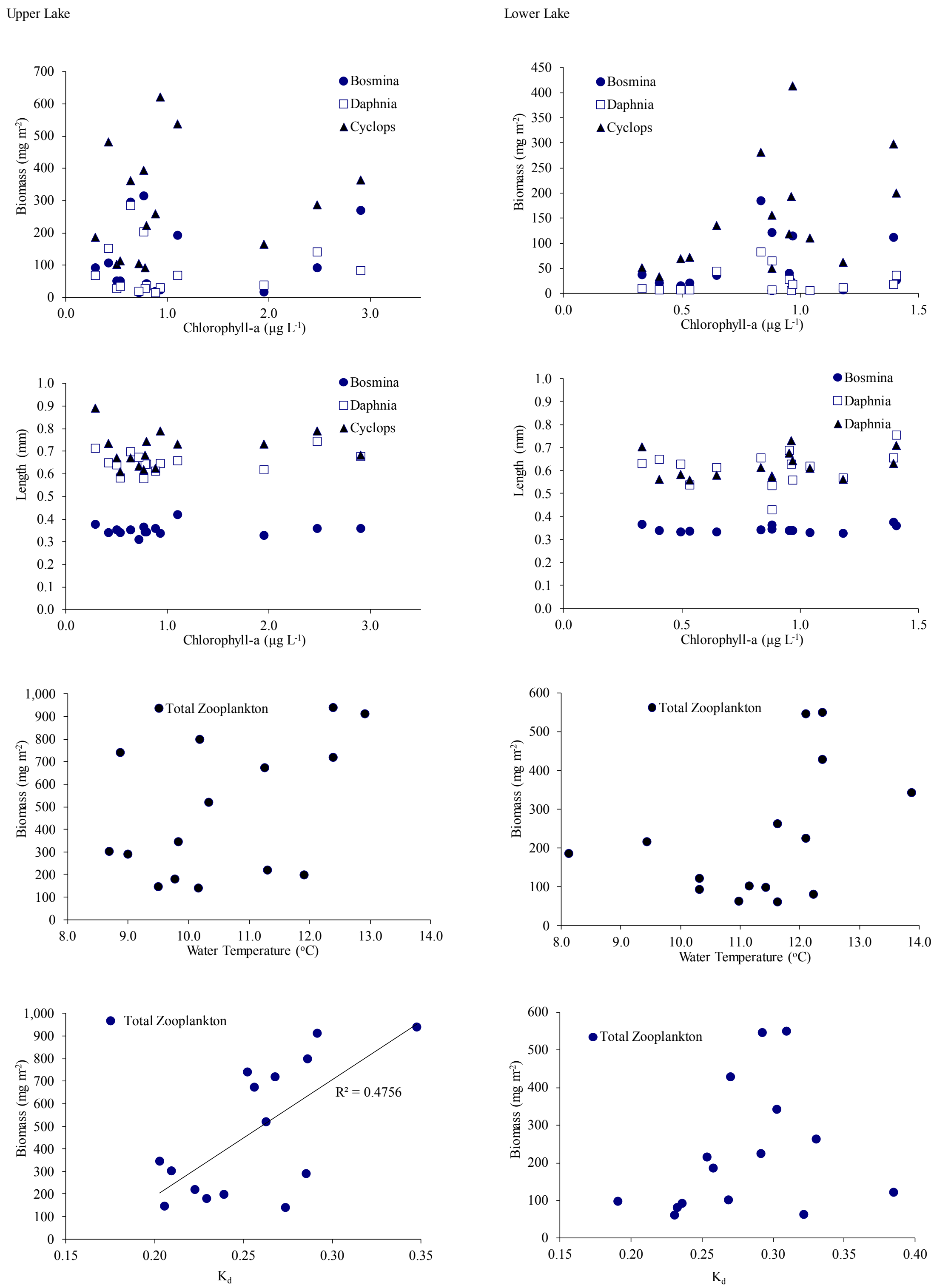


Lower Lake



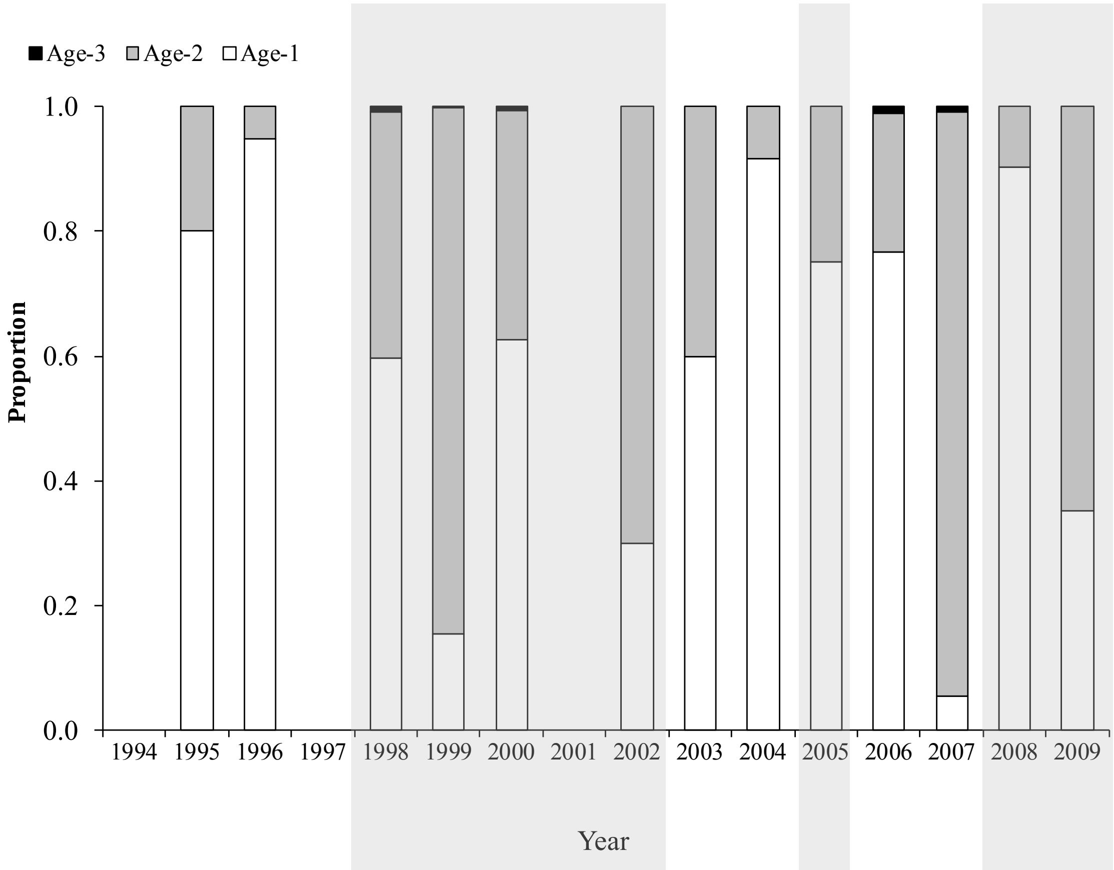
Note: Shading indicates fertilized years.

Figure 6.–Proportion of *Cyclops*, *Bosmina* and *Daphnia* biomass.



