Regional Information Report No. 1J08-10

Assessing the Historical Salmon Presence and Productivity at Transboundary Sockeye Salmon Nursery Lakes Using Stable Isotopes within the Paleolimnologic Sediment Record

by

David L. Barto,

Scott F. Lamoureux,

and

Bruce P. Finney

March 2008

Alaska Department of Fish and Game Division of Commercial Fisheries

Symbols and Abbreviations

The following symbols and abbreviations, and others approved for the Système International d'Unités (SI), are used without definition in the following reports by the Divisions of Sport Fish and of Commercial Fisheries: Fishery Manuscripts, Fishery Data Series Reports, Fishery Management Reports, Special Publications and the Division of Commercial Fisheries Regional Reports. All others, including deviations from definitions listed below, are noted in the text at first mention, as well as in the titles or footnotes of tables, and in figure or figure captions.

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)

Measures (fisheries)	
fork length	FL
mideye-to-fork	MEF
mideye-to-tail-fork	METF
standard length	SL
total length	TL
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

REGIONAL INFORMATION REPORT NO. 1J08-XX

ASSESSING THE HISTORICAL SALMON PRESENCE AND PRODUCTIVITY AT TRANSBOUNDARY SOCKEYE NURSERY LAKES USING STABLE ISOTOPES WITHIN THE PALEOLIMNOLOGIC SEDIMENT RECORD

By
David L. Barto
Alaska Department of Fish and Game, Division of Commercial Fisheries,
Douglas, AK 99811-0024, USA

Scott F. Lamoureux
Department of Geography, Queen's University
Kingston ON, Canada K73N6
and
Bruce P. Finney
Institute of Marine Science, School of Fisheries and Ocean Sciences, University of
Alaska Fairbanks, Fairbanks, AK 99775-7720, USA

Alaska Department of Fish and Game
Division of Commercial Fisheries, Publications Section
802 3rd, Douglas, Alaska, 99811-0020

March 2008

This investigation was partially financed by the Pacific Salmon Commission 2005 Northern Fund

The Regional Information Report Series was established in 1987 and was redefined in 2007 to meet the Division of Commercial Fisheries regional need for publishing and archiving information such as project operational plans, area management plans, budgetary information, staff comments and opinions to Board of Fisheries proposals, interim or preliminary data and grant agency reports, special meeting or minor workshop results and other regional information not generally reported elsewhere. Reports in this series may contain raw data and preliminary results. Reports in this series receive varying degrees of regional, biometric and editorial review; information in this series may be subsequently finalized and published in a different department reporting series or in the formal literature. Please contact the author or the Division of Commercial Fisheries if in doubt of the level of review or preliminary nature of the data reported. Regional Information Reports are available through the Alaska State Library and on the Internet at: http://www.sf.adfg.ak.us/statewide/divreprots/htlm/intersearch.cfm.

David L. Barto,
Alaska Department of Fish and Game, Division of Commercial Fisheries,
802 3rd Street, Douglas, AK 99811-0024 USA

Scott F. Lamoureux,
Department of Geography, Queen's University, Kingston, ON, Canada K7L3N6

and
Bruce P. Finney
Institue of Marine Science, School of fisheries and Ocean Sciences, University of Alaska Fairbanks,
Fairbanks AK 99775-7720, USA

This document should be cited as:
Barto, D.L., S. F. Lamoureux, and B. P. Finney. 2008. Assessing the historical salmon presence and productivity at transboundary sockeye nursery lakes using stable isotopes within the paleolimnologic sediment record. Alaska Department of Fish and Game, Regional Report Series No. 1J08-10, Douglas. AK

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

LIST OF APPENDICES

Appendix **Page**

ABSTRACT

Pacific salmon are a mobile link keystone species that transports nutrients from the northeastern Pacific Ocean to the nutrient poor freshwater environments in Alaska and Canada. Marine derived nutrients (MDN) released from spawned-out sockeye salmon carcasses are an important nutrient source to oligotrophic lakes and streams. Recent studies have shown that the historical distribution of $\delta^{15}N$ in lake sediments can be a useful proxy in reconstructing salmon abundance. Although this historic sediment proxy data cannot describe current salmon stock status, it can be useful in placing the current population abundance in context. Information generated from long-term changes in fish abundance can provide insight into natural ecosystem variability, the impact of human disturbance, and data necessary for sustainable fisheries management.

The thin section varve dating methods employed at these glacial lakes were successful. Varve chronologies and the sedimentary signal from some, if not all of these lakes can help explain the timing of observed changes. Variations in sediment delivery may provide insight into past climate trends, lake flushing, lake turbidity and changes to watershed conditions that may impact salmon ecology.

This study was conducted on Little Trapper, Trapper and Tatsamenie lakes. These lakes are glacial sockeye salmon nursery lakes providing fish to the transboundary Taku River. The glacial sedimentary deposits coupled with low escapements presented numerous $\delta^{15}N$ stable isotope analytical challenges. These challenges resulted in eliminating of a large portion of the replicate $\delta^{15}N$ analyses. The results of this study indicate that salmon MDN are an important nutrient source in these glacial nursery lakes.

The general sediment $\delta^{15}N$ trends observed over the past 135-years indicate that nitrogen levels increased at Little Trapper Lake, remained constant at Trapper Lake and decreased at Tatasamenie Lake. However, the sediment $\delta^{15}N$ signal appears to be quite variable between subsamples at all of the study sites.

Key words: Paleolimnology, stable isotopes, Taku River, sockeye salmon, marine derived nutrients, glacial lake, varve chronologies

INTRODUCTION

Freshwaters in Alaska and British Columbia provide important spawning and nursery environments to all 6 species of Pacific salmon (*Oncorhynchus sp.*). The period of time that juvenile salmon inhabit the freshwater environment depends directly on species and location. This freshwater residence can be limited to several months in the inter-tidal area of a stream mouth for pink (*O. gorbuscha*) and chum (*O. keta*) salmon, but extends to one or more years in a lake environment for sockeye (*O. nerka*). The sockeye salmon is the only Pacific salmon that requires the extensive use of a lake environment for spawning and rearing.

These anadromous fish possess a well documented life-cycle of rearing in freshwater after hatching, migration to the marine environment, and returning to freshwater as adults to spawn once before dying (except steelhead; *O. mykiss*) in their natal habitats. Despite this need to return to freshwater to spawn, Pacific salmon form one of the most dominant fish fauna within the subarctic domain of the North Pacific Ocean. Almost all of the somatic growth of these fish (>99%) occurs during the marine phase of their life cycle. The incorporation of marine derived nutrients (MDN) within their body tissues, and the lack of other abundant anadromous species results in these fish playing a principal role in transporting and delivering significant amounts of MDN to the oligotrophic lakes and streams of North Pacific watersheds, when they return to freshwater to spawn (Bilby et al. 2001).

Prior to the development of the commercial fishing industry at the end off the nineteenth century, sockeye population variability in freshwater was primarily controlled by MDN inputs and environmental factors related to climate. Harvest activities by local aboriginal populations were considered minimal due to low human population numbers and the relative inefficiency of harvest, preservation and transportation methods.

The development of an industrialized commercial fishery began removing larger segments of the adult salmon returns, and presumably reduced the escapements. The only available historical escapement "estimates" for sockeye nursery lakes in Southeast Alaska and British Columbia (1890 to 1930) are confusing; some lakes that historically had unusually large sockeye adult returns now have escapements that are only a fraction of what was recorded prior to 1930. This historical information is difficult to interpret, because these stocks were enumerated using different methods, and were also subject to intensive and shifting commercial fishing pressures.

Current sockeye salmon management activities in both U.S. and Canadian commercial fisheries are based on monitoring spawning escapements and commercial harvest numbers. Application of spawner-recruit models are generally based on weir or mark-recapture escapement estimates, and stock identification techniques applied to commercial harvest data.

Presently, developing spawner-recruit models is difficult, due to limited data. Additionally, the existing short-term data may or may not represent the known influence of natural density independent factors affecting natural population fluctuations. Information generated from long-term changes in fish abundance can provide insight into natural ecosystem variability, the impact of human disturbance and additional data that could be useful for present-day management or enhancement activities.

Nutrient studies with Pacific salmon (Bilby et al. 1996, Kline et al. 1990) indicate that spawning adult fish carcasses contain higher proportions of these heavier (and less frequent) isotopic forms of carbon (^{13}C) and nitrogen (^{15}N), than is available from other sources contributing nutrients to freshwater environments. The $\delta^{15}N$ labeled nitrogen from salmon carcass decomposition is subsequently incorporated into the lacustrine food web, and ultimately the sedimentary record. Thus, stable isotope analysis can allow the tracing of nutrients delivered to lakes and streams and the resultant utilization in the freshwater aquatic ecosystem.

Stable isotope ratios can also provide information regarding the origins of and transformations of organic matter (Altabet and Francois 1994). Recent studies at Karluk Lake (Kodiak Island) have shown that the distribution of $\delta^{15}N$ in lake sediments during the past 500 years can be a useful proxy in reconstructing salmon abundance. Climate and commercial fishing can influence inputs of salmon MDN, thereby affecting lake and salmon productivity (Finney 1998, Finney et al. 2000). Due to these results in Alaskan lakes, the use of a sediment $\delta^{15}N$ proxy may be useful in determining historical salmon escapement and nutrient trends in these sockeye nursery lake study sites. Changes in sediment $\delta^{15}N$ also infer a positive feedback loop, where higher salmon abundance leads to increased nutrient loading. Declines in $\delta^{15}N$ and primary and secondary production within Karluk Lake suggest a disruption in this feedback loop.

Previous studies have documented that the reduced availability of salmon carcass derived nutrients has resulted in a decline in freshwater productivity, which is closely coupled to juvenile sockeye prey and subsequent adult salmon production (Koenings and Burkett 1987). Therefore, changes in the magnitude of returning adult salmon have the potential to alter the amount of MDN transported from the sea to freshwater. By understanding and potentially quantifying the historical escapement levels prior to the commercial exploitation of sockeye salmon populations, it may be possible to identify a "pristine" carrying capacity for a lake.

Although the magnitude of the sockeye escapements are important in delivering MDN to the nursery lake environment, recent work in Southeast Alaska has also indicated that lake water residence time (T_w) directly influences retention of these nutrients within the lake (Barto 2004). Work at Chilkat Lake indicated that lakes with water residence times >3 years had the highest level of $\delta^{15}N$ incorporation in both zooplankton and smolts (Barto 2004). Thus, even with the availability of large quantities of MDN available to some lakes, the physical attributes of the rainfall and watershed surface flows probably play a significant role in lake nutrient availability.

The use of varve counting (distinct annual sedimentary structures commonly associated with glacial systems) and radioisotope dating methods is a key strategy proposed for this study. The potential is high that this technique can be employed at all of these glacial lake study sites to develop accurate high-resolution sediment dating chronologies. The use of the varve dating technique will permit annual sediment sampling resolution and accurate comparisons with the existing sockeye escapement data.

This paleolimnologic study was designed to collect and analyze sediment cores for $\delta^{15}N$ distribution within 2 sockeye salmon nursery lakes (Little Trapper and Tatsamenie) and one control lake (Trapper) that is currently barriered to anadromous salmon. The purpose of this study was to use paleolimnologic sediment analysis techniques to assess the distribution of $\delta^{15}N$ within lake sediment record, as proxy to trace the relative magnitude of MDN inputs, and assess the historical sockeye production from the Canadian lakes in the study.

STUDY SITES

Trapper (58.4667° N, 132.6333° W), Little Trapper (58.4833° N, 132.6000° W), and Tatsamenie (58.3333° N, 132.3333° W) lakes are glacially influenced lakes located within the transboundary Taku River drainage (Figure 1) in British Columbia, Canada. The transboundary Taku River watershed (~45,000 km^2), which originates in the Stikine plateau of northwestern British Columbia, is characterized by rugged, highly dissected mountains and plateaus with numerous glaciers and steep gradient, glacial-melt streams and rivers. The Taku River basin encompasses 7 biogeoclimatic zones from alpine tundra and subarctic interior climates to the maritime coastal rainforest. The merging of 2 principal tributaries, the Inklin and Nakina Rivers, approximately 50 km upstream from the international border forms the Taku River. The river flows southwest from this point though the Coast Mountain Range and empties into Taku Inlet about 30 km east of Juneau, Alaska. Approximately 97% of the Taku River watershed lies within Canada (Mathias 2000, Andel and Boyce 2007).

Trapper, Little Trapper, and Tatsamenie lakes are located in the northern boreal mountain ecoprovince of British Columbia, approximately 150 km west of the town of Dease Lake. The watersheds are characterized by sub boreal spruce, Engelmann spruce and alpine fir forests. Trapper and Little Trapper lakes occupy the same watershed. Trapper Lake discharges water downstream to Little Trapper Lake (Figure 2). Water flows downstream from these lakes via Kowatua Creek to the Inklin River. Tatsamenie Lake occupies an adjacent watershed that is the headwaters of Tatsatua Creek (figure 3). This creek flows downstream through Little Tatsamenie Lake (Tatsatua Lake) to the Sheslay River which is a tributary of the Inklin River.

Tatsamenie and Little Trapper lakes both support indigenous populations of sockeye salmon. Tatsamenie lake also supports fish populations of Chinook salmon (*O. tshawytscha)*, Coho salmon *O. kisutch*, rainbow and steelhead trout (*O. mykiss*), bull trout *Salvelinus confluentus*, lake trout *S. namaycush*, mountain whitefish (*Prosopium williamsoni*), sculpins (*Cottus* spp). and suckers *Catostomus* spp. (Hyatt et al 2005, BC Ministry of Environment 2007) Little Trapper Lake also supports fish populations of Chinook salmon, coho salmon, rainbow (and steelhead) trout, Dolly Varden char (*S. malma*), and lake trout (BC Ministry of Environment 2007). Both Tatsamenie and Little Trapper lakes currently contribute sockeye salmon to subsistence, personal use and commercial fisheries on the Transboundary Taku River.

Falls on the outlet of Trapper Lake form a barrier to the upstream migration of sockeye salmon from Little Trapper Lake. However, Trapper Lake does support a resident population of the non-anadromous kokanee (sockeye) salmon (TTC 1998); presence of kokanee may be evidence that Trapper Lake supported an anadromous sockeye population in the past. This lake also supports fish populations of rainbow trout, lake trout and Dolly Varden char (BC Ministry of Environment 2007).

All of the study lakes are glacially influenced. The euphotic depth (EZD) for these lakes ranged from a low of 6.8 m at Trapper to high of 9.7 m at Tatsamenie. Lake surface areas ranged from 1,679 ha (Tatsamenie) to 199 ha (Little Trapper). Mean depths ranged from 13 m at Little Trapper to 52 m and 53 m respectively for Trapper and Tatsamenie lakes. Lake volumes ranged from 890 x 10^6 m^3 (Tatsamenie) to 26 x 10^6 m^3 (Little Trapper). Lake water residence time (T_w) ranged from 20.5 years (Tatsamenie) to 4.6 years (Little Trapper) (Table 1).

Sockeye salmon escapement density and a limited amount of nutrient water chemistry data exists for these study sites (Table 2). This information is based on weir escapement estimates and limnology sampling conducted in both Department of Fisheries and Oceans, Canada (DFO) and ADF&G. Present day escapement estimates at the Canadian nursery lakes in the study range from 10 years (1995 to present) at Tatsamenie Lake and 22 years (1983 to present) at Little Trapper Lake. Stock identification and recruitment information is presently limited, but is being developed for stocks from these nursery lakes. Existing weir information for these study lakes indicate that sockeye comprise >99% of the salmon at Tatsamenie and >96% of the salmon at Little Trapper. This information indicates that the dominant contributor of MDN to the lake food web is the annual sockeye salmon escapement. No reliable long-term historical escapement data currently exists for these study lakes.

Average spring nutrient concentrations indicate that the range of the phosphorus values (1.4 to 3.0 μg/l) is similar for the glacial Canadian and Alaskan lakes. The spring phosphorus concentration (8.9 μg/l) at Tahltan Lake is much higher at this clear water lake. Unfortunately no spring nitrogen concentration data exist for a comparison of the Canadian and Alaskan lakes.

Mean sockeye salmon escapement density in fish/hectare range from 4 for Tatsamenie Lake to 68 for Little Trapper Lake. The mean sockeye escapement density in Alaska ranged from 14 to 96 fish/hectare respectively for Crescent (Southeast) and Chilkoot lakes.

OBJECTIVES

The objectives for this study were as follows:

1. Collect and analyze 2 to 3 lake sediment cores from each lake.
2. Perform sediment dating chronology, stable isotope ($\delta^{15}N$) and in-lake primary productivity indicator (organic carbon and biogenic silica) analyses of bulk sediment sub-samples

3. Use sedimentary $\delta^{15}N$ results and existing adult escapement data from study lakes to potentially quantify historical proxy escapement levels and determine a lake carrying capacity prior to commercial exploitation.

METHODS

COLLECTION AND PREPARATION OF SEDIMENT CORE SAMPLES

Sediment cores from Trapper, Little Trapper, and Tatsamenie lakes were collected and analyzed in this study to examine the relative importance of salmon derived marine nutrients represented in these glacial lake salmon nursery habitats. Sediment core sampling was accomplished using a combination of either hand operated gravity or slide hammer corers manufactured by *Aquatic Research Instruments* (ARI). These core samplers were designed to utilize thin-walled polycarbonate core sampling barrels attached to a corer head constructed of Delrin® (thermoplastic polymer) and stainless steel. Use of this free-flowing, lightweight design ensured that unconsolidated surface sediment disturbance and compression were minimized. Previous paleolimnological studies indicate that the complete recovery of undisturbed surface sediments at the sediment-water interface is critical to retaining the date of collection as a time reference (Glew 1988).

Selection of core sampling sites was determined by examination of existing lake bathymetric maps (Grant 1985a and 1985b; P. Rankin, DFO, Nanaimo, British Columbia, Canada, *personal communication*) and the location of the principle glacially influenced inlet streams. Sites were selected in areas of flat or gently sloping bathymetric gradients both proximal and distal to the influence of the principle glacially turbid tributary streams. All cores were collected through the ice during the last week of March 2006. The average ice thickness at these sites during sampling ranged from 53 cm (Tatsamenie) to 66 cm (Little Trapper). Core sampling was accomplished at all sites in all lakes using a combination of both gravity and hammer coring equipment. The lengths of cores collected for this study varied from 31 to 109 cm for the gravity corer and 73 to 220 cm for the hammer corer. All of the cores were stabilized in field using hydrophilic floral foam to preserve the top of the core for transport. None of these cores was extruded in the field.

A total of 5 core samples were collected from Trapper Lake (figure 2). Three gravity cores (numbers 1, 3 and 4) ranged in length from 31 to 109 cm. Two hammer cores (numbers 2 and 5) ranged in length from 155 to 182 cm. Cores 1 and 2 were collected in an area of the lake proximal to the influence of the principle glacially influenced streams which were located at the south end of the lake. Cores 3, 4 and 5 were collected in an area of the lake more distal to this glacial influence closer to the lake outlet stream.

Six core samples were collected from Little Trapper Lake (figure 2). Three gravity cores (numbers 1, 2 and 5) ranged in length from 36 to 84 cm. Three hammer cores (numbers 3, 4 and 6) ranged in length from 176 to 220 cm. Cores 1 through 4 were collected in an area of the lake ~19 meters deep proximal to the influence of the outlet stream of Trapper Lake. The Trapper Lake outlet stream forms the principle glacially influenced tributary stream entering Little Trapper Lake. Cores 5 and 6 were collected in an area of the lake about 23 meters deep that is more distal to the glacial influence of the Trapper Lake outlet stream.

Six core samples were collected from Tatsamenie Lake (figure 3). The one gravity core (number 1) at this lake had a length 95 cm. Five hammer cores (numbers 2 through 6) ranged in length from 62 cm to 190 cm. Cores 1 and 2 were collected in an area of the lake about 60 meters deep in a flat area near the southwest end of the lake. The principle glacially influenced inlet stream enters the lake at this southwest end. Core 3 was collected more proximal to this inlet stream in an area about 80 meters deep. However, once the cores were split in the laboratory for visual examination, core 3 was discarded from the study because it contained a large number of small (1–2 cm) rocks. Cores 4, 5, and 6 were collected in an area more distal to the glacial influence of the principle glacial inlet stream closer to the lake outlet.

Cores were transported intact from the field to the Environmental Variability and Extremes Laboratory (EVEX) at Queen's University (Kingston, Ontario, Canada) for processing. All cores were split in half lengthwise using standard procedures. The cores were allowed to air dry for a brief period and examined for the presence of varved layers. Split core faces were cleaned with a plane blade using strokes parallel to the varve layers. All cores were photographed along the entire length of each section (Figure 4) prior to sampling. The cores were sealed in plastic to prevent further drying and stored at 4^{o} C. One half of the core was identified for sub sampling while the remaining half was stored as an archive sample for future use.

Based on a visual examination of the split core halves in the laboratory, Trapper Lake core 5 (58.47333^{o} N, 132.63632^{o} W) was selected for detailed study. One half of this core was sampled along its entire length for radioisotope and thin section dating chronology, and chemical parameters. The top 18 cm sections of cores 3 and 4 were also sampled for thin section dating.

Based on the visual examination of the split core halves in the laboratory, Little Trapper Lake core 3 (58.49167^{o} N, 132.60718^{o} W) was selected for detailed study. One half of this core was sampled along its entire length for radioisotope and thin section dating chronology, and chemical parameters. The top 18 cm sections of cores 1, 2 and 4 were also sampled for thin section dating.

Based a visual examination of the split core halves in the laboratory, Tatsemenie Lake core 1 (58.31432^{o} N, 132.39572^{o} W) was selected for detailed study. One half of this core was sampled along its entire length for radioisotope and thin section dating chronology, and chemical parameters. The top 18 cm section of core 2 was also sampled for thin section dating.

Trapper Lake core 5 (C5), Little Trapper Lake core 3(C3) and Tatsemenie Lake core 1 (C1) were each sampled for a detailed chemical analysis. Due to the variable depths of the varved layers this sub sampling occurred on either a standardized 0.5cm or 1.0cm increment. Wet and dry sediment subsample weights were obtained for all samples by freeze-drying (72 hours at -30^{o} C).

LABORATORY ANALYSIS

Core sediment subsamples from all lakes were analyzed for stable isotope composition ($\delta^{15}N$, $\delta^{13}C$) and the percent by weight of carbon and nitrogen. All cores selected for detailed analysis also received additional multi-parameter sediment analyses. These analyses included magnetic susceptibility, percent carbon (as organic matter and carbonate) and percent biogenic silica. Additionally sediment dating analysis was also performed on the cores collected from each lake. These analyses included radioisotope dating and thin section varve counting. Details of these methods are described below.

Stable Isotope

Stable isotopes and the percent carbon and nitrogen were measured on dry bulk sediment downcore samples. Prior to all stable isotope analyses, sediment was washed with 10% HCL to remove any potential interference of $CaCO_3$. All of the sediment samples were analyzed as bulk sediments for this comparison. This is the method currently employed in similar studies throughout Alaska. This bulk analysis method does not account for the variable amount of glacial material in each subsample that would result in the dilution of the percent nitrogen and $\delta^{15}N$ signal. Therefore, the bulk sediment material used for this analysis contains both inorganic and organic material washed into the lake from the surrounding watershed.

In addition to the sediment analyses, a limited number of zooplankton, sockeye smolt, kokanee (Appendix A) and sockeye adult samples (Appendix B) collected from Canadian transboundary river sockeye nursery lakes between 1995 and 2005 were also analyzed for $\delta^{15}N$ stable isotope ratios and percent carbon and nitrogen. These analyses were conducted to compare the trophic level indicators of salmon-derived nitrogen within the study lakes levels and other glacial sockeye salmon nursery lakes in Southeast Alaska.

Stable isotope analyses were accomplished using continuous-flow isotope ratio mass spectrometry (CFIRMS). Instrumentation was a ThermoFinnigan Delta+ with a Carlo Erba NC2500 elemental analyzer. Stable isotope ratios were reported in δ notation as parts per thousand ($^{0}/_{00}$) deviation from the international standards PDB (carbon) and air (nitrogen). All analyses were performed by the Alaska Stable Isotope Facility, Water and Environmental Research Center (WERC) at the University of Alaska Fairbanks. Analytical instrument precision was typically $<\pm 0.2\ ^{0}/_{00}$.

Magnetic Susceptibility

Downcore sediment subsamples from all detailed study cores utilized for stable isotope analysis were analyzed for magnetic susceptibility (Nowaczyk 2002). This analysis is useful in identifying tephra deposits and changes in the abundance or composition of the lithogenic component. The identification of tephra deposits resulting from known volcanic eruptions could be useful in establishing the chronological age of the sediment layers and determining a lake sediment accumulation rate (SAR). Additionally, there is also a strong correlation between particle size distribution and the relative magnetic susceptibility within a core (Gale and Hoare 1991).

Biogenic Silica

A wet–alkaline extraction procedure method developed by Mortlock and Froelich (1989) was used to determine the biogenic silica content for sediment subsamples utilized for stable isotope analysis. For this method, we dissolved biogenic opal from sediments without strongly dissolving the silica from silt and clay minerals. Dissolved silica was subsequently measured using colorimetric techniques. Recent studies have indicated a close link between percent biogenic silica in surface sediments and biosiliceous (diatom) productivity patterns in overlying surface waters.

Organic Carbon and Carbonate

Lacustrine sediments are composed of both organic and inorganic material. A modified weight loss on ignition method (Dean 1974) was used to determine the carbonate and organic matter content of the sediment subsamples utilized for stable isotope analysis.

Sediment Dating

Due to the absence of identifiable tephra layers, radioisotope measurements and varve counting were the only methods used to estimate the sediment deposition chronology of all 3 study lake cores examined in detail. The radioisotope measurement used the radioisotopes Cesium-137 (^{137}Cs) and Lead-210 (^{210}Pb) to date the recent sediments because of the known global fallout history of ^{137}Cs (peaked in 1963) and relatively short ^{210}Pb half-life of 22.3 years. Varves are sediment layers deposited annually within a body of still water. Glacial varves normally include a lower "summer" layer of sand or silt, which grades upwards into a thinner "winter" layer of clay or organic material (Bates and Jackson 1984). Varve counting utilizes a technique of identifying and counting these annual deposition layers in the sediment based on distinctive grain size makers and layers. The glacial varves identified in our study were composed of a variety of organic and inorganic materials, that were present in all 3 lakes.

Radioisotope

The ^{137}Cs and ^{210}Pb isotopes are ideal for sediment deposition studies over time scales of a century or less (Stihler et al. 1992). This method has proved to be very reliable in stable environments with uniform sediment accumulation rates (SARs) (Appleby 2002). The precision of our chronologies, is estimated at ± 10 years for the past 100 years and ± 25 years for the remainder of the records.

Cesium-137 occurs in the environment mainly as a by-product of nuclear weapons testing. Deposition of atmospheric fallout from nuclear testing was at a maximum in 1963. Therefore, maximum ^{137}Cs deposition is often marked by a distinctive peak in sediment concentration between 1963 and 1964.

Lead-210 (^{210}Pb) is introduced to the environment naturally by decay of Radon-222 (^{222}Rn) and its short-lived daughters. Radon-222 is ultimately derived from Uranium-238 (^{238}U), but its immediate source is Radium-226 (^{226}Ra) in crustal rocks, soils, sediments and seawater. Some of the ^{222}Rn produced is released to the atmosphere, where it rapidly decays (half-life=3.8 days), to ^{210}Pb via several short-lived isotopes. The ^{210}Pb is quickly deposited from the atmosphere, and can be incorporated into lake sediments if deposited on the lake surface or within the watershed. This ^{210}Pb is termed "excess", to distinguish it from ^{210}Pb produced by decay of ^{226}Ra within the sediment. Excess ^{210}Pb decreases with depth, due to radioactive decay according to the length of time since the sediment was deposited. Therefore, it is a very useful way of measuring the SAR. However, bioturbation and other mixing processes can sometimes transport excess ^{210}Pb downward more rapidly than sedimentation. When this occurs, it results in an overestimate of the accumulation rate (Von Damm et al. 1979, Krishnaswami et al. 1980).

Radioisotope dating (^{210}Pb and ^{137}Cs) was completed for Core 1 at Tatsamenie, Core 3 at Little Trapper and Core 5 at Trapper because visual inspection of the cores indicated that they were undisturbed by the coring process, and they were sampled at high resolution (0.5 cm interval). Volumetric samples of the top 35 cm of the cores were dried to determine cumulative mass per unit area, which was necessary to determine sediment mass accumulation rates. Total ^{210}Pb was determined by alpha counting techniques. Both ^{226}Ra and ^{137}Cs were determined using gamma counting techniques. Excess (unsupported) ^{210}Pb was estimated from total ^{210}Pb and ^{226}Ra data. A chronology was developed by fitting a curve to the excess ^{210}Pb data (Appendix C), combined with the assumption that the ^{137}Cs peak corresponded to 1963 (Krishnaswami and Lal 1978).

Varve Counting

Sediment was removed from the selected cores for thin section varve analysis. Sediment subsamples, were removed along the longitudinal axis from one of the cleaned split core halves by overlapping a 70 mm aluminum sampling jig designed to remove a 5 mm thick slab of sediment. In preparation for thin section analysis, subsamples were exposed to liquid nitrogen, freeze-dried, and embedded with epoxy resin. The liquid nitrogen and freeze-drying treatment was used because of the presence of relatively thick varve structures and the desire to minimize shrinkage. Once embedded and cured the epoxy sediment blocks were cut, thin-sectioned and polished for direct microscopic analysis (Lamoureux 2001, Lamoureux 1994). Photomicrographs of the thin section subsamples were scanned and measured using CorelDraw 10 software

DATA ANALYSIS

Sediment Cores

Stable Isotope Ratios

All elements have 2 or more isotopes. Some of these isotopes are stable; unstable isotopes are radioactive, and lose parts of their atomic structure at a specific rate (measured in half-lives) to change into a more stable conformation (de Laeter et al. 2003). While upwards of 10 carbon isotopes can exist, only 3 of these are commonly found: Carbon-12 (^{12}C) which is the most common stable isotope; Carbon-13 (^{13}C) which is also a stable isotope, but less common and atomically heavier; and Carbon-14 (^{14}C) which is an unstable isotope (half-life = 5,700 years). Nitrogen has 2 stable isotopes: Nitrogen-14 (^{14}N), which is most common; and, Nitrogen-15 (^{15}N), which is heavier than Nitrogen-14. All other isotopes of nitrogen are very unstable; most have half-lives measured in microseconds or nanoseconds. Stable isotope tracers of carbon (^{13}C) and nitrogen (^{15}N) have been used successfully to identify trophic interactions and nutrient dynamics in a variety of terrestrial and aquatic ecosystems (Bilby et al. 2001).

Most ecological studies express isotopic composition of a specific element in terms of delta (δ) values, which are in parts per thousand ($^{o}/_{oo}$); δ values are also called del values (Bilby et al. 1996). Let R_x equal the ratio of heavy isotope to light isotope in the sample (in this study, either $^{13}C/^{12}C$, or $^{15}N/^{14}N$). Let R_s equal the ratio of heavy isotope to light isotope in a standard; the standard for carbon is the carbon content of Pee Dee Belemnite (PDB) limestone; the standard for nitrogen is air (N_2). Delta (δ) is then calculated as follows:

$$\delta = ((R_x - R_s) / R_s) \times 1000.$$

Ratios from samples (R_x) enriched in the (uncommon) stable isotope are "heavier" than the ratio of the standard (R_s), and have a higher (or less negative) δ values. Conversely, (ratios from) samples depleted in the (uncommon) stable isotope are "lighter" and have a lower (or more negative) δ values (Bilby et al. 1996).

Removal of Outliers

In the process of running the sediment core analyses, we found that the equipment and procedures could barely process samples to detect nitrogen levels. In addition, the procedures themselves appeared to be introducing error into the results. In order to examine any sort of trend in the data, we needed procedures to identify and remove outliers likely to be spurious analytical results, before proceeding with the data interpretation.

All of the analytical data were initially treated as independent analyses, without consideration as to whether any single datum was a replicate analysis. We used the statistical range of $\delta^{15}N$ values from the salmon samples as a cutoff standard for sediment core samples. Because these fish act as fertilizing agents for a watershed, the nitrogen levels within fish tissues should be considerably more concentrated than nitrogen levels within lake sediments, which receive remnants that have fallen to the lake bottom. Thus, if a sediment subsample had a $\delta^{15}N$ value greater than the lower endpoint of the 99% confidence interval for fish tissue $\delta^{15}N$, the sediment $\delta^{15}N$ value was considered a spurious result. All results from that entire subsample (%N, %C and $\delta^{13}C$) were eliminated from any further analyses.

Despite our first outlier removal procedure, the remaining samples still contained data points with inconsistent values of $\delta^{15}N$. These high values of $\delta^{15}N$ appeared without pattern at all depths of the sediment cores. Furthermore, there was a strong correlation between very low percent N (<0.019), and high corresponding $\delta^{15}N$ values in these subsamples. We performed a regression analysis of the remaining subsamples' percent N and corresponding $\delta^{15}N$ value from each specific lake (Sokal and Rolf 1981). The standardized residuals of the regression were calculated and plotted for the analytical results from each lake. Based on comparisons of the sample replicate analyses and the standardized residual values, we eliminated all $\delta^{15}N$ analytical results (and corresponding %N, %C and $\delta^{13}C$ results) that were >2 standard deviation units from the regression.

Examining Data for Trends

The remaining analytical results were averaged for replicates when possible. If no replicate analyses were available, the remaining single subsample analysis was used in the comparisons of the downcore subsample results.

We then developed graphs, to examine trends over time, in sediments, for percent N, $\delta^{15}N$, C/N ratios, biogenic silica, and total organic matter (TOM). Previous studies in Alaska (McNeil, 1997) have provided evidence that the relationship between sediment $\delta^{15}N$ and C/N ratio can be useful to describe the type of sediment organic matter composition of varying proportions of 3 end members. These end members are terrestrial organic matter (high C/N, low $\delta^{15}N$), aquatic organic matter with low MDN influence (low C/N, low $\delta^{15}N$), and aquatic organic matter with high MDN contribution (low C/N, high $\delta^{15}N$). Lakes with low $\delta^{15}N$ and high C/N ratios are believed to derive most sedimentary organic matter from terrestrial sources in the lake's watershed (allochthonous inputs). However, the C/N ratio of allochthonous terrestrial organic matter is typically 20 to 30. A low C/N ratio (<10) indicates that most of a lake's organic matter fraction is produced within the lake itself (autochthonous inputs from plankton; Dean 1999, Meyers and Ishiwatari 1993).

Sedimentary concentrations of organic carbon (TOM) and biogenic silica sediment analyses were utilized in the core analysis from each lake to describe the historical primary productivity trends within the lake. Previous studies indicate that sediment biogenic silica is a useful proxy indicator of increased or decreased diatom production. Relatively small changes in nutrients can cause a detectable increase or decrease in lake diatom production (Schelske et al. 1986). To examine the possible changes, we constructed graphs of TOM and biogenic silica found in the sediment cores

A combination of nitrogen stable isotope and geochemical analyses have been used successfully in reconstructing historical salmon trends in sockeye nursery lakes (Finney 1998, Gregory-Eaves et al 2004, Schindler et al 2005, Selbie et al 2007). We attempted to do this, by examining graphs of $\delta^{15}N$ in the sediment cores over time, and by developing graphs of recent $\delta^{15}N$ values with known salmon escapement estimates.

Fish Stable Isotope Analysis and Marine Derived Nutrients

There are several ways to assess the importance of sockeye-derived nutrients to specific lake habitats. These include examining the trophic level food web transfers using stable isotope analysis to trace MDN input and pathways within the lake and the ratio of average lake nitrogen and phosphorus inventories (concentration × lake volume), to the average amount of nitrogen and phosphorus delivered by the annual escapement of adult sockeye salmon.

For this study, adult sockeye, kokanee sockeye smolts and zooplankton from Tatsamenie, Trapper Little Trapper, Tahltan and Tuya lakes were analyzed for stable isotopes (Appendices A and B), for comparison with the existing results from Southeast Alaska sockeye salmon nursery lakes (Barto 2004). The Canadian lakes were chosen to represent glacial (Little Trapper, Trapper, and Tatsamenie) and clear water lakes (Tahltan and Tuya). Some of these lakes contain indigenous sockeye populations (Little Trapper, Tatsamenie and Tahltan), while some are currently inaccessible to returning adult salmon salmon (Trapper and Tuya), due to a barrier on the outlet stream. The Southeast Alaska lakes documented in Barto (2004) contain similar habitats, and all are accessible to indigenous sockeye populations.