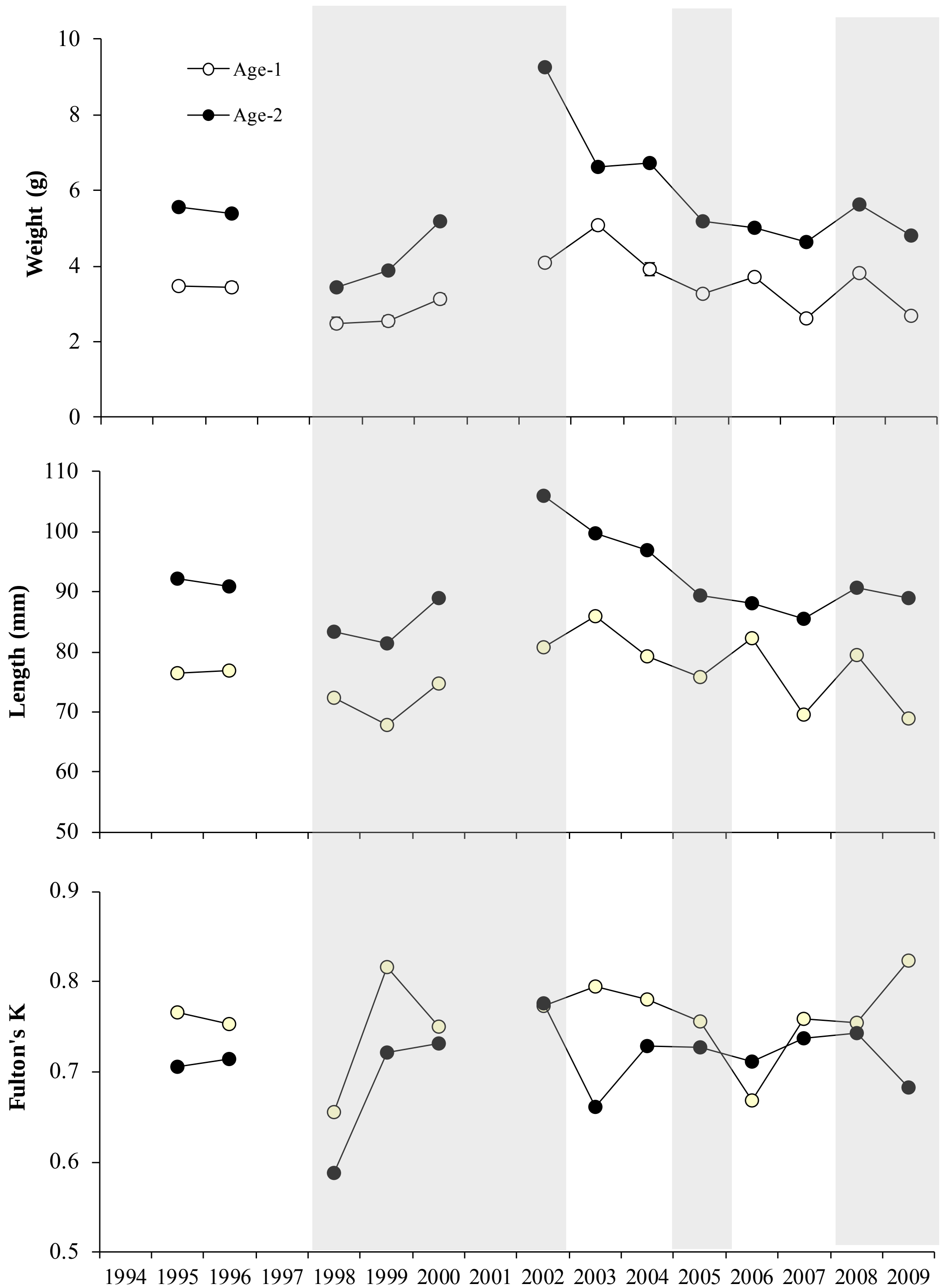
Note: The line shows presence of significant correlation.

Figure 7.–Correlation between chlorophyll-*a* and zooplankton biomass, and chlorophyll-*a* and zooplankton length, water temperature and total zooplankton biomass, and total zooplankton and K_d.



Note: Shading indicates fertilized years during fry stage (shifted 1 year).

Figure 8.–Age class proportions of outmigrating smolt (1995–2009).



Note: Shading indicates fertilized years during fry stage (shifted 1 year).

Figure 9.–Weight (g), Length (mm) and Fulton's Condition factor (Fulton's K) of age 1 and 2 smolt (1995–2009).

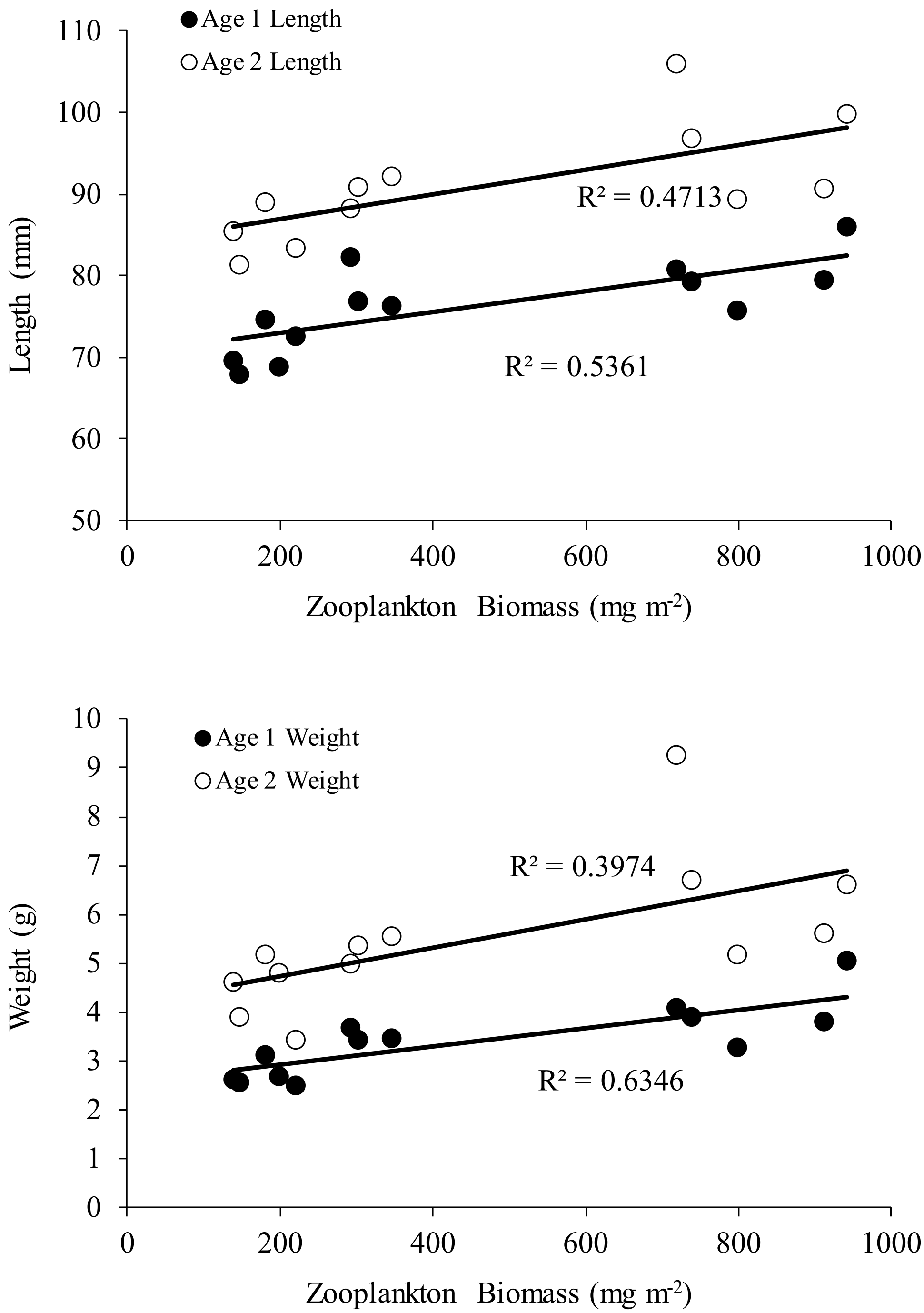
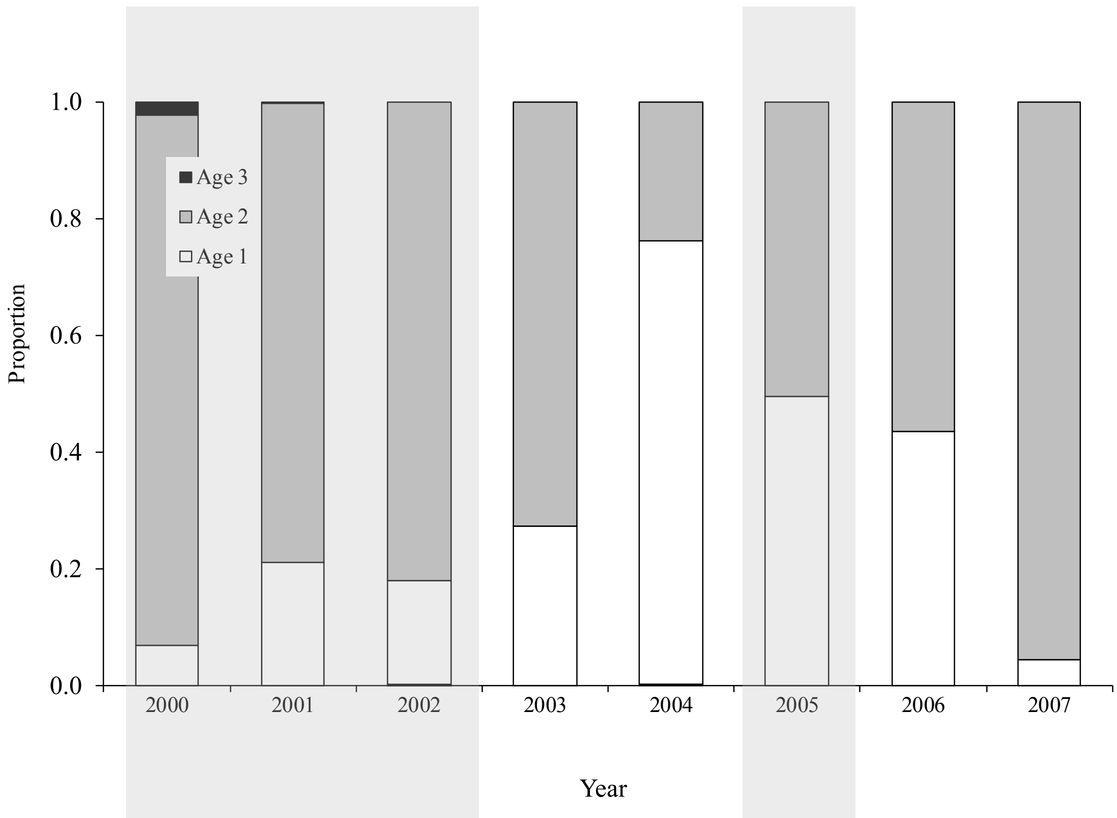
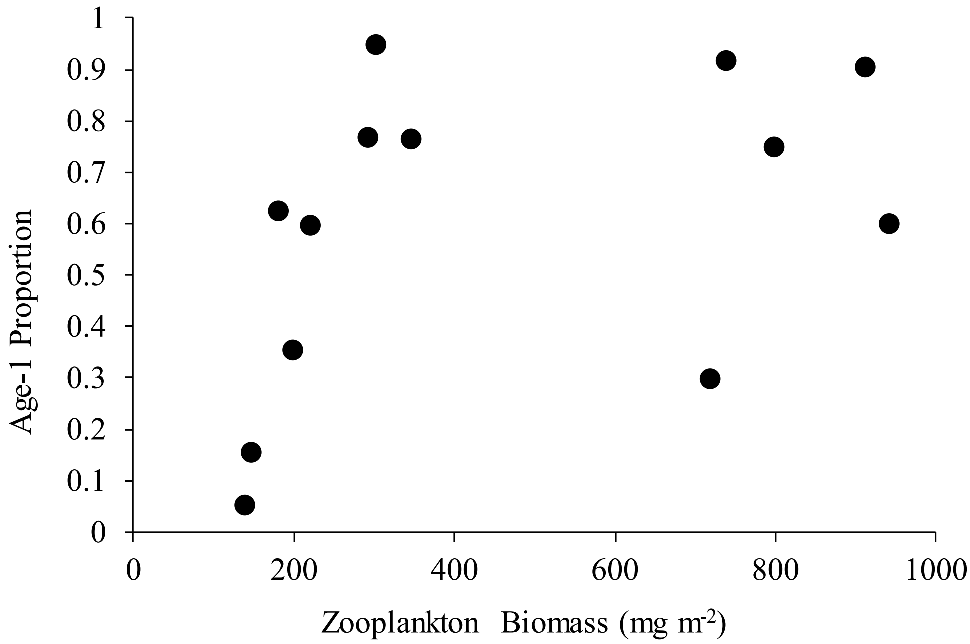


Figure 10.–Correlation between total zooplankton biomass and smolt length and weight.



Note: Shading indicates fertilized years during fry stage (shifted 1 year).

Figure 11.–Age class proportions of returning adults from out-migrating cohort years (2000–2007).



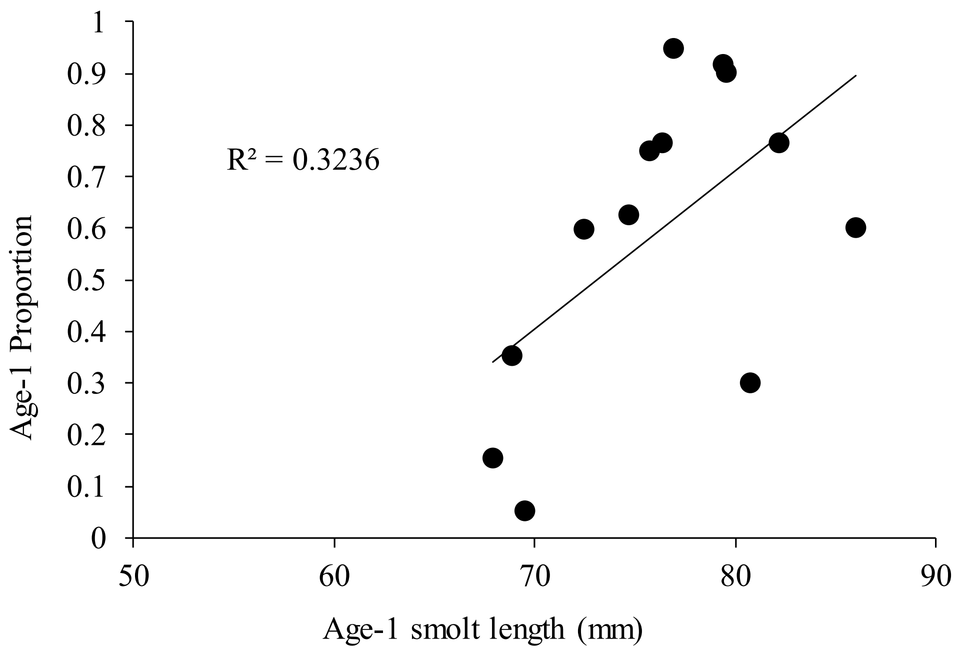


Figure 12.–Correlation between total zooplankton biomass and age-1 smolt proportion, and age-1 smolt length and age-1 proportion.

APPENDIX A: BOAT CONFIGURATION AND PROCEDURES

The liquid fertilizer was applied using a 6 m flat bottom boat fitted with self spraying system, consisting of ABS plastic piping system and *Mazzei* venturi injectors (Figure A1). An inlet pipe was placed under the boat hull faced forward with a 1.5 by 2 inch reducer fitted on the inlet to increase flow. The inlet pipe ran up the back of the transom then forward into the main pipe on the boat. The main inlet pipe was connected to a 1 in. injector pipe with a *Mazzei* injector with ¾ inch tube connecting to fertilizer barrel. The main pipe extended back over the transom on the opposite side from the inlet pipe and connected to a sprayer bar. The sprayer bar was attached to the transom approximately 25 cm above the water line. The sprayer bar was 1 ½ inch pipe with ¼ inch holes every 6 inch.

As boat moves forward, water is forced into the inlet pipe then through to the injector system. By adjusting valves, negative pressure is created in the fertilizer tube, forcing the fertilizer into the injector pipe and the main pipe. While fertilizer moves through the main pipe, it is mixed with water before flowing out through the sprayer bar. In 1999 a second pipe and injector system was added next to the first line to increase the fertilizer application rate and decrease application time required on the lake each week.

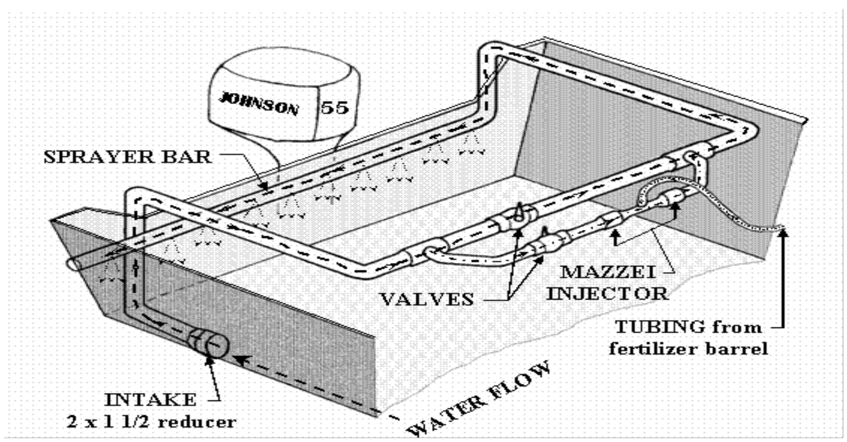


Figure A1.–Diagram of piping system using venturi (*Mazzei* injector) for liquid fertilizer application.

APPENDIX B: HYDROACOUSTIC-TOWNET SURVEYS

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Hydroacoustic surveys were conducted yearly from 1995 to 2002 during September or October to estimate the number and distribution of rearing sockeye salmon juveniles. All surveys were conducted at night because juvenile sockeye salmon are typically more dispersed in the water column during darkness, making fry more detectable by the hydroacoustic gear. All transects were run perpendicular to the longitudinal lake basin axis, at approximately 2 m s^{-1}. In 1995 10 transects were surveyed: 7 in the west basin and 3 in the east basin. From 1996 to 2002 transects were increased to 8 in the west basin and 6 in the east basin.