Adult sockeye samples collected from the Canadian lake stocks and analyzed for $\delta^{15}N$ were adult scales previously collected for age analysis (Appendix A). Salmon scales have been shown to incorporate $\delta^{15}N$ and $\delta^{13}C$ isotopes in similar concentrations to muscle tissue (Satterfield 2002). Sockeye muscle samples were taken at various lakes in Southeast Alaska. Sockeye scale samples were also analyzed for 2 glacial Southeast Alaskan lakes (Chilkoot and Crescent).

Based on expected trophic enrichment of +3 to + 4 $^{o}/_{oo}$ between trophic levels, we subtracted +3 and + 4 $^{o}/_{oo}$ from the zooplankton $\delta^{15}N$ values, to backcalculate expected estimates of phytoplankton $\delta^{15}N$ values. Because zooplankton are generally the dominant forage prey items of rearing juvenile sockeye salmon, we also added +3 and + 4 $^{o}/_{oo}$ to zooplankton $\delta^{15}N$ values, to produce an expected $\delta^{15}N$ value for sockeye smolts, for comparison with actual $\delta^{15}N$ values from smolt samples.

Adult sockeye salmon weights were collected at the enumeration weirs at Little Trapper, Tatsamenie and Tahltan lakes by weir personnel during 2005 and 2006 (Appendix D). This data was collected with the intent of tracking the input of fish (P and N) nutrients via salmon carcasses to these nursery lakes. Average sockeye salmon phosphorous and nitrogen body content was previously reported based on fish wet weight (Barto 2004). Sockeye salmon weights have been collected and reported from a total of 22 lakes from Alaska and Canada (Appendix D). Six of these were glacial lakes.

The average adult sockeye weights from each of the glacial lakes and Tahltan were used in combination with average weir escapement data to calculate the average nutrient loading for total P and total N added to the lakes from salmon carcasses (Appendix E). The ratio of average lake N and P inventories (concentration multiplied by lake volume) to the average amount of N and P delivered by the average annual adult sockeye salmon escapement can be useful in tracking the relative importance of nutrient inputs from the fish.

RESULTS

SEDIMENTARY NITROGEN STABLE ISOTOPE

More than 400 separate bulk sediment subsamples and replicates were analyzed for percent nitrogen and carbon, and the stable isotopes $\delta^{15}N$ and $\delta^{13}C$ for this study. Of the total samples analyzed, 364 were considered to be usable analyses. Of these 364 analyses, 183 were from Little Trapper Lake, 178 from Tatsamenie Lake and 103 from Trapper Lake. The 364 remaining samples were used to adjust the sample size required for the analyses and to examine the problems encountered with sample result replication. Due to inconsistent results of the $\delta^{15}N$ analyses, we decided that all subsamples would have a minimum of 2 replicate samples. Also, due to budget constraints, we decided to concentrate the analytical effort on the top 50 cm of samples from each core selected for detailed analysis.

The $\delta^{15}N$ results presented in the previous paragraph are the result of numerous individual analyses using a variety of sample sizes. Samples sizes for Little Trapper Lake ranged from 15 to 31 mg, with a mean of 25 mg. Sample sizes for both Tatsamenie and Trapper lakes required more material for this bulk analysis technique, in order to produce a detectable nitrogen concentration from the subsamples. Sample sizes for Tatsamenie Lake ranged from 49 to 100 mg. The average sample size for this lake was 51 mg. Sample sizes used for the Trapper Lake analysis ranged from 50 to 101 mg. The average sample size for this lake was 82 mg. By comparison, the average sample size was 5 to 6 mg for Tahltan Lake bulk sediment analyses of stable isotopes and percent nitrogen.

The percent nitrogen levels encountered in this study were challenging the lower detection limit of the instrumentation used for this analysis, and the bulk sediment analytical methods currently used in sediment MDN studies. The instrumentation was limited by its inability to physically accommodate sample sizes >100 mg in the sampling tray and combustion tube. MDN $\delta^{15}N$ signals had already been expected to be low, due to observed low salmon escapements. These signals were further reduced, because the annual glacial sediment inputs to the lakes diluted the nitrogen concentrations.

The percent nitrogen (N) results within Trapper, Little Trapper and Tatsamenie lake sediments were extremely low, when compared to sediments from Alaskan glacial lakes with similar sockeye salmon escapement densities (Table 3). With the exception of Tahltan Lake, all of the lakes presented for comparison were glacially influenced. Not surprisingly, Tahltan Lake (a clear water lake located on the Stikine River) had the highest mean percent nitrogen and carbon values. Although Tahltan Lake had a similar mean sockeye escapement density to Coghill Lake, and Crescent Lake (Cook Inlet), the Tahltan mean percent of sedimentary nitrogen was about 9 times greater than Coghill Lake and about 21 times greater than Crescent Lake (Cook Inlet). Even though Little Trapper and Chilkoot lakes had approximately 1.5 to 2 times greater density of sockeye salmon escapement, the Tahltan mean percent of sedimentary nitrogen was about 9 times greater than Little Trapper Lake, and about 13 times greater than Chilkoot Lake.

One $\delta^{15}N$ sample analysis appeared to be a glaring error. After analyzing the same sample from Tatsamenie Lake 9 separate times, the percent nitrogen values ranged from 0.010 to 0.013 and $\delta^{15}N$ values ranged from +1.96 to +16.96 $^{0}/_{00}$. Analytical instrument precision reported by the WERC laboratory at the University of Alaska Fairbanks for replication is generally <0.2 $^{0}/_{00}$. In comparison, analyses of the $\delta^{15}N$ results of muscle and scale samples collected from individual adult sockeye salmon (Appendix A) produced a mean $\delta^{15}N$ value of +11.05. The (1%) confidence interval calculated for $\delta^{15}N$ values from these fish samples ranged from +10.89 to +11.21. Additionally, the largest observed sediment $\delta^{15}N$ values (+7 to +9) occurred at clear water lakes on Kodiak Island, with salmon escapement densities ranging from 200 to 300 sockeye salmon per hectare (Finney et al 2000). In contrast, mean sockeye escapement density for Tatsamenie Lake (1985 to 2005) was 4 sockeye salmon per hectare. By eliminating this lone high value (+16.96) from the group of 9 replicate Tatsamenie analyses of the same subsample, the $\delta^{15}N$ range for Tatsamenie Lake was drastically reduced (to +1.96 to +4.05), while the percent nitrogen range remained unchanged (0.010 to 0.013).

Inconsistent replicate $\delta^{15}N$ analyses were observed at all of the lakes. High $\delta^{15}N$ values generally occurred when percent nitrogen levels were extremely low (<0.019); high $\delta^{15}N$ values were distributed randomly throughout the length of the cores. If an initial $\delta^{15}N$ result was greater than +10.89, the results of the entire subsample (%N, %C and $\delta^{13}C$) were eliminated from any further analyses. This treatment resulted in eliminating 1.6% of the analytical results from Little Trapper, 9.7% of the Trapper results and 17.4% of the Tatsamenie results.

Our second outlier removal procedure removed all samples that had a variability >2 standard deviation units from the regression line. This treatment of the data resulted in eliminating additional subsample percentages from the analysis: 6.0% from Little Trapper Lake; 7.8% from Trapper Lake; and, 6.8% from Tatsamenie Lake.

The total amount of analytical data eliminated from the sediment data analysis was 24% of the Tatsamenie data points, 17.5% of the Trapper data points and 7.6% of the Little Trapper data points. As a result, we had to change our original plan of using only replicated samples, to using individual data points, when replicates were not available. Single analytical results were used for 12% of the subsamples from Little Trapper, 49% from Tatsamenie, and 33% from Trapper.

Although differences between some of the replicate analyses were > 2 δ (delta or del) units, the 2 procedures previously outlined were the only systematic methods employed to eliminate the analytical result outliers. Because of the number of $\delta^{15}N$ outliers removed, we believe that the bulk analytical method for these glacial lakes was likely introducing errors into the analysis.. This bulk method appeared to be problematic for sediments that contained a low percentage of nitrogen (due to the observed low sockeye salmon escapement densities), in combination with dilution of the nitrogen signal, caused by deposition of glacial material.

The results from these analyses exhibited a high variability in the percent nitrogen and $\delta^{15}N$ analytical data. The percent nitrogen results ranged from 0.002 (Trapper Lake) to 0.234 (Little Trapper Lake), and the $\delta^{15}N$ results ranged from -6.06 to +28.78. These high and low $\delta^{15}N$ values occurred at Trapper Lake. Relatively low $\delta^{15}N$ values were observed in the downcore subsamples from all of the lakes in this study. The average $\delta^{15}N$ values for Little Trapper, Tatsamenie and Trapper lakes were respectively +1.84, +1.78 and +0.66

The measured sedimentary $\delta^{15}N$ signal was a result of the phytoplankton buried within the sediment. One explanation to account for the variability of $\delta^{15}N$ signals throughout the sediment cores was the variable amount of glacial material entering the lakes on an annual basis. The amount of glacial material was likely diluting the percent N and $\delta^{15}N$ signal. In addition, the variability of annual glacial inputs appeared to be interfering with the ability to replicate consistent analytical results.

The percent C/N ratio for all the lakes ranged from 6.2 (Little Trapper Lake) to 64.4 (Trapper Lake). The terrestrial component of these end members (high C/N ratios and low $\delta^{15}N$), was strongly represented in the data set from the study lakes (Figure 5). The average C/N ratios for all subsamples from these same lakes were respectively 20.6, 28.6 and 39.8. It appears that these lakes received organic material from terrestrial sources, regardless of the influence of marine-derived nutrients.

The extremely high observed C/N ratios (>30) was another indicator of analytical problems encountered in bulk sampling for sediment. The low percent nitrogen values were contributing to the average C/N ratios ranging from 15.2 to 28.6 for Little Trapper Lake and 19.6 to 64.4 for (non-anadromous) Trapper Lake. Generally lakes with high allochthonous inputs have C/N ratios between 20 and 30 (Meyers and Ishiwatari 1993). The extremely high C/N ratios (>30) and low percent nitrogen values could indicate that the organic fraction of the terrestrial material in these watershed is relatively low, with the lake sediments dominated by inorganic glacial material.

Percent C/N ratio values for this study were probably a misleading indicator concerning MDN, due to the low percent nitrogen values, and the dilution of the organic matter present in the sediment with glacial material. Generally, a sediment C/N ratio of 22 is considered to be composed entirely of terrestrial material. Previously, the highest observed C/N ratio (21.7) for a Southeast sockeye nursery lake was at Klawock Lake. This lake also produced a relatively low narrow range of $\delta^{15}N$ (+2.79 to +2.81). Twenty-six percent of the Little Trapper Lake C/N ratios were >22. In addition, 75% of the Tatsamenie Lake and 98% of the Trapper Lake C/N ratios were > 22.

By comparison, Chilkoot Lake, a large glacial sockeye nursery lake in Southeast Alaska, had a low range of sediment $\delta^{15}N$ (+2.33 to +2.71) and a relatively low narrow range of C/N ratios (14.9 to 15.0). This relatively low sedimentary C/N ratio (< 15) was probably due to a mixture of autochthonous (planktonic) and allocthonous (terrestrial) inputs. Any marine-nutrient influence in Chilkoot Lake is probably diluted by inputs of glacial material. Lakes with low $\delta^{15}N$ and low C/N ratio probably have freshwater plankton as a major contributor to sediment organic matter, but MDN are not important as a nutrient source.

All of the Total Phosphorus (TP) values presented in Table 2 are reported as turbidity corrected total phosphorus (CTP) values. Once corrected for turbidity, the CTP levels placed all 3 lakes in the ultra oligotrophic range. Ultra-oligotrophic lakes are characterized by total phosphorus concentrations of $\leq$ 5 μg/l and total nitrogen concentrations of < 400 μg/l (Wetzel 2001).

LITTLE TRAPPER LAKE SEDIMENT CORE

Dating Chronology

The excess ^{210}Pb profile exhibited an exponential decline with increasing depth (Appendix C). The ^{137}Cs profile displayed a well-defined peak at 11.5 to 13.5 cm depth. These data were used to establish a preliminary sediment accumulation rate (SAR) of 2.8 years/cm for the top 16.5 cm of the core, based on a linear model of the ^{137}Cs analysis. The ^{210}Pb analysis suggested lower sedimentation rates, and did not agree with the clear ^{137}Cs peak of 24 years. Thus, the ^{210}Pb dating model may not be reliable in this setting. Similar observations are common in lakes with highly variable sediment accumulation rates, where the assumptions of the ^{210}Pb dating model were not held constant**.** However, given the clear sedimentology and ^{137}Cs dating results, the sedimentary chronology were interpreted as sound. The thin section analysis estimated the age of bottom of Core 3 (164 cm) to be approximately 1490 AD. This date could vary by as much as 40 years (~10%), due to uncertainties in the varve analysis associated with vague sedimentary structures. The SAR for this analysis varied annually, and depended on sediment load entering the lake. However, a straight linear analysis for the entire core was 3.7 years/cm.

Sediment Core Analysis

Core 3 sediments were analyzed for $\delta^{15}N$ and inferences about lake paleoproductivity trends using $\delta^{15}N$, percent total organic matter and biogenic silica (Figure 6). Analyses focused on the top 50 cm of this core. This core was sampled on a 0.5 cm interval from 0.0 to 50 cm. After 50 cm was reached, the core was sampled at 56 cm, 89 cm, 120 cm and 170 cm, to provide an indication of stable isotope levels throughout the entire length of the core.

Turbidite layers of varying thickness and composed of coarse sand with detrital organic material were observed throughout the entire sediment core. Turbidite layers of 1.0 cm or greater were observed at the following depths (in cm) within the core: 154.0–155.0, 141.0–145.0, 97.0–99.5, 73.0–66.0, 44.0–43.0, 42.5–41.0, 35.0–34.0, 24.0–22.0, and 4.5–3.0. These thick layers were clearly visible and documented (Figure 4), during the examination of the cores after splitting and cleaning. The turbidite layers were not sampled when the core was subsampled for stable istotope analysis.

Sedimentary analyses in the upper 50 cm of Core 3 represented conditions during the most recent 128-year period for Little Trapper Lake (1877–2005 AD). The mean $\delta^{15}N$ levels in this core ranged from -1.3 to +5.47. Fluctuations occurred in $\delta^{15}N$ levels throughout the sampled time period, and did not appear to have a regular cyclic pattern. However, the overall trend appeared to indicate that the $\delta^{15}N$ levels are increasing from 50 cm to the top of the core (Figure 7). Neither the TOM nor the biogenic silica concentrations coincided with the $\delta^{15}N$ results.

The mean $\delta^{15}N$ value for all of the subsamples reported for this lake was +1.84 δ units. The highest $\delta^{15}N$ levels occurred around 2000 AD. Nitrogen stable isotope values > 4.0 δ units were observed 6 times, at depths (in cm) of 39.0, 25.5, 12.5, 7.5, 5.5, and 5.0. Negative $\delta^{15}N$ values occurred 4 times, at depths (in cm) of 48, 42.5, 39.5, and 2.5. The trend in the top 50 cm of the core appeared to be generally increasing.

The percent total organic matter remained relatively flat (between 3% and 5%), with non-cyclic fluctuations throughout the entire length of the core. Values > 5% were only observed at the sediment surface, and at depths (in cm) of 44.0, 42.5, 21.0, and 1.5.

The biogenic silica in the top 20 cm of the core had relatively high fluctuating values when compared to the values in the core deeper than 21 cm. These silica values fluctuated between 2.5% to 13.5% in this section of the core. The results were almost entirely >4%, with only 3 exceptions at depths (in cm) of 15.5, 8.5, and 2.5. The average biogenic silica for the top cm of the core was 6.8%. There appeared to be a dramatic shift in biogenic silica concentration below 20 cm in the core. Results below 20 cm averaged 3.2%, and ranged from 2.1% to 3.9%. There was only one exception, at a core depth of 40.5 cm, when a single value of 4.3% was observed. There were no high TOM values corresponding to the pattern of biogenic silica concentration within the top 20 cm of the core.

TRAPPER LAKE SEDIMENT CORE

Dating Chronology

The excess ^{210}Pb profile exhibited an exponential decline with depth (Appendix C). The ^{137}Cs profile displayed a well-defined peak at 12.5 cm depth. These data were used to establish a preliminary sediment accumulation rate (SAR) of 3.4 years/cm, based on a linear model from the ^{137}Cs analysis for the top section of this core. The ^{210}Pb analysis indicated similar sedimentation rates; the estimated 1963 ^{210}Pb age was within 1 cm of the prominent ^{137}Cs peak. A comparison of the lowermost ^{210}Pb date (1928) suggested an offset of 15 years, but this comparison was limited by low unsupported lead levels in the sediments**.** Therefore, given the clear sedimentology, and ^{137}Cs and ^{210}Pb dating results, the sedimentary chronology was interpreted as sound. The thin section analysis indicated that the estimated date of bottom of undisturbed section of Core 3 (86 cm) was approximately 1710 AD. It was not possible to definitively establish the age of the core below this depth, because the part of the core between 86 and 178 cm was disturbed during transport.

Based on a simple linear model the SAR for the 86 cm section of this core was 3.4 years/cm. If this sedimentation rate was constant (which it was not), the age of the bottom of this 178 cm core could be 1400 AD. This projected age could be conservative. One method useful in determining the age of the bottom of this core would be a radiocarbon analysis of any recovered organic material.

Sediment Core Analysis

Core 5 sediments were analyzed for $\delta^{15}N$, and inferences were made about lake paleoproductivity trends using $\delta^{15}N$, percent total organic matter, and biogenic silica (Figure 8). The analysis was focused on the top 50 cm of this core. This core was sampled on a 1.0 cm interval from 0.0 to 50 cm. After this point the core was sampled at 50 cm, 60 cm, 70 cm, 80 cm and 178 cm to provide an indication of stable isotope levels throughout the entire length of the core.

Coarse grain sand and organic material turbidite layers of varying thickness were observed throughout the entire sediment core. These turbidite layers are relatively small and ranged from 1 and 5 mm thick. These layers were clearly visible as very dark thin lines between 8–9 and 3–4 centimeters, in the photographs documenting the cores after splitting and cleaning (Figure 4). These turbidite layers were each <2 mm thick. Due to these relatively thin turbidite layers in the core, it was not possible to physically subsample the core for stable isotopes and not include these layers. In addition to the turbidite layers previously mentioned, thin turbidite layers were also observed at depths (in cm) of 85.0–82.0, 79.0–78.0, 71.0–70.0, 68.0–63.0, 25.0–24.0, and 17.0–13.0.