Hydroacoustic Survey History

1995-1999: During the survey, boat speed was monitored with a *Marsh McBirney* model-201M flow meter attached to the hydroacoustic V-fin tow body, and transect courses were maintained with a lighted *Ritche* compass mounted on the starboard gunwale of the boat. A *BioSonics* model-105 echo-sounder system with a 6/15^{o} dual-beam 420 k Hz transducer was used. Collection parameters were: data threshold -65 decibels (dB), 5 pings s^{-1} ping rate, and 0.4 milliseconds pulse width. The transducer was mounted in a *BioSonics* V-fin tow body, and suspended at approximately 1 m depth from a boom off the bow of the boat. Fish signals or targets were recorded electronically using a Sony model-TCD-D10 digital audio tape recording system, and on paper using a *BioSonics* model-115 chart recorder. The recorded hydroacoustic tapes were analyzed by the *BioSonics* Inc. under a State of Alaska contract.

2000-2002: During the survey boat speed was monitored with A *Garmin* model-175 global positioning system (GPS) receiver. A *BioSonics* DT-6000 scientific echo sounder with 6.6^{o} circular diameter, 200 kHz split-beam digital transducer attached to a *Dell Inspiron* laptop computer via a PCMICA data connection cable was used. The transducer was attached to a 1.5 m aluminum tow-sled, and suspended at 1 m depth for the surveys. Prior to the surveys the following collection parameters were entered into the program: data threshold –65 decibels (dB), 5 pings s^{-1} ping rate, and 0.2 milliseconds pulse width. The Visual Acquisition program was used for all data collection, and *BioSonics* Visual Analyzer program were used for analyses.

Townet Survey

After the hydroacoustic surveys tow netting was conducted to subsample the acoustically-counted fish, to apportion the targets to species, and to collect biological (size and age) data on juvenile sockeye salmon.

The net was suspended to the desired tow depth by metered rope lines to buoys. When using one boat, a sealed PVC pipe was attached to the top of the net as a float bar, and a steel pipe filled with gravel (weight bar) was attached to the bottom to hold the net open when towing. Two boats were used to try to reduce fish avoidance of the townet; net bridle and tow lines do not converge in front of the net opening when towing with two boats. Pipes (metal filled with gravel) were attached to the net sides when using two boats. The pipes hold the net open horizontally and when towing the boats open the net vertically. Beginning in 1996, and for all other years, two boats were used for tow netting. For all years the majority of tow netting was conducted in the west (deeper) basin. In the east basin, one tow was conducted in 1996 and 1997, and two tows in 1999 and 2000 (Table B1).

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All captured fish were enumerated by species. In most years, species other than sockeye salmon were released. Some least cisco were retained. The retained fish were placed in poly bottles and preserved with 10 percent buffered formalin solution. The fry remained in the preservative for a minimum of 60 d before they were sampled for AWL.

Fry abundance and size

Fry abundance was available only from 1995 to 1998 (Table B2). Hydroaccoustic data from 1999 to 2002 were considered lost. Total fry abundance estimates ranged from 962,324 to 2,262,554. Based on townet species compositions, the majority of counts are sockeye salmon fry. However, because of low sample sizes, it was not possible to separate these abundances by species. We were unable to locate hydroaccoustic data for 1999–2002.

Yearly catch totals from fall tow-netting in Salmon Lake (all species) from 1995 to 2001 ranged from a low of 4 in 1995 to a high in 1999 of 290, with a yearly mean catch of 93 (Table B3). The proportion of sockeye salmon fry in the catch also varied greatly among years, from 41.2 % in 2000 to 100% in 1995, and mean catch was 76.5% sockeye salmon fry and 17.3% least cisco. Other species caught, from highest to lowest proportions, include least cisco, stickleback, and sculpin (when townet hit the lake bottom). With tow-netting conducted during two nights each year except 1996, we averaged 10 tows and a total tow-netting time (actual time net was deployed and towed) of 4.2 hours yearly.

Sockeye salmon fry sizes and age compositions varied between years, and could be biased because of small sample sizes (< 100) for all years except for 1996 and 1999 (Table B4). Age-0 fry mean lengths were smallest in 1998 (50.6 mm) and largest in 2000 (61.5 mm, n = 2), and mean for all years was 53.7 mm. Mean weights of age-0 fry ranged from 1.3 g in 1996 to 2.8 g in 2000, and mean for all years was 1.6 g. Age-1 fry mean lengths were smallest in 1998 (76.6 mm) and largest in 2001 (95.0), and all years mean was 79.9 mm. Mean weights of age-1 fry ranged from 4.7 g in 1998 to 9.4 g in 2001, and mean for all years was 5.5 g. The age composition was predominated by age-0 fry from 1995 to 1998 (58.0–89.8%), but shifted to age-1 beginning in 1998, with a peak of 95.5% age-1 in 2001. For all years combined, the age composition was approximately 50% age-0 and age-1, and only two age-2 fry were caught during tow-netting.

TABLES AND FIGURES

Table B1.–Townet survey configurations: 1995–2002.

Year	Sampling date	Depth (m)	Tow speed (km h^{-1})	Tow net
1995	9/27 (6) [1] 9/28 (2)	9/27: 5, 15(5) [1] 9/28: 15,	1.0-2.5	2 x 2 m monofilament
1996	9/27 (6)	surface (2), 5, 10, 15(2)	1.5-3.5	2 x 4 m horizontal townet
1997	9/10 (7) 9/11 (4)	9/10: 5, 10, 15(5) 9/11: 10, 20(3)	1.5-3.5	2 x 2 m townet
1998	9/9 (6) 9/10 (7)	9/9: surface, 10, 15(3), 20 9/10: 15, 20(6)	1.5-4.0	2 x 3 m townet
1999	9/8 (8) 9/9 (5)	9/8: surface, 5(2), 10(2), 15(3) 9/9: 5(2), 15(3)	1.5-3.5	2 x 3 m townet
2000	9/7 (2) 9/8 (5)	9/7: 15, unknown 9/8: 1(2), 5, 10(2),	1.5-4.0	1.5 x 5 m horizontal (baitfish) trawl
2001	10/4 (6) 10/5 (6)	10/4: surface, 10(2), 25(3) 10/5: surface, 5, 10, 15, 25(2)	1.5-4.5	10/4: 7 x 3 m vertical 10/5: 2 x 4 m horizontal
2002	10/1 (4) 10/3 (4)	10/1: surface (2), 10(2) 10/3: surface, 10, 15, 30	NA	7 x 3 m vertical

[1]: The number of tows

[2]: The number of tows more than 1.

Table B2.–Fry abundance estimates

Year	Abundance estimate	±95 % C.I.	S.E.
1995	2,262,554	870,084	338,478
1996	1,407,683	354,701	162,796
1997	1,975,849	655,337	300,777
1998	962,324	268,034	123,018
1999	NA	NA	NA
2000	NA	NA	NA
2001	NA	NA	NA
2002	NA	NA	NA

Note: NA indicates data are missing or lost.

Table B3.–Catch and species composition from townetting conducted at night in Salmon Lake by date.

Year	Date	No. of tows	Sockeye	Least cisco	Stickleback
1995	27 Sep	6	4		
	28 Sep	2	0		
1996	7 Sep	6	108	3	3
1997	10 Sep	7	2	3	
	11 Sep	4	67	10	
1998	9 Sep	6	41	36	2
	10 Sep	7	12/29[a]	9/29[a]	2/105[a]
1999	8 Sep	6	78	29	10
	9 Sep	5	154	6	13
2000	7 Sep	2	0		4
	8 Sep	5	7	5	1/20[a]
2001	4 Oct	6	3	7	1
	5 Oct	6	20	4	4
2002	1 Oct	NA	NA	NA	NA
	3 Oct	NA	NA	NA	NA

Note: NA indicates data are missing or lost.

[a] Counts from townet that hit the bottom.

Table B4.–Mean size and age composition of sockeye salmon fry caught townetting in Salmon Lake, September through October 1995–2001.

Year	Dates	Age	Sample size	Age comp.	Mean length (mm)	SE	Mean weight (g)	SE
1995	27–28 Sep	0	3	75.0%	59.3		1.9	
		1	1	25.0%	84.0		6.0	
1996	7 Sep	0	97	89.8%	52.5	3.710	1.3	0.297
		1	11	10.2%	79.7	5.020	4.8	0.985
1997	10–11 Sep	0	52	76.5%	59.7	3.128	2.4	0.379
		1	14	23.5%		3.384	4.9	0.669
1998	9–10 Sep	0	40	58.0%	50.6	4.113	1.4	0.350
		1	29	42.0%	76.6	3.489	4.7	0.727
1999	8–9 Sep	0	56	24.1%	51.9	5.358	1.5	0.392
		1	174	75.0%	78.6	3.314	5.2	0.656
		2	2	0.9%	93.0		8.2	
2000	7–8 Sep	0	2	28.6%	61.5		2.8	
		1	5	71.4%	90.0		8.3	
2001	4–5 Oct	0	1	4.5%	53.0		2.0	
		1	21	95.5%	95.0	3.721	9.4	0.949
Least cisco 1998–1999			100		107.6	17.317	12.0	5.917

APPENDIX C: PILGRIM RIVER SMOLT ABUNDANCE ESTIMATION

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To examine smolt production, the abundance of out-migrant smolt was estimated on the Pilgrim River using a one-site mark–recapture one site method. In this method, smolt were trapped and marked, transferred and released upriver of the trapping site, and then were recaptured when they passed the trapping site again.