Sedimentary analyses in the upper 50 cm of Core 5 represented conditions during the most recent 197-year period (1808–2005AD) for Trapper Lake. The mean $\delta^{15}N$ levels in this core ranged from -2.53 to +4.14. No regular cyclic patterns were apparent in fluctuations of $\delta^{15}N$ levels occurring throughout this period. The $\delta^{15}N$ levels were relatively constant at a low level from the top of the core to a depth of 50 cm (Figure 7). The mean $\delta^{15}N$ value for all of the subsamples reported for this lake is +0.66 del units. The highest $\delta^{15}N$ level (+4.14) occurred at 22 cm (1925 AD). Nitrogen stable isotope values > 2.0 del units were only observed 6 times, at cm depths of

40, 31, 24, 22, 20, and 19. However, negative $\delta^{15}N$ values occurred in over 31% of the core, and were concentrated between 39 and 34 cm deep.

The total organic matter exhibited a gradually increasing trend from 50 cm depth to the top of the core, which fluctuated around a mean value of 3.0%. The TOM values in this top section of the core ranged from a low of 1.9% at 13 cm to a high of 4.2 % at 3 cm. This increasing trend was most pronounced in the core between 35 cm and the top. Below 35 cm, the TOM content of the core fluctuated from a high of 2.9% at 41 cm to a low of 1.49% at 35 cm. However, the high 2.9% value at 41 cm was the only value above 2.3% for the 50–35 cm section of the core. The average value for this section was 1.9%. There appeared to be a change in TOM content in the upper and lower sections of the core.

Biogenic silica levels averaged 3.5% throughout the length of the top 40 cm of this core. These levels generally fluctuated within a narrow range, between 3 and 4 %. Only 2 subsamples had silica levels above 4%; these were near the top of the core (4.1% at 3cm and 4.8% at 4 cm). One subsample was below 3% (2.8% at 23 cm). There are no cyclic patterns or trends apparent in the distribution of biogenic silica in this core.

TATSAMENIE LAKE SEDIMENT CORE

Dating Chronology

The excess ^{210}Pb profile exhibited an exponential decline with depth (Appendix C). The ^{137}Cs profile displayed a well-defined peak at 18.0 cm depth. This peak was used to establish a preliminary sediment accumulation rate (SAR) of 3.0 years/cm (0.33 mm/year); the linear model based on the ^{137}Cs analysis for the top section of this core also accounted for the 4 cm turbidite layer found in this section of the core. The revealed low unsupported lead levels (<0.1 Bq/g); the linear model based on ^{210}Pb analysis estimated a lower sedimentation rates than the clear ^{137}Cs peak. The ^{210}Pb dating technique appeared to be less reliable. This result was similar to lakes with highly variable sediment accumulation rates, where the assumptions of the ^{210}Pb dating model were not held constant**.** However, given the clear sedimentology and ^{137}Cs dating results, the sedimentary chronology was considered suitable for use. A definitive thin section analysis was not possible, due to inconsistent results in the thin section analyses from different cores. However, a simple linear model estimated the age of bottom of Core 1 (88 cm) at approximately 1798 AD. Based on this model, and accounting for the turbidite layers throughout the core, the SAR for the entire 86 cm section of this core was 2.5 years/cm (0.40 mm/year).

Sediment Core Analysis

Core 1 sediments were analyzed for $\delta^{15}N$ and inferences made about lake paleoproductivity trends used $\delta^{15}N$, percent total organic matter and biogenic silica (Figure 9). The analyses focused on the top 50 cm of this core. This core was sampled at 0.5 cm intervals from 0.0 to 40 cm, and then was sampled at 1.0 cm intervals from 50 to 41 cm. The core was also sampled at 88 cm, 75 cm, and 62 cm, to provide an indication of stable isotope levels throughout the entire length of the core.

Coarse large grain sand and organic material turbidite layers of varying thicknesses were observed throughout the entire sediment core. Turbidite layers of 0.5 cm or greater were observed at depths (in cm) of 53.5–52.5, 32.0–31.5, 24.0–22.5, and 9.0–5.0. These layers were clearly visible and documented during preliminary examination of the cores after splitting and cleaning. The 4.0 cm turbidite layer (at 9.0–5.0 cm depth) is clearly visible in Figure 4. During the subsampling of the core for stable isotope analysis, these turbidite layers were not sampled.

Sedimentary analyses in the upper 50 cm of Core 1 for Tatsamenie Lake represented conditions during the most recent 115-year period (1890–2005 AD). The mean δ^{15}N value for all of the subsamples reported for this lake was +1.78 del units. The δ^{15} N levels in this core ranged from -1.37 to +3.69. No regular cyclic pattern was observed in the fluctuations in δ^{15}N levels throughout the period. The highest δ^{15}N level (+3.69) occurred at 47.0 cm (~1897). Nitrogen stable isotope values > 3.0 δ units were observed 9 times, at depths (in cm) of 62.0, 48.0, 47.0, 45.0, 44.0, 40.0, 34.5, 20.5, and 1.5. These high values appeared to be concentrated in the deeper section of the core, between 48 and 40 cm. Additionally 51% of the δ^{15}N values are > +2 del units. These highest results are concentrated between 88 and 30 cm deep. Only 5 negative δ^{15}N values were recorded, at cm depths of 28.5, 27.0, 21.0, 16.5, and 9.0. The overall trend of δ^{15}N levels was decreasing from 50 cm to the top of the core (Figure 7).

There were 2 broad events occurring in the distribution of total organic matter in this core: an increasing trend in percent TOM within in the core between 25.0 cm and the top of the core; and, a steep decrease, . This increasing trend occurs after the occurrence of the turbidite layer identified at 22.5–24.0 cm. The percent TOM increased from 1.6% before the turbidite layer to 3.5% at 11.5 cm in this section. There were fluctuations in percent TOM in the section but the general trend was increasing from 25 cm to the top of the core. There is also broad oscillation in percent TOM in the 50.0 to 25.0 cm section of the core. Below 25 cm the TOM content of the core increased from 1.6 at 25 cm to 4.3% at 29 cm. These were the highest and lowest TOM percentages in the entire length of the core. This steep decline in percent TOM occurs immediately before the turbidite layer. The high 4.3% TOM level then decreases to <2.5% at 33.0 cm. After this point there is a narrow peak of 3.1% at 34.5 cm. Below this point in the core the TOM decreases and remains relatively constant to between approximately 2.0 to 2.5%.

Biogenic silica levels indicate a gradually increasing trend from 40 cm to the top of the core. The biogenic silica levels in this core ranged from a low of 2.0% at 37.5 cm to a high of 4.5% at 11.5 cm. There are no cyclic patterns apparent in the distribution of biogenic silica in this core.

FISH STABLE ISOTOPE ANALYSIS AND MARINE DERIVED NUTRIENTS

The δ^{15}N values for the Southeast Alaska sockeye stocks ranged from +10.36 to +11.62; the δ^{15}N values were +10.39 for Crescent Lake and +11.05 for Chilkoot Lake (Barto 2004). In comparison, adult sockeye scale samples analyzed from Little Trapper, Tatsamenie and Tahltan lakes were +10.70, +10.62, and +10.56, and are well within the range previously identified for sockeye salmon.

The sockeye smolt samples analyzed for δ^{15}N from Tahltan, Tatsamenie and Tuya lakes ranged from a high of +11.19 at the clear water Tahltan Lake, to a low of +8.29 at the glacial Tatsamenie Lake (Appendix B). These analyses were within the range (+12.57 to +6.98) observed for sockeye smolts from Southeast Alaska lakes. All of these δ^{15}N values were the result of analyzing whole fish samples. Smolts from the Southeast Alaska glacial lakes Chilkoot and Crescent had δ^{15}N values of +9.87 and +10.20 respectively.

The δ^{15}N analyses of the 3 kokanee samples from Trapper Lake had a relatively low value of +6.12. This δ^{15}N value is comparable to the results from both Sweetheart Lake (+6.98) and Tuya

Lake (+8.64), which also do not support indigenous sockeye populations. Sweetheart and Tuya are both clear water lakes. Because of the similarity of these results, it appeared that the low $\delta^{15}N$ values were a result of the isolated rearing habitat, not glacial influence.

Spring zooplankton samples (appendix B) were analyzed for $\delta^{15}N$ from Tahltan, Tuya, and Tatsamenie lakes. These results were +9.04, +4.81 to +3.68 respectively. These results corresponded to the range of $\delta^{15}N$ values (+3.15 to +11.28) previously observed in Southeast Alaska lakes.

Assuming an expected trophic enrichment of +3 to + 4 $^{o}/_{oo}$ between trophic levels, the phytoplankton $\delta^{15}N$ values should have ranged from <+1.0 at Tatsamenie Lake to +5 or +6 at Tahltan Lake. The enrichment of $\delta^{15}N$ values between zooplankton and sockeye smolts (+3 to +4 $^{o}/_{oo}$) at Tahltan and Tatsamenie lakes was also expected, given the zooplankton are generally the dominant forage prey items of rearing juvenile sockeye in the lake.

Adult weights averaged 2.27 kg for all lakes surveyed and ranged from 1.63 kg (Tahltan) to 3.43 kg (McDonald). An average weight of sockeye from clear and stained lakes was 2.27kg. The average weights observed at glacial lakes averaged 2.72 kg.

The ratio of average lake N and P inventories (concentration multiplied by lake volume) to the average amount of N and P delivered by the average annual adult sockeye salmon escapement can be useful in tracking the relative importance of nutrient inputs from the fish. These nutrient ratios for P ranged from 0.1 (Tatsamenie Lake) to 5.1 (Little Trapper Lake), and for N this ratio ranged from 0.04 (Tahltan and Crescent lakes) to 0.35 (Chilkoot Lake). This comparison indicates that salmon-derived nutrients were substantial in some glacial lakes, and that there was a wide range in their relative magnitude across the lakes. One factor that complicated this comparison was that the average spring nutrient concentrations in the lake compared with nutrient inputs to the lake from escapement estimates were not matched to specific brood years. This type of matched comparison was not possible for the glacial lakes in this study. Additionally there was a complete lack of lake nitrogen data for all of the Canadian lakes except Tahltan.

DISCUSSION

STABLE ISOTOPES AND MARINE DERIVED NUTRIENTS

Pacific salmon can be described as a mobile link keystone species that transports nutrients from the nutrient rich northeastern Pacific Ocean to the nutrient poor freshwater environments in Alaska and transboundary river watersheds (Helfield and Naiman 2006). Marine derived nutrients released from spawned-out sockeye salmon carcasses have been shown to be an important nutrient source to oligotrophic lakes and streams. The sockeye salmon is the only Pacific salmon that requires an extensive use of a freshwater lake environment to complete its life cycle.

Nitrogen stable isotopes have been used as a proxy indicator of sockeye salmon, because stable isotope ratios can be traced through the environment using trophic level transfers. The delivery of enriched levels of this ^{15}N can provide information on the marine derived nutrients from the decomposing sockeye salmon carcasses entering the study lakes.

Previous salmon nutrient studies at Alaskan lakes (Donaldson 1968, Koenings and Burkett 1987, Barto 2004) have indicated that the sockeye salmon returning to spawn annually provide important amounts of nutrients to their rearing lakes. Based on these studies, the proportion of nutrient contributions to a lake from annual salmon escapements varied from 24.0% to 86.9% for phosphorus, and from 4.1% to 20.0% for nitrogen. The principal difference between the P and N nutrient loading at a specific lake is directly related to the magnitude of the escapement and the size of the lake.

The transboundary river Canadian glacial sockeye salmon nursery lakes investigated in this study are similar to the glacial Alaskan sockeye nursery lakes (Tables 1 and 2), both physically and chemically. Spring nutrient values were used in this comparison, because the values resulted from the deposition and decomposition of sockeye salmon carcasses in the lake from the previous fall and early winter. Thus, spring values represented the best indicator of the direct input of phosphorus and nitrogen

The principle differences between the Southeast Alaska and Canadian transboundary lake habitats are the surface elevation, the amount of precipitation and the lake flushing rates between these 2 lake categories. Recent work from lakes in Alaska and British Columbia provided evidence that lakes with low escapements and high flushing rates caused a dilution effect of the sediment $\delta^{15}N$ (Holtham et al 2004). High terrestrial inputs also ameliorated the $\delta^{15}N$ signal.

Additionally these Canadian lakes occupy a different biogeoclimatic zone than the lakes in Southeast Alaska. The Alaskan lakes are all coastal lakes that are characterized by cool climates, steep forested watersheds and high rainfall. The transboundary river lakes are located in the northern boreal mountain ecoprovince of British Columbia. This region is characterized by low rainfall, very cold interior climates and forested alpine glacial watersheds. These physical differences contribute to the chemical, hydrologic, and glacial processes occurring within the lake watersheds.

The chemical characteristics of surface waters entering a lake are closely related to soil characteristics in the watershed. Surface drainage is often the major contributor of phosphorus to streams and lakes. The amount of phosphorus entering surface run-off varies, depending on the amount present in the soils, vegetative cover, quantity and duration of run-off flow, and land-use (Wetzel 2001).

Phosphorus content of precipitation and particulate fall-out is highly variable. Generally, the phosphorus concentration is less than the nitrogen concentration. The phosphorus content of precipitation is generally low (<30 µg P/l) over land, in non-populated regions. Atmospheric contributions of phosphorus range from 0.01 to 1.0 kg/ha/y, with the majority of the data in the lower portion of the range. Phosphorus content of ground water is generally low, with average concentrations of approximately 20 µg/l (Wetzel 2001).

The phosphorus pool in glacial lakes is principally derived from inorganic silt; this inorganic particulate phosphorus (IPP) source is biologically unavailable (Edmundson and Carlson 1998, Edmundson and Edmundson 2002).

Nitrogen occurs in many forms in freshwater: dissolved molecular N_2, a large number of amino acids and other organic compounds, refractory humic acids, ammonium (NH4+), nitrite (NO2-) and nitrate (NO3-). Sources of nitrogen include: a) precipitation directly to the lake surface, b) nitrogen fixation in both water and sediments and c) inputs from surface and ground water drainage. The amount of nitrogen input from terrestrial run-off has been shown to exceed atmospheric sources in Alaskan boreal forests with discontinuous permafrost (Jones et al 2005).

Previous studies across a variety of forest types indicated that the majority of stream water nitrogen output from undisturbed watersheds occurs as biologically unavailable forms of dissolved organic nitrogen (Brenner et al 2006, Stednick 1981). Total nitrogen (TN) values from boreal forest lakes in southern Yukon ranged from 200 to 400 μg/l (Pienitz et al 1997). These lake TN values are within the oligotrophic definition. Due to ecoclimatic location of these lakes in the mountain rainshadow, the dominance of Engelmann spruce, subalpine fir and lodgepole pine forests and the low sediment nitrogen levels, it is likely that watershed nitrogen inputs are low. The percentage N and $\delta^{15}N$ results from this study indicate a large variability in the analytical data. The nitrogen levels identified within these lake sediments are extremely low, when compared to similar glacial lakes previously analyzed in Alaska (Table 3). These low levels provide evidence that the MDN $\delta^{15}N$ signal that was already expected to be low due to the observed low escapements is being further diluted by the amount of the annual glacial sediment inputs to the lakes. The low nitrogen levels observed at these lakes are challenging the lower detection limit of the bulk sediment analytical methods currently used in sediment MDN studies.

A visual examination of the sediment cores (Figure 4) from Little Trapper, Trapper and Tatsamenie lakes clearly demonstrated that the annual sediment deposited is highly variable for each of the lakes. These changes in suspended sediment loads would directly affect the turbidity of the lake.

Turbidity resulting from inorganic particles has been described as a modifier of primary production. Glacial silt particles affect temperature regimes, light profiles and phosphorus cycling. Even low turbidities (5–10 NTU) severely restrict light penetration. This in turn restricts the volume of lake water capable of autochthonous production (Koenings et al 1986). Previous work by Koenings et al. (1990) indicated that lake turbidity levels >5 NTU were necessary to uncouple the limitation of primary production from nutrients to light. Primary production in Alaskan glacial lakes is largely a function of light penetration, and not nutrients.

By using the available adult, smolt and zooplankton $\delta^{15}N$ analyses and the expected $\delta^{15}N$ enrichment of +3 to + 4 $^{o}/_{oo}$ between trophic levels, it is possible to back calculate an estimate of the phytoplankton available for sediment burial. All of the adults analyzed for $\delta^{15}N$ content ranged between were between +10.39 and +11.62 (Appendix A). This is a relatively narrow range. Therefore the expectation would be that the differences in the contribution of MDN would be a direct result of the escapement magnitude. Examination of the $\delta^{15}N$ concentrations of smolts from Tahltan (+11.19), Tatsamenie (+8.29) and Chilkoot (+9.87) lakes indicated that the MDN are an integral component of the nutrients available to the lake food web.

Sedimentary concentrations of organic carbon (TOM) and biogenic silica sediment analyses were utilized in the core analysis from each lake to describe the historical primary productivity trends within the lake. In freshwater oligotrophic lakes primary producers are primarily composed of diatoms. Diatoms form mineralized cell walls composed of silica, which are deposited as microfossils in sediments (Stoermer et al. 1996). Diatom valves and zooplankton (Cladocera) body parts in lake sediment have been shown to be the dominant microfossil bioindicators in Alaskan sockeye nursery lakes (Finney et al. 2000). Unfortunately, these primary productivity indicators (Figures 6, 8 and 9) from any of the lakes did not closely coincide with the variations observed in the total organic matter or sedimentary $\delta^{15}N$. This is specifically illustrated by the silica results from Little Trapper Lake (Figure 6). The abrupt observed decrease at 20 cm in biogenic silica concentration did not coincide with similar decreases in either total organic matter or the sedimentary $\delta^{15}N$.

In conclusion, it appears that the nutrients entering the study lakes are similar in content to previously reported values for sockeye salmon in Alaskan lakes. The differences observed in this study are most likely the result of the magnitude of the salmon escapement, and glacial inputs. The escapement density at Little Trapper (68 adults/ha) is greater than the density observed at Tahltan Lake (50 adults/ha). However the mean sediment $\delta^{15}N$ levels are ~60% lower at Little Trapper (+1.84) than Tahltan (+4.83). This means the Little Trapper value is almost equal to the mean $\delta^{15}N$ at Tatsamenie (+1.78) which has a sockeye escapement density of 4 adults/ha. Additionally the mean percent TOM concentrations at Tahltan (10.7) are 60 to 80 % higher than the mean concentrations at Little Trapper (4.2), Trapper (2.6) and Tatsamenie (2.5). These low average sediment total organic matter concentrations are similar for the study lakes. Low organic content is typically characteristic of glacial lake sediments due to large inputs of the clastic glacial material. This is strong evidence of a variable dilution of the sediment $\delta^{15}N$ values in these glacial study lakes.

Analytical Problems Associated with Lake Sediment Analyses

The C/N ratios for the study lakes were extremely high, compared to other paleolimnology studies. Generally the C/N ratios reflect the relative amounts of autochthonous and allochthonous organic matter inputs to lake sediments. These sediment ratios indicate the source of either terrestrial or aquatic organic material. Bulk C/N ratios in the range of 20 to 30 indicate a large terrestrial influence of terrestrial vascular plant material. Phytoplankton organic material is generally in the range of 4 to 10. However, given the physical processes within the lake and watershed, lake sediments contain a mixture of both sources. The C/N ratios encountered in our study lakes ranged from a low of 15.2 to 28.6 at Little Trapper, 15.3 to 52.2 Tatsamenie and 19.6 to 64.4 at Tatsamenie. Carbon/nitrogen ratio values generally higher than 30 are the result of 100% terrestrial vascular plant material (Meyers and Ishiwatari 1993). Since none of our sediments contained 100% plant material the high C/N ratio values observed are probably the result of the extremely low nitrogen content of the sediment.

The $\delta^{15}N$ sediments presented numerous replication problems during this study. Results were inconsistent and no plausible explanation could be developed by the stable isotope analytical laboratory in Fairbanks. As previously mentioned the analytical precision for $\delta^{15}N$ from the WERC lab is generally <0.2 $^{o}/_{oo}$ (δ or del units). Unfortunately in this study we considered replicate results of about $\pm$ 2.0 $^{o}/_{oo}$ to be good replicates. Some replicate $\delta^{15}N$ results varied by greater than $\pm$ 10 $^{o}/_{oo}$. Therefore, analytical data identified as spurious were eliminated from the final presentation of this data. Unfortunately, this resulted in discarding 24%, 17.5% and 7.6% of the analysis replicate results from Tatsamenie, Trapper and Little Trapper lakes samples, respectively. Little Trapper had the highest percent nitrogen values in the sediment. This was encouraging because it resulted in the least amount of spurious data eliminated from the analysis. In some cases only one subsample analysis value was reported. It is likely that the problems encountered were a direct result of the dilution of the low nitrogen signal in combination with variable annual inputs of glacial material.

FISHERY MANAGEMENT IMPLICATIONS

Although historic proxy data generated by examining the $\delta^{15}N$ distribution in lake sediments cannot describe current salmon stock status, it can be useful in placing the current population size and abundance in context. Information generated from long-term changes in fish abundance can provide insight into natural ecosystem variability, the impact of human disturbance, and data necessary for sustainable fisheries management. Researchers have argued for an ecosystem management approach that treats salmon, MDN food web interaction feedbacks, watershed influences and climate cycles as an integrated system (Koenings and Burkett 1987, Knudsen et al 2003 and Naiman et al 2002).

A combination of nitrogen stable isotope and geochemical analyses have been used successfully in reconstructing historical salmon trends in sockeye nursery lakes (Finney 1998, Gregory-Eaves et al 2004, Schindler et al 2005, Selbie et al 2007). The general trends observed over the past 135 years for the distribution of sediment $\delta^{15}N$ in the study lakes (figure 10) indicate that these nitrogen levels have been increasing at Little Trapper Lake, have remained relatively constant at Trapper Lake and been decreasing at Tatasamenie Lake. However, the $\delta^{15}N$ signals appear to be quite variable between subsamples.

It is not surprising that the $\delta^{15}N$ values have remained relatively stable over time at Trapper Lake. This lake does not currently support an anadromous fish run and the sediment analysis appears to confirm this fact. Although the age for bottom of the Trapper core is projected to be 1400 AD, there are no indications that an anadromous sockeye population had access to this lake during the past 600 years. The $\delta^{15}N$ isotope results from of the bottom of the core at 178 cm (1.63) indicates that the value was within the range of values (-2.5 to 4.1) observed throughout the upper 86 cm of the core. Due to the low nitrogen content, the analytical replication problems encountered during the $\delta^{15}N$ analyses, and glacial material diluting the sample, it is likely that this value is not much above the background levels for this lake.

Given the analytical problems encountered during the stable isotope analyses and the amount of spurious data encountered during this process, it is unreasonable to attempt to quantify the existing $\delta^{15}N$ results into a retrospective escapement forecast and determine a lake carrying capacity prior to commercial exploitation. At present these trends are the best indicator available indicator of the distribution of $\delta^{15}N$ in the lake sediments.

Recent work has been successful in isolating the autochthonous fraction of organic matter (which contains the $\delta^{15}N$) present in sediments from Fraser Lake in British Columbia (Hobbs and Wolfe 2007). This method could be employed at these study lakes to concentrate the diatom fraction of the sediments and remove the dilution affect from the glacial material present in each subsample.

The total organic matter and biogenic silica concentrations have been used in similar studies as an indicator of in-lake primary production trends. However, these trends do not coincide with the $\delta^{15}N$ signal at any of study lakes. This is likely a function of the variable amount of clastic glacial material entering the lake annually which is low in organic matter. This volume of glacial sediment material is also acting to dilute the organic matter signal present.

A comparison was made in an attempt to match the sediment $\delta^{15}N$ subsample analysis to the specific escapement enumeration data (Figure 11) available for Little Trapper (1983–2005) and Tatsamenie (1995–2005) sockeye populations. The escapement enumeration data represented 23 and 11 years respectively. The thin section varve analysis dating chronology was used for this comparison. It was possible to match 18 out of 23 years of escapement data for Little Trapper and 7 out of 11 years at Tatsamenie to the varve analysis.

It is apparent from this comparison that the $\delta^{15}N$ sediment results from Little Trapper (Figure 11-A) did not closely match the fluctuations in escapement estimates. However, the $\delta^{15}N$ sediment results from Tatsamenie (figure 11-B) are a very close match to the escapement observations. If the sediment dating chronology was shifted one or 2 years there would be very close agreement between the sediment $\delta^{15}N$ results and observed escapements.

Varve chronologies from some, if not all of these lakes can help explain the timing of any observed changes. Additionally, the sedimentary signal for past climate or hydrological signals is useful to assess changes in salmon numbers inferred from the isotopic record. Variations in sediment delivery may provide insight into past lake flushing and turbidity and changes to watershed conditions that may impact salmon ecology.

Although this study encountered numerous analytical problems with $\delta^{15}N$ sample analysis replication, the thin section varve analysis was very successful. This dating analysis needs to be refined given the close match with the Tatsamenie escapement and sediment $\delta^{15}N$ data. At present it is not unreasonable to assume that the varve dates could be offset by one or 2 years. Additionally a re-analysis of the Little Trapper varve dating could explain the variation observed between the dating, sediment $\delta^{15}N$ and the observed escapements.

Additional work needs to be conducted on these study lakes. This study should be viewed as a first attempt to refine the varve chronology analysis and the analytical sediment $\delta^{15}N$ problems encountered. A method needs to be determined that would provide for a way to concentrate the diatom fraction present in glacial sediment to resolve the sample size and replicate problems encountered by the UAF-WERC stable isotope laboratory. Additionally samples should be distributed for a blind testing to other stable isotope labs in both the US and Canada. In that way the analytical problems encountered can be examined to determine if the problems are ubiquitous for low level nitrogen bulk sediment samples or if the replication problem is related to specific mass spectrophotometery instrumentation.

The results of this study are promising and will be extremely useful in refining the analytical approaches employed for glacial lakes. The close agreement between the Tatsamenie sediment $\delta^{15}N$ results and the observed escapement data is especially encouraging, given the analytical problems encountered. A continuation of this study at these lakes could result in developing methods to concentrate the $\delta^{15}N$ diatom fraction of these clastic sediments. The results of this study are extremely valuable, given the number and distribution of glacial sockeye salmon nursery lakes in both Alaska and British Columbia.

REFERENCES CITED

Altabet, M.A. and R. Francois, 1994. Sedimentary nitrogen isotopic ratio as a recorder of surface nitrate utilization. Global Biogeochemical Cycles. 8:1, 103–116.

Andel, J.E. and I.A. Boyce. Mark-Recapture Studies of Taku River Adult Sockeye Salmon Stocks in 2004. PSC Tech. Rep. No. 20, February 2007.

Appleby, P.G. 2002. Chronostratigraphic techniques in recent sediments. In: Tracking Environmental Change: Using Lake Sediments Volume 1: Basin analysis, coring and Chronological Techniques. W.A. Last and J. P. Smol editors. Kluwer. New York. Pp 171–203.

REFERENCES CITED (Continued)

Barto, D.L. 2004. Assessing the production of sockeye salmon (Oncorhynchus nerka) at Chilkat lake Southeast Alaska, using current trophic conditions and the paleosediment record. M.S. Thesis, University of Alaska – Fairbanks.

Bates, R.L. and J.A. Jackson., editors. 1984. Dictionary of Geological Terms. third edition, Prepared by The American Geological Institute. Double Day, New York.

BC Ministry of Environment. 2007. Fisheries Inventory Data Queries. http://srmapps.gov.bc.ca/apps/fidq/ Accessed 9/2007

Bilby, R.E., B.R. Fransen and P.A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning Coho salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53: 164–167

Bilby, R.E., B.R. Fransen, J.K. Walter, C.J. Cederholm and W.J. Scarlett. 2001. Preliminary evaluation of the use of nitrogen stable isotope ratios to establish escapement levels for Pacific salmon. Fisheries. 26:1.

Brenner, R.E., R.D. Boone, J. Jones, K. Lajha, and R. Ruess. 2006. Successional and physical controls on the retention of nitrogen in an undisturbed boreal forest ecosystem. Oecologia 148:602–611.

Donaldson, J.R. 1968. The Phosphorus budget of Iliamna Lake, Alaska, as related to the cyclic abundance of sockeye salmon. Ph.D. Thesis, University of Washington, Seattle.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sediment. Petrology 44: 242–248.

Dean, W.E. 1999. The carbon cycle and biogeochemical dynamics in lake sediments. Journal of Paleolimnology. 21:375–393.

deLaeter, J.R., J.K. Böelke, P. DeBievre, H. Hidaka, H.S. Peiser, K.J.R. Rosman, and P.D.P. Taylor. 2003. Atomic weights of the elements. Review 2000 (IUPAC Technical Report). Pure and Applied Chemistry 75(6):683–799.

Edmundson, J.A. and S.R. Carlson. 1998. Lake typology influences on the phosphorus-chlorophyll relationship in subarctic, Alaskan lakes. Lake and Reservoir Management 14(4):440–450

Edmundson, J.M. and J.A. Edmundson. 2002. Sockeye salmon production relative to changes in rearing capacity of Crecent Lake, Upper Cook Inlet. Alaska Department of Fish and Game-Commercial Fisheries Division, Regional Information Report No. 2A02-08, Anchorage.AK.

Finney, B.P. 1998. Long-term variability of Alaskan sockeye salmon abundance determined by analysis of sediment cores. North Pacific Anadromous Fish Commission. Bulletin 1:388–395.

Finney, B.P., I. Gregory-Eaves, J. Sweetman, M.S.V. Douglas, and J.P. Smol. 2000. Impacts of climate change and fishing on Pacific salmon over the past 300 years. Science. 27:795–799.

Gale, S.J. and P.G. Hoare. 1991. Quaternary Sediments: Petrographic Methods for the Study of Unlithified Rocks. Halsted Press, John Wiley & Sons, Inc., New York.

Glew, J. R., 1988. A portable extruding device for close interval sectioning of unconsolidated core samples. Journal of Paleolimnology 1:235–239

Grant, D.J. 1985a. A reconnaissance survey of Little Trapper Lake. Recreational Fisheries Branch Technical Report. BC Ministry of Environment and Parks.

Grant, D.J. 1985b. A reconnaissance survey of Tatsamenie Lake. Recreational Fisheries Branch Technical Report. BC Ministry of Environment and Parks.

Gregory-Eaves, I., B.P. Finney, M.S.V. Douglas and J.P. Smol. 2004. Inferring sockeye salmon (Oncorhynchus nerka) population dynamics and water quality changes in a stained nursery lake over the past ~500 years. Can. J. Fish Aquatic Sci. 61:1235–1246.

Helfield, J.M., and R.J. Naiman. 2006. Keystone interactions: salmon and bear in riparian forests of Alaska. Ecosystems 9:167–180.

REFERENCES CITED (Continued)

Hobbs, W.O. and A.P. Wolfe. 2007. Caveats on the use of paleolimnology to infer Pacific salmon returns. Limnol. Oceanogr 52(5):2053–2061.

Holtham. A. J., I. Gregory-Eaves, M. G. Pellatt, D.T. Selbie, L. Stewart, B.P. Finney and J.P. Smol. 2004. The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon (Oncorhynchus nerka) nutrient dynamics in Alaska and British Columbia. J. of Paleolimnology 32:2559271.

Hyatt, K.D., K. L. Mathias, D.J. McQueen, B. Mercer, P. Milligan and D.P. Rankin. 2005. Evaluation of hatchery versus wild sockeye salmon fry growth and survival in two British Columbia lakes. North American Journal of Fisheries Management. 25:745–762

Kline, T.C. Jr., J.J. Goering, O.A. Mathisen, P.H. Poe and P.L. Parker. 1990. Recycling of salmon nutrients transported upstream by runs of Pacific salmon: I. δ 15N and δ 13C evidence in Sashin Creek, southeastern Alaska. Canadian Journal of Fisheries and Aquatic Sciences 47:136–144.

Koenings, J.P., R.D. Burkett, G.B. Kyle, J.A. Edmundson and J.M. Edmundson. 1986. Trophic level responses to glacial meltwater intrusion in Alaskan lakes. Cold Regions Hydrology Symposium. American Water Resources Association.

Koenings, J. P. and R. D. Burkett. 1987. Population characteristics of sockeye salmon (Oncorhynchus nerka) smolts relative to temperature regimes, euphotic volume, fry density, and forage base within Alaskan lakes. Pages 216–234. in H. D. Smith, L. Margolis, and C. C. Wood, editors. Sockeye salmon (Oncorhynchus nerka) population biology and future management. Special Publication of the Journal of Fisheries and Aquatic Sciences. 96.

Koenings, J.P., G.B. Kyle, J.A. Edmundson and J.M. Edmundson. 1987b. Limnology field and laboratory manual: Methods for assessing aquatic production. Alaska Department of Fish and Game, Division of Fisheries Rehabilitation, Enhancement and Development. F.R.E.D. Tech. Rpt. Ser. 71, Juneau.

Koenings, J.P., R.D. Burkett, J.M. Edmundson. 1990. The exclusion of limnetic Cladocera from glacier-meltwater lakes. Ecology 71(1):57–67.

Krishnaswami, S.D., and D. Lal. 1978. Radionuclide Limnochronology. In Lakes-Chemistry, Geology, Physics. Edited by A. Lerman. Springer-Verlag, New York. pp. 153–177.

Krishnaswami, S.D., L.K. Benninger, R.C. Aller and K.L. Von Damm. 1980. Atmospherically derived radionuclides as tracers of sediment mixing and accumulation in near shore marine sediments and lake sediments; evidence from Be-7, Pb-210 and Pu-239,240. Earth Planet Sc. Lett. 47: 307–318.

Knudsen, E.E., E.W. Symmes and F.J. Margraf. 2003. Searching for a life history approach to salmon escapement management. In Nutrients in Salmon Ecosystems: Sustaining Production and Biodiversity. Edited by J.G. Stockner. Am. Fish. Soc. Symp. No. 34. pp. 261–276.

Jones, J.B., K.C. Petrone, J.C. Finlay, L.D. Hinzman and W.R. Bolton. 2005. Nitrogen loss from watersheds of interior Alaska underlain with discontinuous permafrost. Geophysical Research Letters. 32:L02401.

Lamoureux, S.F., 2001. Varve chronology techniques. In W.M. Last and J.P. Smol editors. Tracking Environmental Change Using Lake Sediments. Volume 1: Basin Analysis, Coring and Chronological Techniques. Kluwer Academic, Dordrecht, The Netherlands.

Lamoureux, S.F., 1994. Embedding unfrozen lake sediments for thin section preparation. Journal of Paleolimnology. 10:141–146.

McNeil, S.L. 1997. The paleoproductivity of sockeye salmon: Assessment by sediment core analysis. M.S. Thesis, University of Alaska, Fairbanks.

Mathias, K.L. 2000. Growth and survival of sockeye salmon (Oncorhynchus nerka) in three Northwestern British Columbia lakes-an evaluation of an international enhancement program. M.S. Thesis. York University

Mortlock, R.A. and P.N. Froelich. 1989. A simple method for the rapid determination of biogenic opal in pelagic marine sediments. Deep-Sea Res. 36: 1415–1426.

REFERENCES CITED (Continued)

Myers, P.A. and R. Ishiwatari. 1993. The early diagenesis of organic matter in lacustrine sediments. In Organic Chemistry-Principles and Applications. Edited by M.H. Engles and S.A. Macko. Plenum Press. New York. pp. 867–900.

Naiman. R. J., R.E. Bilby, D.E. Schindler, and J.M. Helfield. 2002. Pacific salmon, nutrients and the dynamics of freshwater and riparian ecosystems. Ecosystems 5:399–417.

Nowaczyk, N.R. 2002. Logging of magnetic susceptibility. In: Tracking Environmental Change: Using Lake Sediments Volume 1: Basin analysis, coring and Chronological Techniques. W.A. Last and J. P. Smol editors. Kluwer. New York. Pp 155–170.

Pienitz, R., J.P. Smol and D.R.S. Lean. 1997. Physical and chemical limnology of 59 lakes located between the southern Yukon and the Tukoyaktuk peninsula, Northwest Territories (Canada). Can. J. Fish. Aquat. Sci. 54:330–346.

Satterfield, F.R. and B.P. Finney. 2002. Stable isotope analysis of Pacific salmon: insight into trophic status and oceanographic conditions over the last 30 years. Progress in Oceanography 53:231–246.

Schindler, D.E., P.R. Levitt, C.S. Brock, S.P. Johnson and P.D. Quay. 2005. Marine-derived nutrients, commercial fisheries and production of salmon and lake algae in Alaska. Ecology 86(12):3225–3231.