Capture and Enumeration Methods

The smolt capture site was located approximately 10 km below the outlet of Salmon Lake and 1.5 km upriver from the confluence with Crater Creek (Figure C1). The smolt were captured using one or two inclined-plane traps (Todd 1994: Table C1). The trap(s) were anchored inriver with ¾-inch metal rebar driven into the river bottom through eye bolts attached to the bottom of each side of the upriver end of the trap which rested on the river bottom. To increase trap efficiency, leads of one-half inch mesh vexar plastic screening extended upriver from each side of the trap. The vexar was supported by metal fence posts pounded into the river bed. Support posts were placed every 2 to 4 meters as well as tied on at each end of the vexar. Additional support at the upriver end of the lead was provided by *Duck bill* anchors or fence posts. Trap and lead configuration varied each year depending on water conditions.

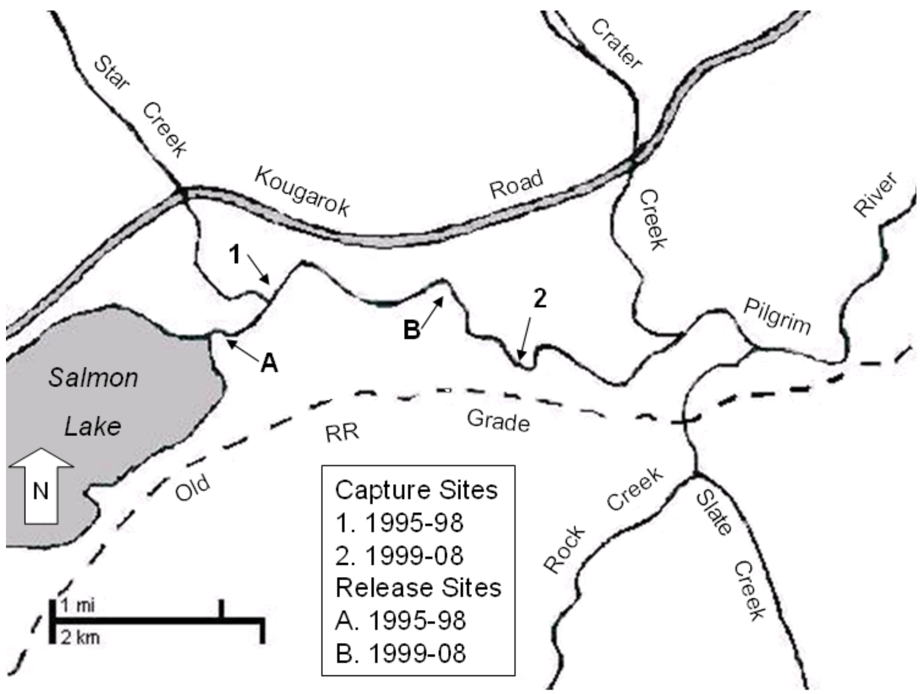

Figure C1.–Smolt capture and release sites for mark–recapture experiments.

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Trap(s) were checked and smolt were counted approximately every four hours to avoid overcrowding, predation and mortality. When there were too many smolt to count, the smolt abundance was estimated by dividing total smolt weights by mean smolt weight. For the first year, the mean seasonal smolt weight was used. In subsequent years, the mean smolt weight was calculated using smolt caught that day. In this method, sub-samples of the weighed nets were individually counted and approximately every 8th to 10th net was hand counted.

Detailed annual trap configuration

1995: One inclined-plane trap with leads was installed approximately 2 km below the lake outlet on 7 June (Figure C1). On 9 June the leads were removed because of ice in the river. From 16 to 21 June the trap was removed because of continued inriver ice. On 27 July 1995 the trap was removed for the season.

1996: Two traps were installed just below the lake outlet on 13 June, and adult weir sections overlaid with *Vexar*, were placed against the outsides of the traps and angled upstream for leads. On 15 June, the outside lead was pulled that evening because of floating ice, and all traps and leads were removed because of continued ice. On 20 June one trap was reinstalled, and the second trap was reinstalled on 21 June. However, the velocity was too great at this location to do a total smolt enumeration. On 22 June the traps and leads were removed and relocated downstream near the 1995 trap location. On 24 June the outside trap was moved further out and downstream of the first trap. On 25 June both trap were removed and installed in a staggered configuration upstream at a shallower site, and remained at this location throughout the project duration of 9 July.

1997: The smolt program was not conducted.

1998: The traps (in staggered configuration) with leads were installed on 17 June at the 1996 location. On 23 June the traps and lead were moved downstream and further out in the river because of lowering water levels, and fished at that location and configuration until 10 July.

1999: The smolt enumeration project was relocated to a location, approximately 10 km below the outlet and approximately 1 km upriver from the confluence with Crater Creek (Figure 1 top). This site was selected for several reasons: 1) to avoid most lake ice inriver during breakup, so the traps or leads would not have to be removed as often during project operations, 2) river morphology looked favorable for possible increased smolt interception because of water depth and flow characteristics; an island divided the river into two channels, and 3) to be on State lands. On 23 June both traps were placed in the river, one trap upstream and outside of the island (in the larger channel). The second trap was placed downstream of the island and centered in the inside channel. On 24 June the outside trap was replaced against the inside channel trap. The leads were run from upriver to shore on both sides, one to the downstream end of the island and the other to the river bank. This effectively blocked the whole inside channel (approximately one-third of river). The traps were removed on 12 July for the season.

2000: Because of low water level (approximately 40% lower than in 1999), one trap was placed downstream of the island in the inside channel at the approximate location as the previous year.

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Leads were connected to the island and almost to the river bank on opposite side, blocking 80–90% of this channel. The second trap was placed above the island and in the main channel. Leads were placed upstream on both sides, with the inside lead first running upstream then running back downstream to block a shallow bar above the island, to force downstream migrating fish to the downstream island trap. The traps were removed on 10 July for the season.

2001: No smolt information was collected because of snow. All equipment and traps were buried under approximately 3 to 4 m of snow, and exact storage locations were not known. Another trap was sent to Nome for the season, but was not used because of continued high spring runoff conditions.

2002: Pilgrim River water levels during spring 2002 were lower than any previous year that the smolt program was conducted. Trap configurations were similar to 2000: one trap with leads blocking the inside island channel and the second trap and leads placed above the island in the main channel. Trap installation began on 7 June, with both traps and all leads completed on 8 June. Both traps were fished continually until 28 June except when live boxes were pulled the evening of 22 June because of ice damming in the trap openings.

2003: Late spring with high river level prevented permanent trap installation until 8 June. Initially one trap was installed on 4 June and fished until 6 June when inriver ice damaged and pushed the trap downriver. A second trap was installed on 19 June. Both traps were pulled for the season on 28 June. Both traps had leads and leads were changed or lengthened depending on water levels and ice conditions.

2004: Only 1 trap was fished in 2004 and was installed on 2 June and fished until 2 July. Trap was relocated from inside channel to midriver on 3 June after ice pushed the trap down from original location. On 17 June the trap was moved back to the inside channel and remained at this location until pulled for the season.

2005: One trap with short leads was installed on 27 May. A second trap was installed on June 4 and fished for one week only. The first trap was relocated several times during the season and was fished through 4 July. As with previous years leads were replaced and/or lengthened as river and ice conditions changed.

2006: Late spring with ice remaining on both banks and on gravel bars in mid river delayed installation of the trap until 6 June. Only one trap was fished during 2006, and leads were reset and changed often because of inriver ice and high water conditions encountered throughout most of the smolt season.

2007: One trap was installed periodically to assist in a sockeye smolt tagging program operated cooperatively by NSEDC and USGS, with technical support from ADF&G.

2008-09: One trap was installed cooperatively by NSEDC and ADF&G to sample smolt condition.

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Age, Weight and Length

Age, weight and length (AWL) samples of emigrating sockeye salmon smolt were collected proportionally to the number of smolt caught in the trap. Samples were removed randomly from the trap by using a hand net with an opening approximately 1 ft by 9 in, large enough to prevent size selective bias.

The smolt were anesthetized in a solution of MS-222 (methanesulfonate) (1995–2007), and their fork length (snout to fork in the tail) were measured to the nearest 1 mm, and weighed to the nearest 0.1 gram. A scale smear was taken with a scalpel from the scale primary growth area (Clutter and Whitesel 1956) then spread on a labeled glass slide. The scales were aged by counting annuli (winter checks) using a microfiche reader.