Schelske, C.L., D.J. Conley, E.F. Stoermer, T.L. Newberry and C.D. Campbell. 1986. Biogenic silica and phosphorus accumulation in sediments as indices of eutrophication in the Laurentian Great Lakes. Hydrobiologia. 143: 79–86.

Selbie. D.T., B.A. Lewis, J.P. Smol, and B.P. Finney. 2007. Long-term dynamics of the endangered Snake River sockeye salmon: evidence of past influences on stock decline and impediments to recovery. 2007. Trans. Am. Fish. Soc. 136:800–821.

Sokal, R.R., and F.J. Rolf. 1981. Biometry. W.H. Freeman and Company, New York. 859 pp.

Spafard, M.A and J.A. Edmundson. 2000. A morphometric atlas of Alaskan lakes: Cook Inlet, Prince William Sound and Bristol Bay areas. Alaska Department of Fish and Game-Commercial Fisheries Division, Regional Information Report No. 2A00-23, Anchorage.AK.

Stednick, J.D. 1981. Precipitation and streamwater chemistry in an undisturbed watershed in Southeast Alaska. U.S. Department of Agriculture, Pacific Northwest Forest and Range Experiment Station, Research Paper PNW-291.

Stihler, S.D., D.B. Stone, and J.E. Beget. 1992. Varve counting vs. tephrochronology and ^{137}Cs and ^{210}Pb dating: a comparative test at Skilak Lake, Alaska. Geology, 20:11 1019-1022.

Stoermer, E.F., G. Emmert, M.L. Julius and C.L. Schelske. 1996. Paleolimnologic evidence of rapid recent change in Lake Erie's trophic status. Can. J. Fish. Aquat. Sci. 53: 1451–1458.

TTC (Transnoundary Technical Committee). 1998. Transboundary river sockeye salmon enhancement activities final report for summer 1992 to spring 1995. Pacific Salmon Commission TCTR (98-1), Vancouver, British Columbia.

Von Damm, K.L., L.K. Benninger and K.K. Turekian. 1979. The lead-210 chronology of a core from Mirror Lake, New Hampshire. Limnol. Oceanogr. 24: 434–439.

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems. 3rd edition. Academic Press, San Diego.

FIGURES

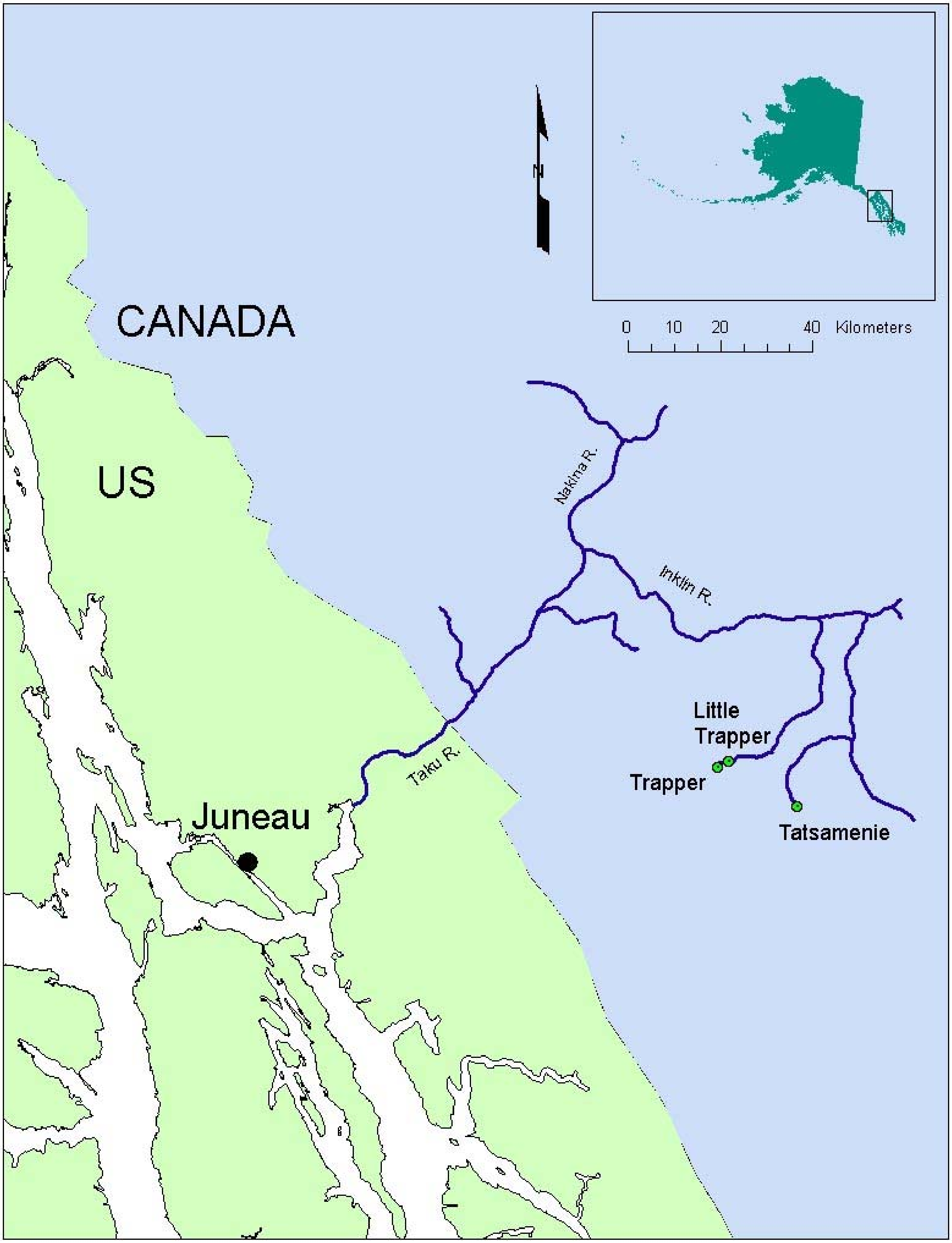


Figure 1.–Location of Taku River lake study sites in Southeast Alaska and Canada

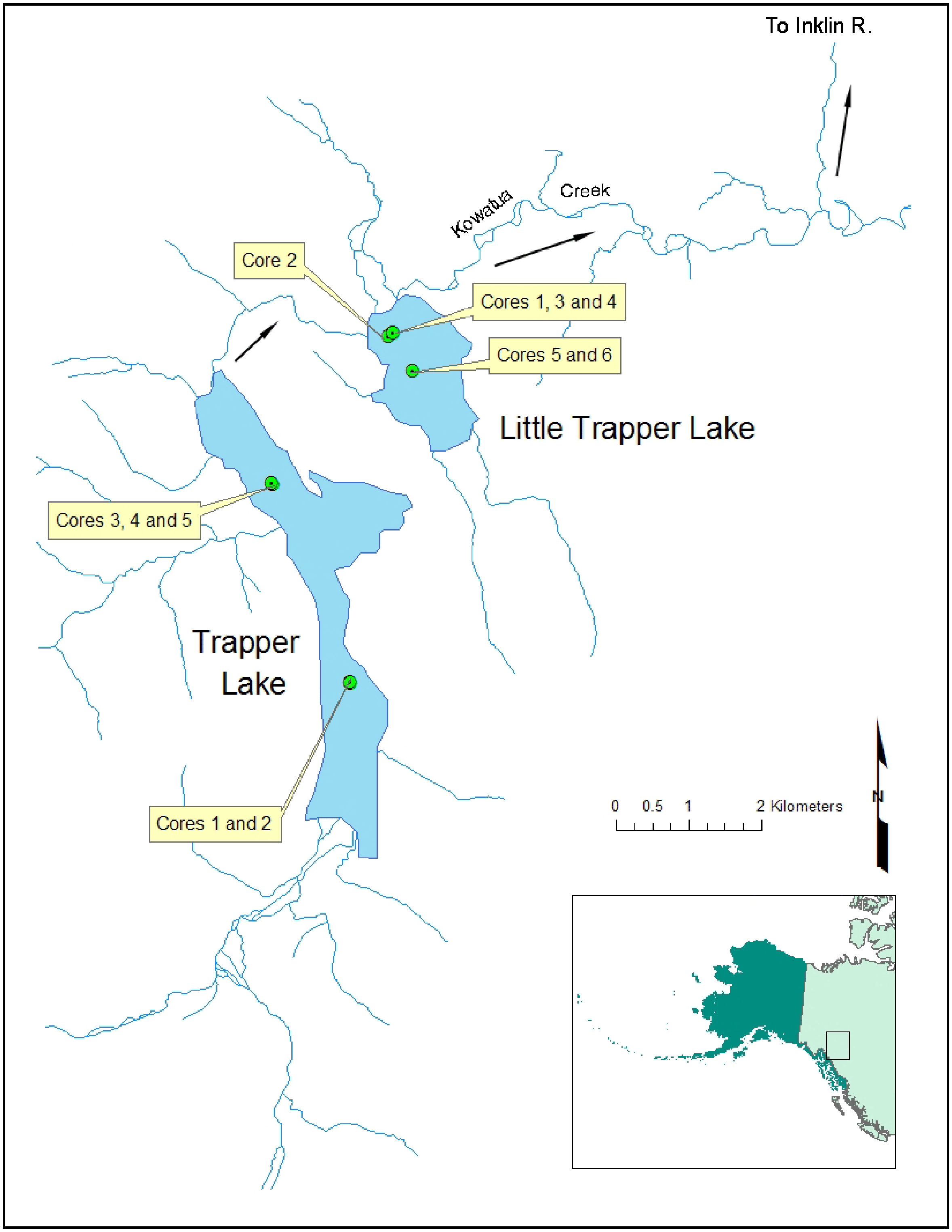


Figure 2.–Trapper and Little Trapper Lake 2005 core sampling locations

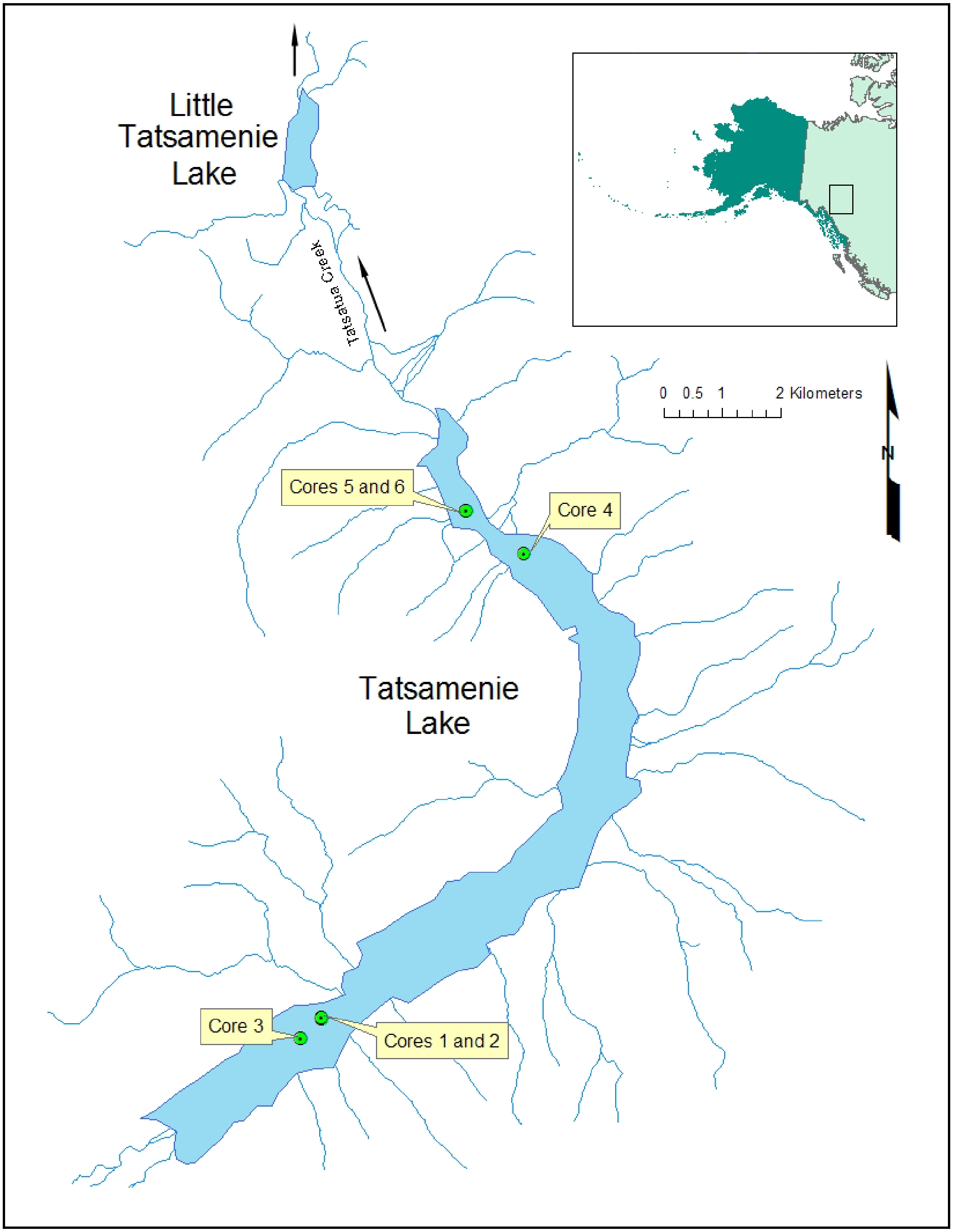


Figure 3.–Tatsamenie Lake 2005 core sampling locations

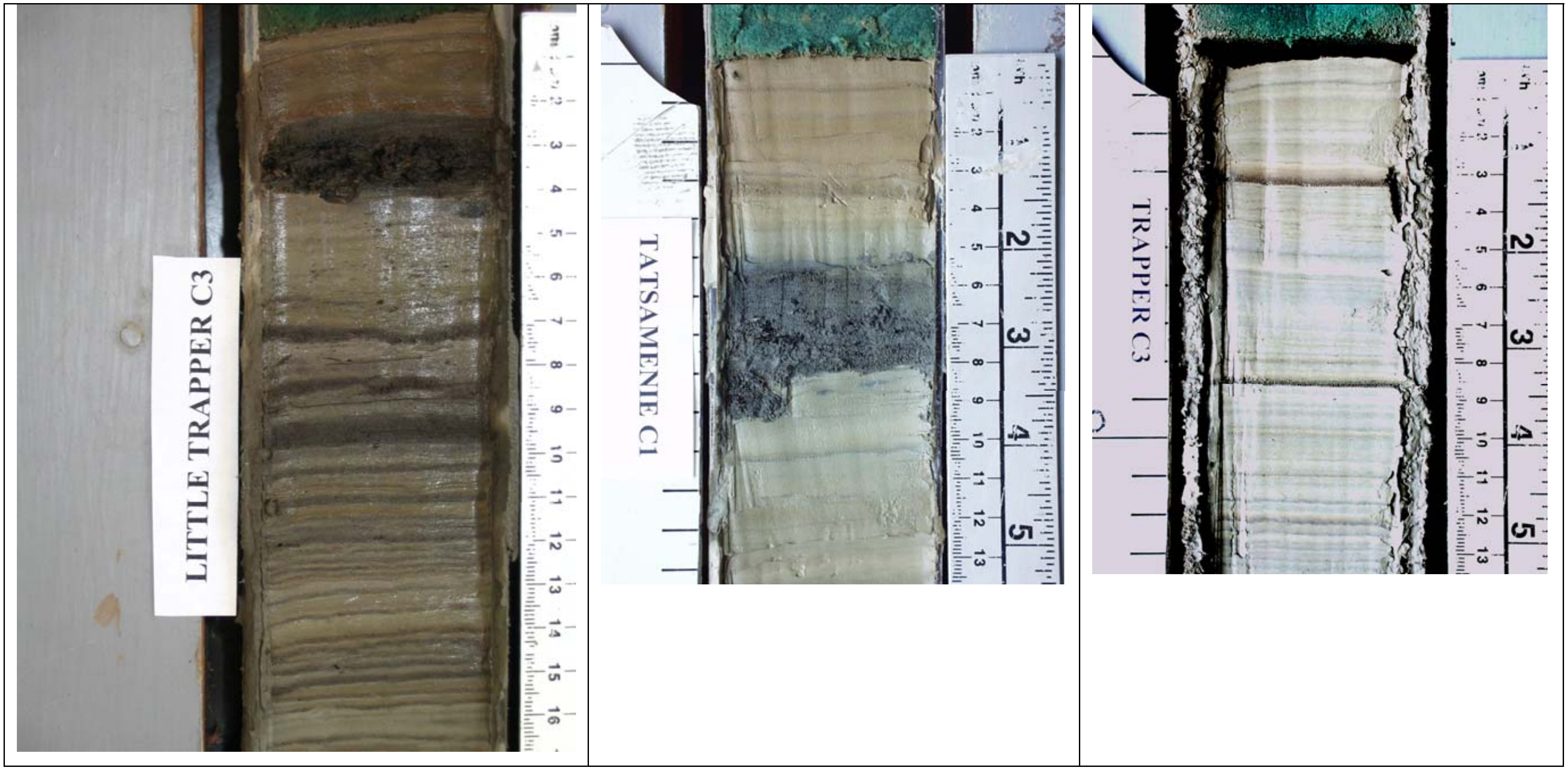


Figure 4.–Examples of observed downcore varve layers in the Little Trapper (Core 3), Tatsamenie (Core 1) and Trapper (Core 5) sediment cores used for thin section sampling and varve counting chronology analysis.

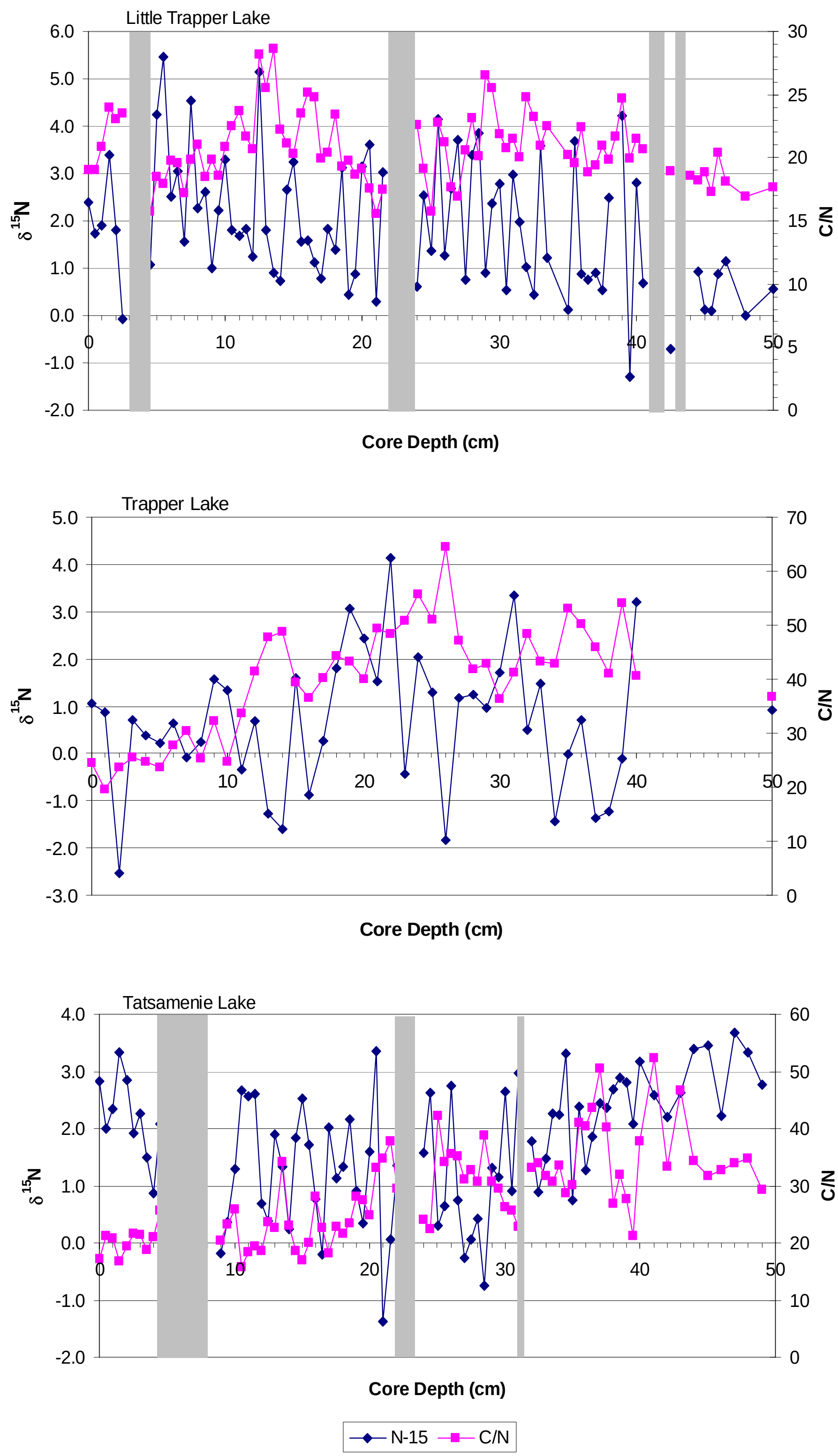


Figure 5.–Sediment $\delta^{15}N$ and %C/%N ratio results for Taku transboundary river study sites . Highlighted areas indicate turbidite layers with no samples analyzed.

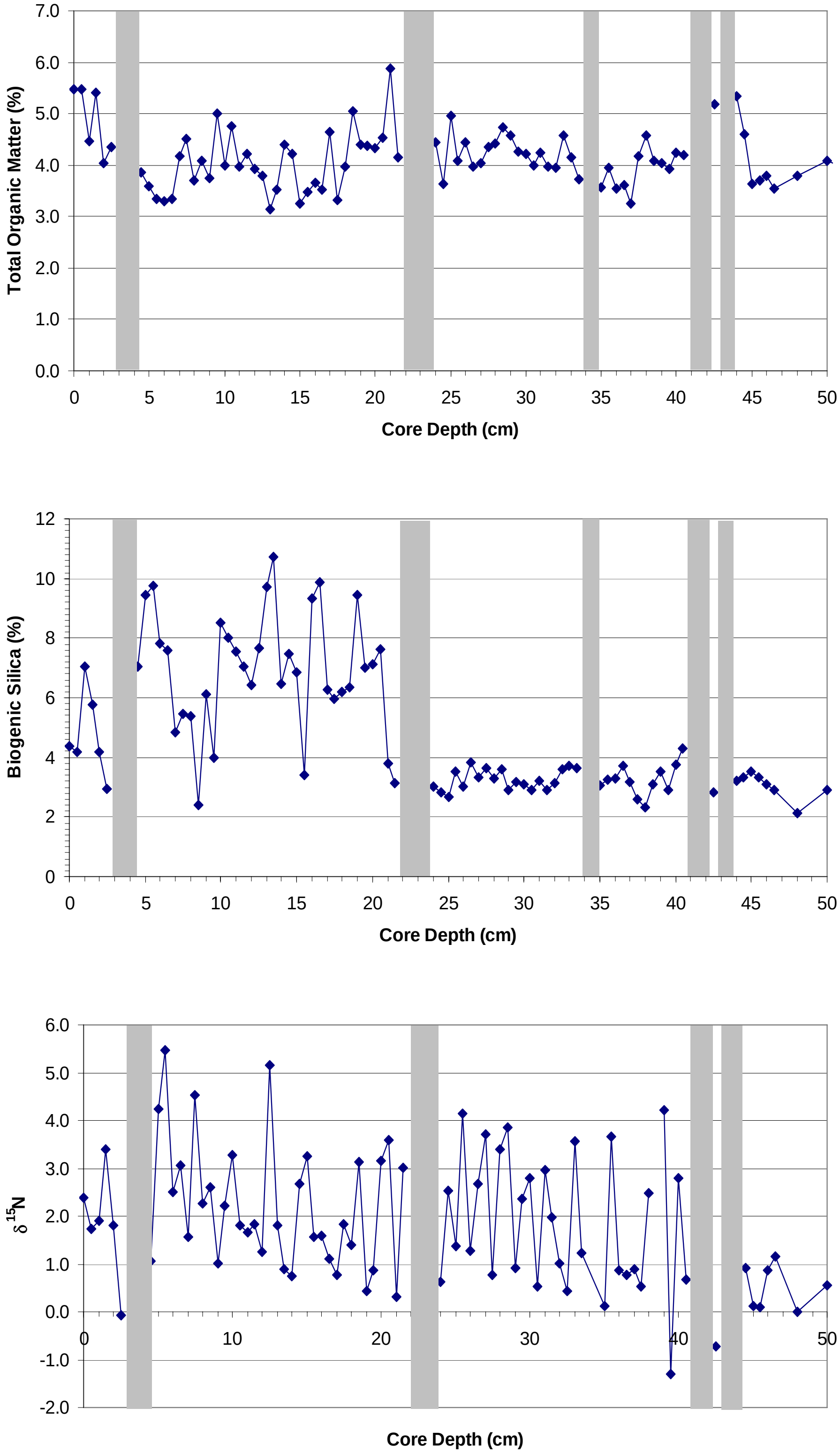


Figure 6.–Sediment total organic matter, biogenic silica and $\delta^{15}N$ analyses for Core 3 (2006) at Little Trapper Lake. Highlighted areas indicate turbidite layers with no samples analyzed.

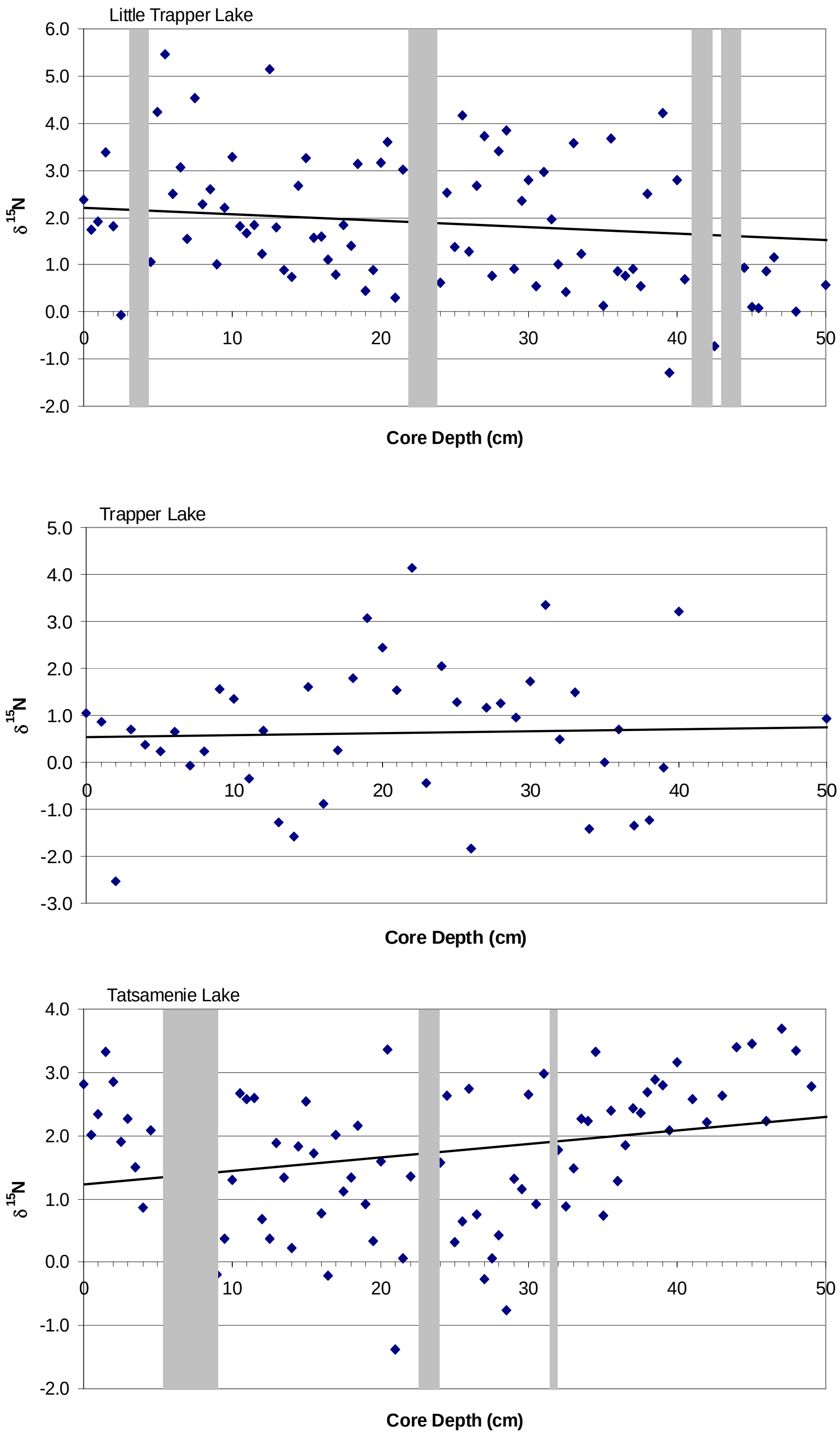


Figure 7.–Sediment $\delta^{15}N$ results and trends from Little Trapper, Trapper, and Tatsamenie lakes. Highlighted areas indicate turbidite layer with no samples analyzed.

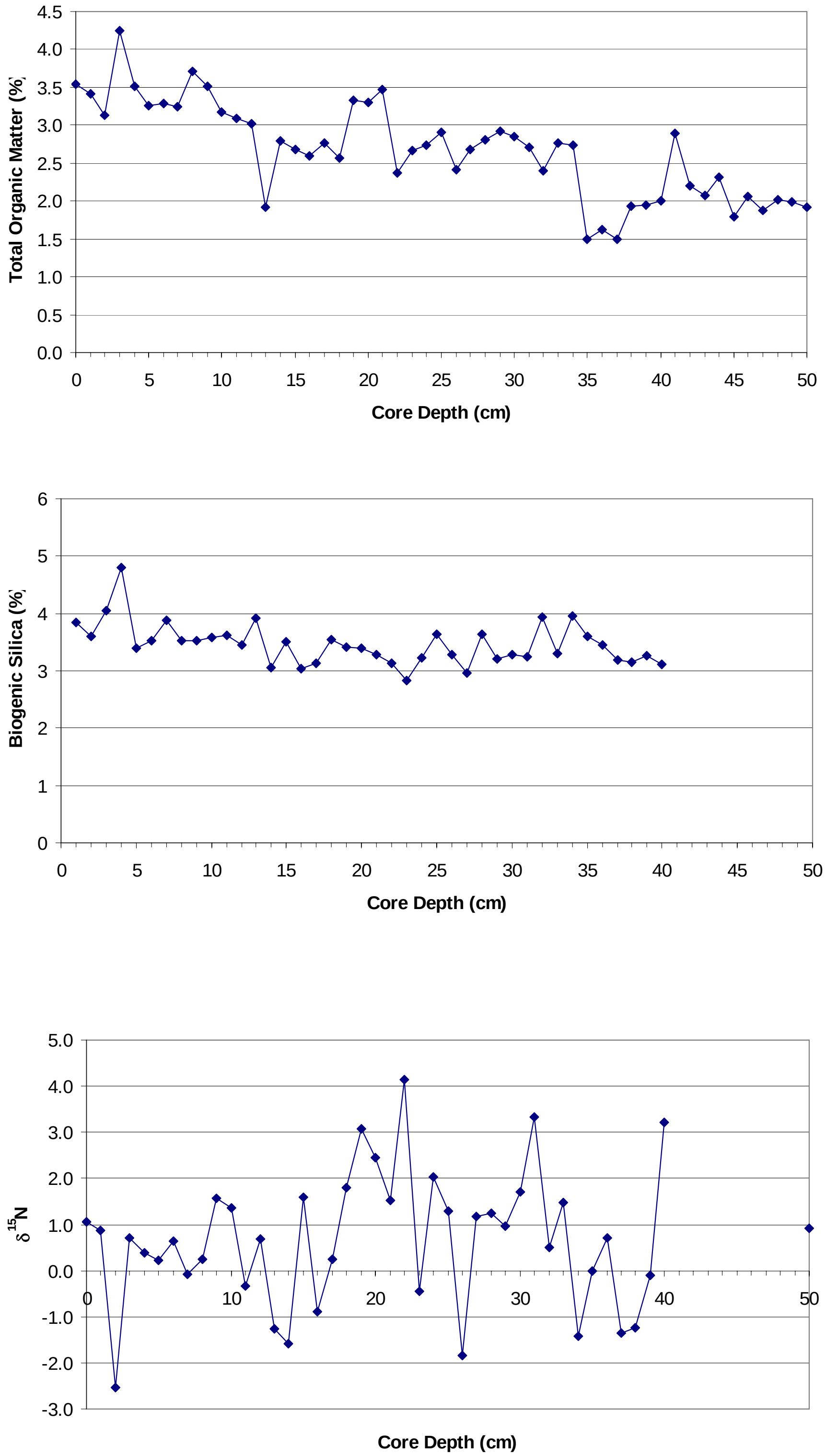


Figure 8.–Sediment total organic matter, biogenic silica and mean δ15N analyses for Core 5 (2006) at Trapper Lake.

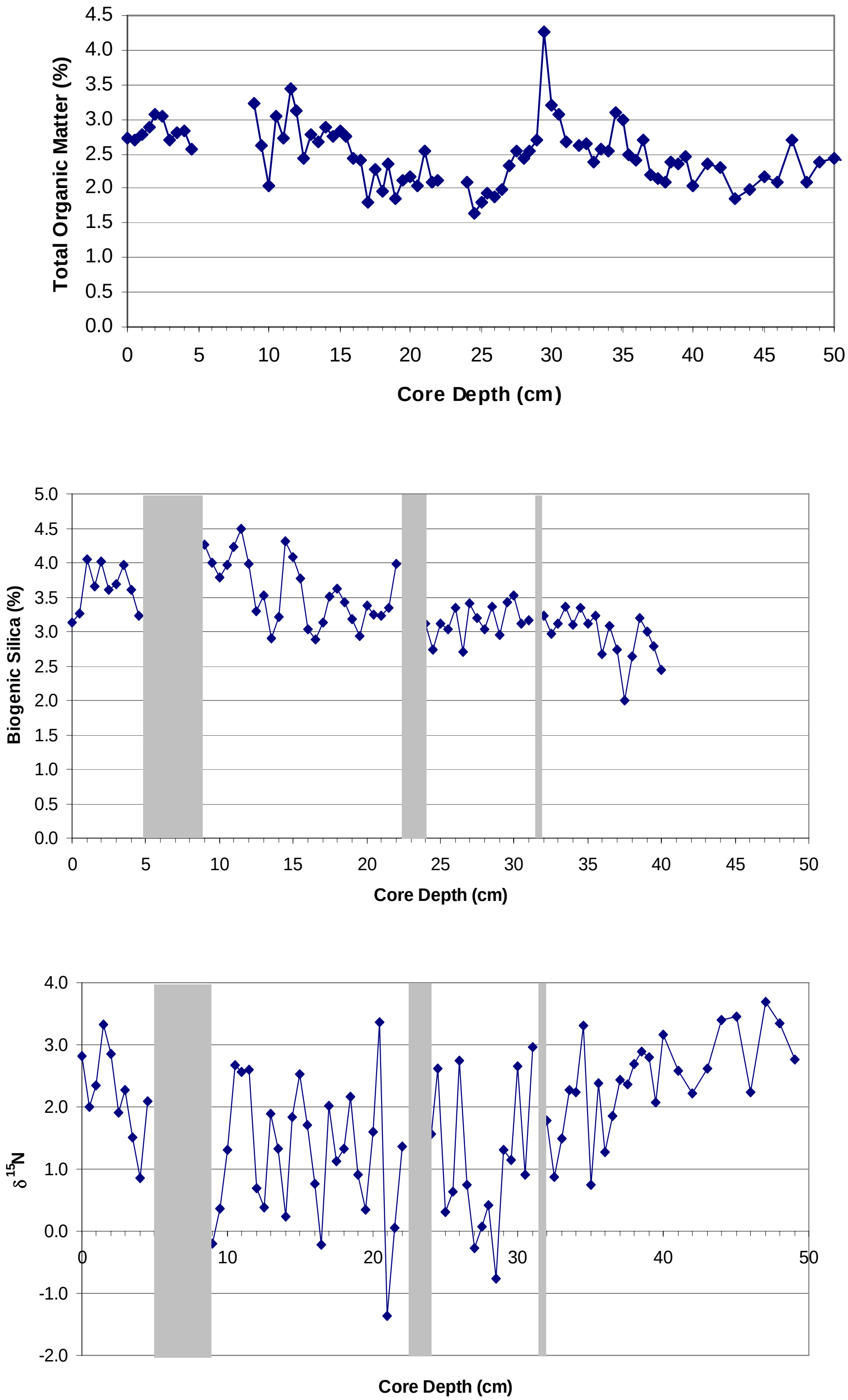


Figure 9.–Sediment total organic matter, biogenic silica and $\delta^{15}N$ analysis results for Core 1 (2006) at Tatsamenie Lake. Highlighted areas indicate turbidite layers with no samples analyzed.