To measure smolt growth relative to length, Fulton's condition factor (K) was calculated as:

$$K = \frac{W \times 10^5}{L^3}$$

where W is weight in grams, L is length in mm.

Marking and Recapture

The trapped smolt were retained in the live box for up to three nights in order to collect a sufficient number (~1000) and to reduce mortality (Bouwens and Newland 2003). The smolt were netted from the live box, counted, transferred into a 55 gallon container, and dyed with Bismarck Brown Y solution (2 g in 60 L of water). After 30 minutes, they were transported upriver to release locations (Figure C1). At the release site, the smolt were held in a live box in the river for four to six hours of recovery time. At midnight, the fish were released into fast moving water to disperse them and prevent schooling.

At the downriver trapping site, the number of smolt recaptured in the trap(s) was recorded for several days until recaptures ceased.

The above mark–recapture experiments were conducted repeatedly every 3 to 12 days throughout the smolt migration season.

Abundance Estimation

A stratified mark–recapture (M-R) technique with sampling at one location was used to estimate the abundance of a migrating smolt population Carlson et al. 1998. The stratified design is intended to account for potential changes in capture probability over time caused by the changing smolt emigration rate as a whole and potentially by age, through the season.

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Denote:

M_h = the number of marked smolt released in the *h*th stratum (mortality censored).
R_h = the number of marked smolt recaptured.
C_h = total number of smolt captured in the downstream.

Total number of smolt at *h*th stratum was estimated as:

$$\hat{U}_h = \frac{(C_h + 1)(M_h + 1)}{(R_h + 1)} - 1 \quad , \tag{1}$$

with the variance estimated as:

$$V[\hat{U}_h] = \frac{(M_h + 1)(C_h + 1)(M_h - R_h)(C_h - R_h)}{(R_h + 1)^2 (R_h + 2)} \quad . \tag{2}$$

Total number of emigrating smolt was estimated as:

$$\hat{U} = \sum_h \hat{U}_h \quad , \tag{3}$$

with 95% Confidence Interval:

$$\hat{U} \pm 1.96 \sqrt{\sum_h V[\hat{U}_h]} \quad . \tag{4}$$

To estimate of emigrating smolt, proportion of each age class of smolt in the *h*th stratum was estimated as:

$$\hat{\theta}_{hj} = \frac{A_{hj}}{A_h} \quad , \tag{5}$$

where A_{jh} = the number of age *j*th smolt sampled in the *h*th stratum, and A_h = the number of smolt sampled in the *h*th stratum. Its variance was calculated based on binomial distribution as:

$$V[\hat{\theta}_{hj}] = \frac{\hat{\theta}_{hj}(1 - \hat{\theta}_{hj})}{A_h} \quad . \tag{6}$$

Abundance of *j*th age class at *h*th stratum was estimated as:

$$\hat{U}_{hj} = \hat{U}_h \hat{\theta}_{hj} \quad , \tag{7}$$

-continued-

and its variance was estimated as Goodman 1960:

$$V[\hat{U}_{hj}] = \hat{U}_h^2 V[\hat{\theta}_{hj}] + \hat{\theta}_{hj}^2 V[\hat{U}_h] - V[\hat{\theta}_{hj}]V[\hat{U}_h] \quad (8)$$

Total number of emigrating *j*th smolt was estimated as:

$$\hat{U}_j = \sum_h \hat{U}_{hj}, \quad (9)$$

with 95% Confidence Interval:

$$\hat{U}_j \pm 1.96\sqrt{\sum_h V[\hat{U}_{hj}]} \quad (10)$$

The trap efficiency *e* was estimated by:

$$\hat{e}_h = \frac{R_h + 1}{M_h + 1} \quad (11)$$

The estimates of emigrating age-1 smolt varied from 1,131 in 1996 to 763,918 in 2005 (Table C2). The estimates of abundance of age-2 smolt varied from 11,557 to 285,882. The estimate for the total smolt emigration (Table C3) varied from 61,306 (1999) to 1,049,800 (2005). The CV for all abundance estimates were high.

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Table C1.–Daily sockeye salmon smolt catches in the Pilgrim River, 1995–1996, 1998–2000, and 2002–2006.

Day	1995 [a]	1996 [a]	1998	1999	2000	2002	2003	2004	2005	2006	2007	2008	2009
No. traps	1	2	2	2	2	2	1	1	1	1	1	1	1
1 Jun									100				
2 Jun								9	202				
3 Jun								1,953	220				
4 Jun							[b]	2,311 [b]	1,925 [d]				
5 Jun							[b]	1,110	250 [d]				
6 Jun							[b]	887 [b]	785 [d]		1 [b]		
7 Jun						4,008	[b]	607 [b]	991 [d]	80			
8 Jun	1					20,606	12 [b]	239 [b]	502 [d]	346			
9 Jun	10					8,385	8 [b]	**525** [b]	893 [d]	736	100		
10 Jun	7					7,558 [b]	11 [b]	3,237 [b]	3,541 [d]	679			
11 Jun	9					24,352	13 [b]	87 [b]	1,838 [d]	144			
12 Jun	19					**22,311**	10 [b]	1,030	1,022	194		1079	132
13 Jun	0					9,430	0 [b]	431	725	235		**627**	131
14 Jun	0	375				13,727	6 [b]	813	85	124		87	3
15 Jun	0	82 [b]				10,640	3 [b]	230	6,118	101	47	78	14
16 Jun	[b]	[b]				2,560	[b]	423	6,144	73	**33**	19	0
17 Jun	[b]	[b]	7			19,219	300	262	**5,955**	[b]	7 [b]	36	22
18 Jun	[b]	[b]	0			2,339	165	20	1,820	[b]	24 [b]	94	65
19 Jun	[b]	[b]	95 [b]			0	73	49	9,602	[b]	5 [b]	301	26
20 Jun	[b]	[b]	0 [b]			6,657	104 [d]	148	1,322	19	2 [b]	38	273
21 Jun	[b]	289	61		506	5,119	**1,112** [d]	164	5,704	19	12	133	**51**
22 Jun	[b]	12,740 [c]	118		4,339	600 [b]	275 [d]	286	1,899	46	36	292	
23 Jun	8	100	14 [b]	3	**1,978**	1,781	282 [d]	355	4,481	46	20	50	235
24 Jun	7	100	463	7	3,710	1,809	38 [d]	127	681	48	42	73	437
25 Jun	**16**	183	3,970	27	1,456	3,132	94 [d]	69	1180	**346**			190
26 Jun	3		973	238	693	1,191	91 [d]		715	836			649
27 Jun	10	**300**	1,143	193	631	401	19 [d]	132	1888	580			548
28 Jun		1,289	4,090	263	174	116	15 [d]		211	644			353
29 Jun	4	413	**3,818**	1,434	307			222	324	364	9		28
30 Jun	0	108	2,101	**645**	437				159	443			64
1 Jul	4	169	2,977	663	553				66	156			167
2 Jul	1	8	2,734	584	726			322	72	162			21
3 Jul	1	9	2,662	243	560				67	320			
4 Jul	1	16	1,015	146	294				40	128			
5 Jul	0	3	578	108	193				40	49			
6 Jul	0	50	442	29	87					88			
7 Jul	0	71	1,756	136	93					89			
8 Jul	1	19	574	150	0								
9 Jul	2		137	79	17								
10 Jul		15	147	34	18								
Total	137	3,785	29,875	5,000	16,772	165,941	2,631	16,048	61,604	7,095	338	2907	1389

Note: Counts prior to 1 June or after 10 July not shown. Blank cells indicate that no traps were operating successfully. Bold numbers indicate seasonal enumeration midpoint (50% total count).

[a] Traps fished until 23 July 1995, and 14 August 1996. Totals include catches to 15 July, except 22 June 1996 catch- trap installed with partial weir.

[b] Trap removed due to ice inriver or high water, or partial counts due to leads down.

[c] Traps at outlet with weir leads, approximately 40% outlet width fished. Traps pulled and moved downstream. Counts not used in midpoint calculation.

[d] Second trap installed and fished.

Table C2.–Total estimated smolt migration, CV and 95% confidence intervals.

Year	Estimate	CV	lower 95%	upper 95%
1996	225,527	6.7%	195,924	255,130
1998	313,329	5.9%	276,962	349,696
1999	61,306	8.2%	51,503	71,109
2000	151,549	15.5%	105,501	197,598
2002	366,909	2.9%	346,294	387,523
2003	208,313	30.9%	82,121	334,505
2004	193,720	12.9%	144,822	242,617
2005	1,049,800	7.8%	888,668	1,210,931
2006	189,013	16.9%	132,240	245,787

Table C3.–Estimated emigration of smolt for by age $\hat{U}$, CV($\hat{U}$) with 95% confidence intervals.

Year	Age-1	CV	Age-2	CV	Age-3	CV
1996	213,657	6.9%	11,870	30.1%	0	
1998	169,504	7.7%	140,629	9.4%	3,195	54.0%
1999	8,468	14.6%	52,723	2.4%	114	99.6%
2000	119,337	19.2%	31,885	71.8%	327	60.5%
2002	146,904	3.9%	218,943	4.0%	1,062	50.9%
2003	116,946	43.4%	91,367	43.4%	0	
2004	182,162	13.5%	11,557	38.4%	0	
2005	763,918	9.5%	285,882	13.6%	0	
2006	148,256	18.5%	39,126	23.7%	1,632	71.2%

APPENDIX D: SALMON LAKE STATION FROM 1994 THROUGH 2008.

Appendix D1.–Salmon Lake station 1 at 1 m: mean annual nutrient content, chemical profile, and primary production characteristics from 1994 through 2008.

		Year														
Parameter	Units	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Conductivity	mmhos cm^{-1}	134	125	132	129	126	127	124	128	119						
pH		7.5	7.4	7.4	7.9	7.6	7.5	7.4	7.4	7.3						
Alkalinity	mg L^{-1}	50.0	48.3	47.3	49.0	47.9	50.3	44.6	47.0	45.6						
Turbidity	NTU	0.5	0.6	0.5	0.8	1.2	0.8	1.3	0.7	0.5						
Color	Pt units	4	3	5	6	5	6	6	6	8	7	7	4	3	5	6
Calcium	mg L^{-1}	19.8	17.7	17.6	17.9	18.1	19.2	17.9	18.3	17.0						
Magnesium	mg L^{-1}	2.9	4.8	3.2	3.2	3.5	3.8	3.3	3.6	3.4						
Iron	mg L^{-1}	20	27	23	17	14	33	19	29	40						
Total-P	mg L^{-1}	1.8	1.9	3.2	9.8	9.1	5.3	8.9	6.1	3.6	4.3	8.8	4.7	3.1	5.5	4.1
Total filterable P	mg L^{-1}	1.4	0.9	2.1	4.8	2.1	2.0	2.8	3.3	2.6	2.0	2.7	1.4	0.7	3.3	2.0
Filterable reactive P	mg L^{-1}	1.8	0.6	1.6	3.8	1.5	0.9	2.3	1.2	1.7	1.4	0.6	1.4	1.4	2.1	2.2
Kjeldahl-N	mg L^{-1}	24	43	66	121	121	85	117	85	62	59	152	66	113	88	67
Ammonia	mg L^{-1}	1.7	3.2	7.9	8.8	11.1	7.7	3.2	3.7	7.5	1.7	17.0	1.9	3.0	5.0	5.2
Nitrate+nitrite	mg L^{-1}	4.1	4.1	14.3	9.5	11.6	15.0	10.7	6.3	8.1	9.3	7.8	15.3	15.0	5.4	4.6
Total-N (Nitrogen)	mg L^{-1}	28	48	81	130	133	100	128	89	70	68	75	81	127	93	72
Total N:Total P [a]		34.8	55.8	61.9	33.2	40.0	54.2	33.0	45.6	44.3	36.0	46.9	42.9	90.0	50.5	35.8
Reactive silicon	mg L^{-1}	1,924	1,888	1,750	1,356	1,509	1,685	1,281	1,489	1,659						
Particulate organic C	mg L^{-1}	67	131	62	253	183	218	255	181	162						
Chlorophyll-*a*	mg L^{-1}	0.29	0.79	0.93	1.95	0.78	0.50	2.48	2.91	0.64	0.42	1.10	0.88	0.72	0.77	0.53
Phaeophytin	mg L^{-1}	0.08	0.12	0.13	1.05	0.30	0.33	0.51	0.32	0.21	0.09	0.44	0.19	0.23	0.12	0.14

Note: Shaded cells indicate years that fertilizer was applied.

[a] Total N:Total P is the atomic ratio of N:P.

Appendix D2.–Salmon Lake station 1 at 30 m: mean annual nutrient content, chemical profile, and primary production characteristics from 1994 through 2008.

		Year														
Parameter	Units	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Conductivity	mmhos cm^{-1}	135	133	134	151	144	132	140	128	131						
pH		7.4	7.1	7.3	7.2	7.4	7.2	7.2	7.3	7.3						
Alkalinity	mg L^{-1}	49.3	52.3	49.8	54.8	53.4	49.7	50.1	47.2	50.5						
Turbidity	NTU	0.5	0.6	0.6	0.6	1.1	0.7	1.0	0.6	0.5						
Color	Pt units	5	4	4	6	6	6	5	6	9	7	7	3	3	6	7
Calcium	mg L^{-1}	19.7	18.6	18.0	20.3	20.4	19.5	20.0	17.9	18.7						
Magnesium	mg L^{-1}	3.5	4.5	3.2	3.7	3.8	3.7	3.7	3.5	3.8						
Iron	mg L^{-1}	12	28	22	19	14	30	18	32	33						
Total-P	mg L^{-1}	5.4	1.9	3.7	2.4	4.6	3.6	4.4	4.1	4.0	4.4	11.3	3.8	3.0	4.7	1.9
Total filterable P	mg L^{-1}	5.1	0.7	1.8	1.5	1.8	1.8	1.9	2.1	2.5	4.2	4.0	1.2	0.7	1.6	1.4
Filterable reactive P	mg L^{-1}	2.0	0.7	1.4	1.7	1.6	1.2	2.0	1.1	1.7	3.2	0.4	1.0	0.6	1.2	2.1
Kjeldahl-N	mg L^{-1}	34	48	54	54	77	68	60	63	59	54	178	39	122	32	52
Ammonia	mg L^{-1}	1.7	6.8	9.6	11.6	9.1	15.4	5.7	9.7	16.5	3.6	13.8	9.2	6.5	6.0	12.4
Nitrate+nitrite	mg L^{-1}	4.3	31.4	4.1	35.1	30.8	35.0	24.3	22.7	37.0	38.7	24.0	42.8	38.7	28.0	58.8
Total-N (Nitrogen)	mg L^{-1}	38	80	58	89	108	103	84	86	96	93	146	82	161	60	111
Total N:Total P [a]		20.5	98.0	34.6	84.4	59.8	67.4	43.5	52.3	57.6	47.0	41.6	53.0	118.9	42.5	101.9
Reactive silicon	mg L^{-1}	2,000	2,284	1,865	2,314	1,999	2,081	1,785	1,686	1,990						
Particulate organic C	mg L^{-1}	100	72	39	86	81	102	106	114	94						
Chlorophyll-*a*	mg L^{-1}	1.35	1.26	0.96	1.03	0.49	0.32	1.00	1.27	0.61	0.49	1.07	0.64	0.80	0.83	0.96
Phaeophytin	mg L^{-1}	0.05	0.16	0.13	0.55	0.28	0.42	0.25	0.19	0.17	0.14	0.29	0.20	0.15	0.15	0.24

Note: Shaded cells indicate years that fertilizer was applied.

[a] Total N:Total P is the atomic ratio of N:P.

Appendix D3.–Salmon Lake station 3 at 1 m: mean annual nutrient content, chemical profile, and primary production characteristics from 1994 through 2008.

		Year														
Parameter	Units	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Conductivity	mmhos cm^{-1}	137	126	129	129	127	132	124	130	115						
pH		7.2	7.5	7.5	7.9	7.7	7.5	7.4	7.4	7.4						
Alkalinity	mg L^{-1}	49.0	47.9	48.6	47.5	46.3	48.6	43.0	46.6	44.5						
Turbidity	NTU	0.4	0.8	0.7	0.4	0.8	0.7	1.1	0.7	0.6						
Color	Pt units	10	4	6	7	7	6	6	7	10	7	10	4	5	6	6
Calcium	mg L^{-1}	18.9	17.6	17.1	17.4	17.9	19.3	17.6	18.4	16.4						
Magnesium	mg L^{-1}	2.6	4.0	3.2	3.2	3.3	3.7	3.1	3.5	3.2						
Iron	mg L^{-1}	23	39	28	15	15	33	24	32	40						
Total-P	mg L^{-1}	2.2	3.1	3.9	5.6	5.3	4.4	6.6	5.5	5.1	5.3	7.3	5.5	3.8	3.5	3.9
Total filterable P	mg L^{-1}	6.2	1.0	2.1	2.8	2.5	1.9	2.9	3.4	4.0	2.5	5.3	1.6	0.6	1.7	1.7
Filterable reactive P	mg L^{-1}	6.2	0.6	1.7	2.2	1.9	0.9	2.2	1.6	2.5	1.8	0.3	1.4	1.2	1.3	1.7
Kjeldahl-N	mg L^{-1}	33	51	55	80	82	71	97	75	74	65	85	101	123	81	13
Ammonia	mg L^{-1}	1.7	2.0	5.3	3.7	6.5	7.9	1.7	4.4	6.6	9.9	5.0	2.0	3.7	3.3	6.4
Nitrate+nitrite	mg L^{-1}	4.1	4.1	5.7	4.1	5.5	8.9	8.3	4.7	3.5	8.5	4.3	5.0	6.0	2.3	4.9
Total-N (Nitrogen)	mg L^{-1}	37	55	60	84	88	80	105	80	78	73	89	106	129	83	18
Total N:Total P [a]		37.1	45.0	35.9	40.6	40.0	46.4	35.6	42.0	34.9	32.0	26.4	42.9	83.1	56.8	8.9
Reactive silicon	mg L^{-1}	1,904	1,925	1,755	1,540	1,470	1,707	1,342	1,555	1,581						
Particulate organic C	mg L^{-1}	64	109	98	182	152	179	208	185	210						
Chlorophyll-*a*	mg L^{-1}	0.33	0.95	0.96	1.18	0.50	0.40	1.41	1.40	0.83	0.65	0.97	1.04	0.88	0.88	0.53
Phaeophytin	mg L^{-1}	0.05	0.20	0.22	0.70	0.23	0.48	0.41	0.26	0.23	0.19	0.32	0.36	0.30	0.23	0.21

Note: Shaded cells indicate years that fertilizer was applied.

[a] Total N:Total P is the atomic ratio of N:P.

Appendix D4.–Salmon Lake station 1 at 15 m: mean annual nutrient content, chemical profile, and primary production characteristics from 1994 through 2008.

		Year														
Parameter	Units	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Conductivity	mmhos cm^{-1}	136	123	131	131	130	134	134	130	116						
pH		7.4	7.5	7.4	7.6	7.5	7.5	7.3	7.4	7.5						
Alkalinity	mg L^{-1}	48.3	48.0	48.4	47.3	49.1	50.4	47.1	46.6	43.4						
Turbidity	NTU	0.5	0.7	0.6	0.6	1.2	0.9	1.1	0.8	0.8						
Color	Pt units	6	5	5	7	6	5	5	7	10	8	9	5	5	7	6
Calcium	mg L^{-1}	19.2	17.6	17.8	17.7	18.6	19.4	18.9	18.1	16.6						
Magnesium	mg L^{-1}	3.5	3.7	3.2	3.2	3.4	3.8	3.4	3.5	3.3						
Iron	mg L^{-1}	13	52	27	16	17	39	22	30	38						
Total-P	mg L^{-1}	2.6	2.7	4.4	5.0	5.3	5.4	6.9	5.0	5.3	6.5	6.3	5.1	4.5	4.8	5.6
Total filterable P	mg L^{-1}	1.8	1.7	2.0	2.1	1.4	1.8	2.3	3.1	3.5	2.3	5.1	1.9	0.9	1.8	2.8
Filterable reactive P	mg L^{-1}	1.9	1.4	1.7	2.1	1.1	0.8	2.1	1.5	2.2	1.6	0.2	1.3	2.7	1.8	2.2
Kjeldahl-N	mg L^{-1}	34	52	73	81	87	75	94	69	65	69	358	87	174	26	94
Ammonia	mg L^{-1}	1.7	2.2	6.2	4.2	6.1	8.9	1.7	7.4	6.2	5.3	7.5	7.3	4.3	3.3	6.8
Nitrate+nitrite	mg L^{-1}	4.1	4.1	4.1	4.5	9.9	14.9	14.6	6.9	6.1	10.0	13.5	13.4	9.5	6.2	3.1
Total-N (Nitrogen)	mg L^{-1}	39	56	77	86	97	90	108	76	71	79	129	100	183	32	97
Total N:Total P [a]		34.5	45.8	39.1	38.7	41.4	39.3	35.2	39.7	29.9	27.0	148.6	43.5	92.7	14.7	47.2
Reactive silicon	mg L^{-1}	2,020	2,012	1,812	1,853	1,899	1,884	1,579	1,560	1,732						
Particulate organic C	mg L^{-1}	141	164	91	150	127	175	206	173	163						
Chlorophyll-*a*	mg L^{-1}	0.79	1.86	1.39	1.66	0.70	0.69	1.78	1.66	0.63	0.83	1.96	1.36	1.68	1.52	0.96
Phaeophytin	mg L^{-1}	0.14	0.42	0.30	1.09	0.44	0.32	0.45	0.28	0.21	0.29	0.71	0.38	0.39	0.38	0.23

Note: Shaded cells indicate years that fertilizer was applied.

[a] Total N:Total P is the atomic ratio of N:P.

Appendix D5.–Mean annual zooplankton biomass and length at 4 stations from 1994 to 2008.

	Year														
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Station 1															
Biomass (mg m^{-2})															
Bosmina	84.91	27.12	23.14	14.36	30.98	43.09	47.94	346.06	198.97	137.23	248.34	18.68	15.52	317.37	53.11
Daphnia	42.92	27.05	21.70	29.08	32.35	23.28	107.82	85.61	203.42	183.14	40.85	10.77	16.08	175.20	28.10
Cyclops	177.20	154.09	591.80	178.21	104.28	102.46	262.05	363.40	252.51	531.26	489.44	238.98	94.87	428.47	143.59
Length (mm)															
Bosmina	0.37	0.34	0.35	0.32	0.34	0.35	0.35	0.35	0.36	0.34	0.41	0.38	0.34	0.36	0.34
Daphnia	0.71	0.64	0.64	0.61	0.62	0.66	0.75	0.68	0.71	0.64	0.65	0.60	0.62	0.58	0.55
Cyclops	0.90	0.72	0.80	0.74	0.70	0.67	0.80	0.68	0.66	0.75	0.74	0.62	0.61	0.63	0.61
Station 2															
Biomass (mg m^{-2})															
Bosmina	98.24	58.40	22.95	18.96	22.49	59.80	137.52	194.63	425.00	63.78	134.63	20.27	12.55	310.93	46.94
Daphnia	91.91	43.65	38.30	47.80	24.42	30.04	172.35	82.36	391.58	110.52	96.46	17.53	23.85	231.00	39.53
Cyclops	197.05	291.94	648.44	151.13	79.48	100.89	310.54	366.02	505.24	414.37	585.00	276.89	114.81	361.48	84.19
Length (mm)															
Bosmina	0.38	0.35	0.33	0.34	0.35	0.35	0.36	0.37	0.35	0.34	0.43	0.34	0.28	0.37	0.34
Daphnia	0.71	0.65	0.65	0.63	0.66	0.62	0.74	0.67	0.68	0.66	0.67	0.63	0.73	0.57	0.61
Cyclops	0.88	0.77	0.78	0.72	0.67	0.67	0.78	0.68	0.69	0.72	0.73	0.63	0.65	0.61	0.61

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	Year														
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Station 3															
Biomass (mg m^{-2})															
Bosmina	46.33	21.38	26.67	9.39	14.88	15.06	38.02	92.06	161.20	35.76	145.39	6.86	6.24	127.42	29.32
Daphnia	15.24	35.28	6.85	16.96	6.59	5.44	49.86	20.72	66.70	50.78	15.58	7.88	6.29	39.79	10.32
Cyclops	48.49	117.06	175.72	76.44	39.06	31.64	154.94	226.43	250.86	155.28	480.74	108.83	61.52	131.77	93.46
Length (mm)															
Bosmina	0.36	0.34	0.34	0.33	0.34	0.35	0.37	0.35	0.34	0.34	0.44	0.34	0.38	0.35	0.34
Daphnia	0.65	0.74	0.60	0.59	0.65	0.67	0.76	0.63	0.65	0.63	0.83	0.68	0.59	0.44	0.52
Cyclops	0.80	0.72	0.70	0.57	0.53	0.56	0.68	0.63	0.59	0.60	0.72	0.60	0.58	0.59	0.56
Station 4															
Biomass (mg m^{-2})															
Bosmina	28.88	58.68	22.48	5.10	17.14	28.79	10.43	131.98	218.07	36.75	84.04	4.86	6.49	116.32	14.53
Daphnia	4.81	19.92	6.52	7.30	7.80	8.91	17.34	16.43	103.60	37.00	20.22	4.55	7.35	89.56	5.21
Cyclops	53.98	120.80	210.99	47.48	99.80	34.47	261.19	369.61	321.68	107.74	344.78	111.48	37.47	179.59	51.79
Length (mm)															
Bosmina	0.37	0.34	0.34	0.33	0.33	0.33	0.35	0.40	0.35	0.33	0.24	0.32	0.35	0.34	0.33
Daphnia	0.60	0.64	0.66	0.55	0.61	0.62	0.75	0.68	0.65	0.59	0.29	0.55	0.48	0.41	0.56
Cyclops	0.61	0.63	0.76	0.56	0.64	0.56	0.75	0.64	0.65	0.55	0.56	0.63	0.57	0.55	0.55