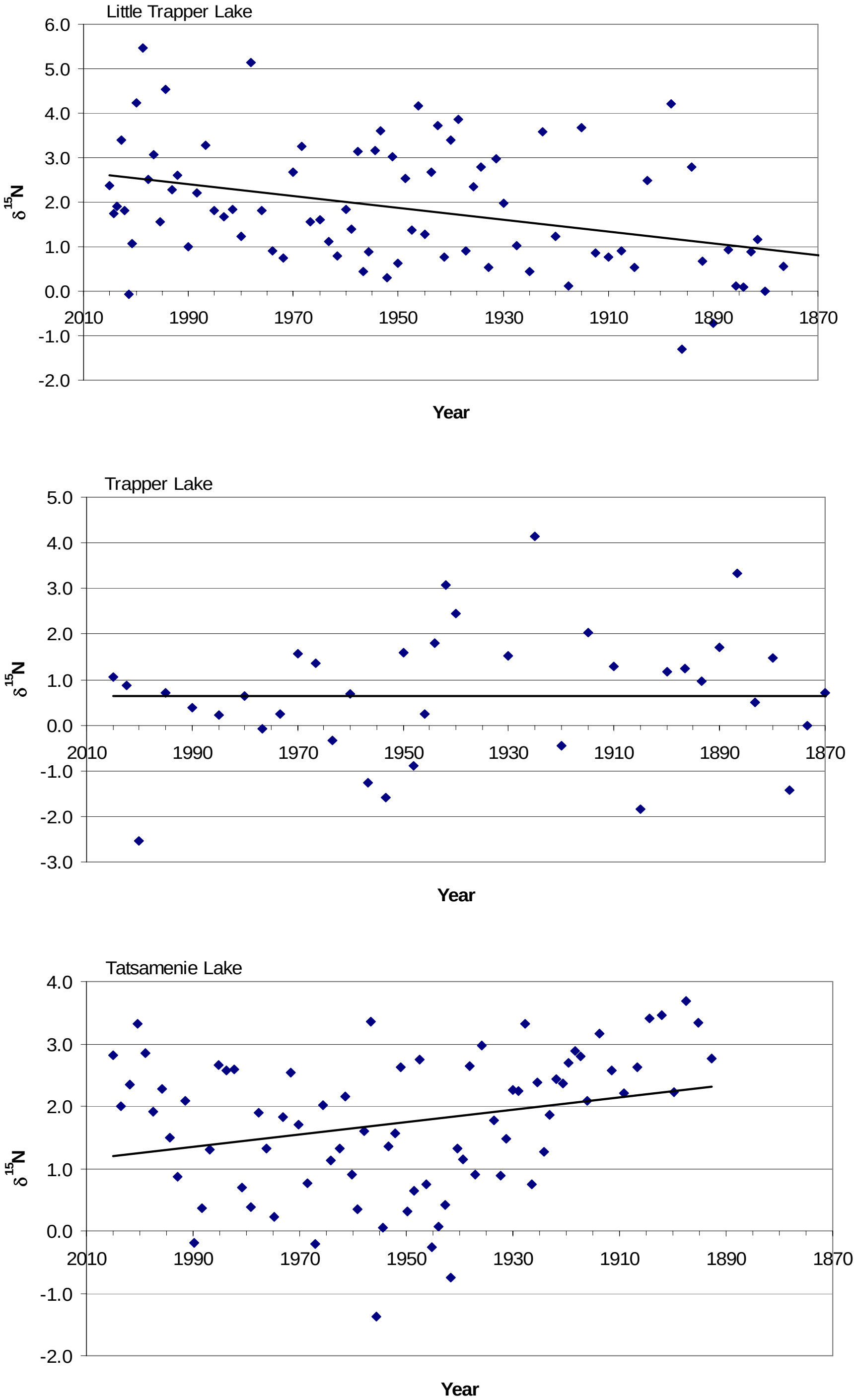
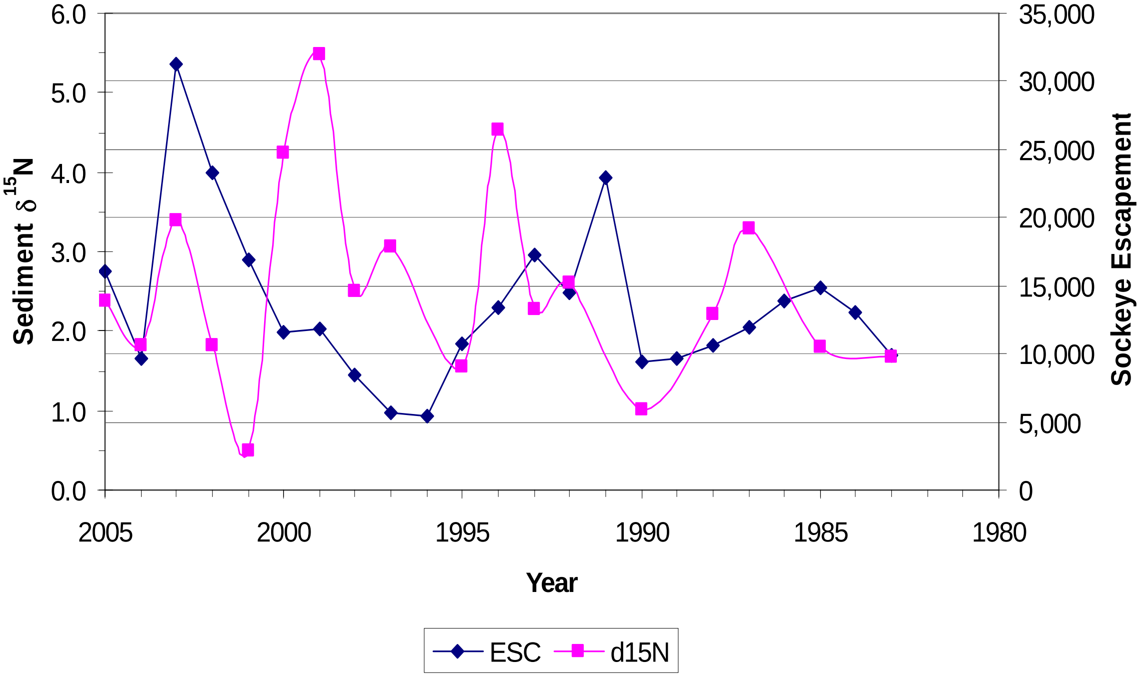


Figure 10.–A comparison of the sediment δ15N stable isotope linear trends at Little Trapper, Trapper and Tatsamenie lakes during the last 135-year period based on sediment varve analysis.

A



B

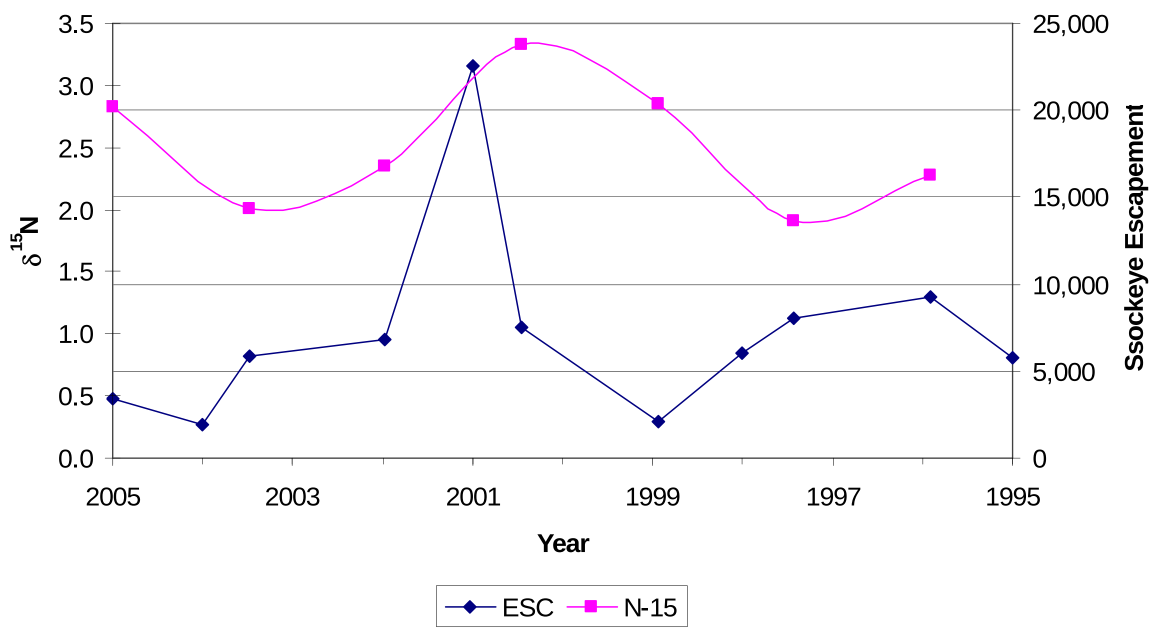


Figure 11.–A comparison of the observed sockeye escapement and sediment $\delta^{15}N$ distribution at Little Trapper Lake (A) Tatsamenie Lake (B) based on varve chronology analysis.

TABLES

Table 1.–A comparison of the morphometric characteristics of Canadian transboundary river lakes and glacial sockeye nursery lakes in Alaska. Data included in this table was collected from Mathias (2000), Grant (1985a and b), Spafard and Edmundson (2000) and unpublished ADF&G limnology data. All ADF&G, EZD and secchi disc data represents multi-month (May–Oct/Nov) and multi-year means. Geographic locations in Alaska are Prince William Sound (PWS-AK), northern Southeast Alaska (NSE-AK) and Cook Inlet (CI or CI-AK).

Lake	**Lake Water Type**	**Geographic Location**	**Elevation (m)**	**Max Depth (m)**	**Mean Depth (m)**	**Volume (x 10^6 m^3)**	**Surface Area (km^2)**	**Drainage Area (km^2)**	**Mean Annual Precip (cm)**	**Lake Water Residence T_w (yr.)**	**EZD (m)**
Trapper	glacial	Taku River	769	101	52	288	5.6	185	29	11.3	6.8[1/]
Little Trapper	glacial	Taku River	727	23	13	26	2.1	247	29	4.6	8.9[1/]
Tatsamenie	glacial	Taku River	975	142	53	890	16.2	308	29	20.5	9.7[1/]
Tahltan	clear	Stikine River	825	48	23	113	4.9	57	37	8.9	19.2[1/]
Coghill [7/]	glacial/ meromictic	PWS-AK	18	78	30	323	12.7	127	330	0.9	7.6
Crescent [8/]	glacial	NSE-AK	53	67	31	99	3.3	128	457	0.2	7.9
Crescent (CI)	glacial	CI-AK	183	31	23	379	16.5	648	28	0.8	7.2
Chilkoot [9/]	glacial	NSE-AK	9	89	55	382	7.0	332	229	0.6	5.2
Farragut [8/]	glacial	NSE-AK	135	108	67	321	4.8	64	432	1.3	3.0
Skilak [10/]	glacial	CI-AK	63	160	73	7213	99.0	3,215	51	5.7	7.4

1/ Calculated based on Secchi Disc observations (Koenings et al. 1987b)

Table 2.– A comparison of observed spring nutrient concentrations and mean sockeye salmon escapement of Canadian transboundary river lakes and glacial sockeye nursery lakes in Alaska. The Crescent Lake locations are in northern Southeast Alaska (SE) and Cook Inlet Alaska (CI).

Core Sample Date	Lake	Lake Water Residence Tw (yr)	Mean Spring Total Phosphorus [a] TP_{sp} (µg/l)	Standard Deviation	Mean Spring Total Nitrogen [b] TN_{sp} (µg/l)	Standard Deviation	Sockeye Escapement Mean (#)	Mean Density (#/ha)	Weir Operation [c] (years)
2006	Trapper [d]	11.3	2.2 [e]	0.77	--	--	--	--	--
2006	Little Trapper	4.6	1.9 [e]	1.56	--	--	13,573	68	1983–2005
2006	Tatsamenie	20.5	1.4	0.34	--	--	7,203	4	1985–2005
1995	Tahltan	8.9	8.4	3.11	--	--	24,793	50	1959–2005
1994	Coghill	0.9	1.7	0.66	100.1	22.82	55,271	44	1974–2005
--	Crescent (SE)	0.2	1.2	0.28	190.0	21.75	4,658	14	1977–79, 83–92
1998	Crescent (CI)	0.8	2.2	0.87	303.5	73.10	71,796	44	1979–2005
1995	Chilkoot	0.6	1.7	0.26	157.6	29.53	67,223	96	1976–2005
--	Farragut [1]	1.3	3.0	0.69	72.4	9.59	--	--	--
1999	Skilak	5.7	2.2	0.93	236.6	24.61	294,399	19	1981–2005

a/ Turbidity and Inorganic Particulate Phosphorus (IPP) corrected (CTP) TP; Edmundson and Carlson 1997.

b/ Total Nitrogen (TN) = Total Kjeldal Nitrogen (TKN)+ Nitrates (NO3)

c/ from Integrated Fisheries Database (IFDB) in 2006

d/ no known anadromous fish access

e/ July values reported because this was the only data available

Table 3.–A comparison of sockeye salmon escapement density (adults/ha) and observed sediment nitrogen and carbon percentages and confidence intervals (C.I.) in Canadian and Alaskan nursery lakes.

	Sockeye	% N			% C		
Lake	**adult/ha**	**Mean**	**Lower C.I.**	**Upper C.I.**	**Mean**	**Lower C.I.**	**Upper C.I.**
Trapper	--	0.006	0.002	0.012	0.219	0.105	0.307
Tatsamenie	4	0.011	0.005	0.023	0.280	0.170	0.482
Crescent (Cook Inlet)	44	0.023	0.016	0.032	0.328	0.246	0.448
Chilkoot	96	0.036	0.017	0.224	0.562	0.199	3.936
Coghill	44	0.052	0.042	0.099	0.564	0.411	1.384
Little Trapper	68	0.056	0.028	0.132	1.128	0.508	2.129
Skilak	19	0.077	0.077	0.118	0.631	0.443	1.034
Tahltan [1/]	50	0.484	0.070	1.319	4.839	0.700	12.127

1/ clear water lake

APPENDIX

Appendix A.–Average stable isotope values for adult sockeye from Canadian transboundary river lakes and glacial sockeye nursery lakes in Alaska. (SD = standard deviation).

Lake	Sample Year(s)	n	$\delta^{15}N$ ($^o/_{oo}$)	SD	$\delta^{13}C$ ($^o/_{oo}$)	SD	C%/N%
Auke	1997	3	10.72	0.25	-20.95	0.32	3.26
Benzemen	1996	1	11.36	--	-20.88	--	3.55
Chilkat	1990, 97	6	11.03	0.81	-21.96	1.89	4.66
Chilkoot [1/]	1990, 1997	4	11.05	0.46	-20.25	0.24	3.34
Crescent [1/]	1991	3	10.39	0.48	-20.39	0.53	3.45
Eva	1995	3	11.62	1.02	-20.86	0.33	3.37
Hugh Smith	1992	3	11.52	0.38	-21.88	0.80	4.74
Little Trapper	1995	5	10.70	0.14	-17.74	0.46	2.90
Redoubt	1996	1	11.46	--	-20.37	--	3.31
Speel	1992	3	11.38	0.60	-21.55	0.83	4.16
Sweetheart	1997	4	11.28	0.50	-20.76	0.66	3.74
Tahltan	1994	5	10.56	0.36	-17.45	0.43	2.86
Tatsamenie [1/]	1995	5	10.62	0.75	-17.90	0.44	2.87

Appendix B.–Average $\delta^{15}N$ content of sockeye salmon smolt and zooplankton from Canadian transboundary river and Alaskan lakes. Spring zooplankton samples were collected during May unless noted. (SD = standard deviation).

Lake	**Sampling year(s)**	**n**	**Smolt $\delta^{15}N$**	**SD**	**Sampling year(s)**	**n**	**Spring Zooplankton $\delta^{15}N$**	**SD**
Auke	1997	10	12.57	0.53	1995, 1997–2001	6	10.79	1.48
Chilkat	1996–1997	20	13.20	0.86	1995–1997	3	9.63	0.03
Chilkoot [1/]	1996–1997	15	9.87	0.91	1997–1999	3	8.20	0.80
Coghill [1/]	1997	5	9.42	0.41				
Crescent (SE) [1/]	1996	18	10.20	2.36	--	--	--	--
Falls	--	--	--	--	2002	1	3.15	--
Hugh Smith	1996	10	8.38	0.29	1996–1997	2	7.25	0.85
Kanalku	1997	5	7.66	0.54	1995, 1997	2	5.02	0.14
Klawock	--	--	--	--	2001–2002	2	7.01	1.90
Kook	--	--	--	--	1995–1996	2	7.70	0.28
McDonald	1997	10	10.99	0.92	1996–1997	2	11.28	1.08
Sitkoh	1996	10	10.36	0.55	--	--	--	--
Speel	1996	10	7.07	0.68	--	--	--	--
Sweetheart	1996	14	6.98	0.20	1996	1	3.68 [2/]	--
Tahltan	1996–1998	20	11.19	0.68	1996–1997	2	9.04 [3/]	0.53
Tatsamenie [1/]	1997–1998	10	8.29	0.26	1997	1	3.68 [3/]	--
Trapper [1/]	2005	3	6.12	0.75	--	--	--	--
Tuya	1998	5	8.64	0.21	1998	1	4.81 [3/]	--

1/ glacial lakes
2/ sample collected in September
3/ Samples collected in June due to May ice conditions

Appendix C.–Lead-210 sediment dating analysis results from Tatsamenie, Little Trapper and Trapper lakes

Tatsamenie Lake			Little Trapper Lake			Trapper Lake		
Depth (cm)	Pb-210 (Bq/g)	Precision 1 SD (%)	Depth (cm)	Pb-210 (Bq/g)	Precision 1 SD (%)	Depth (cm)	Pb-210 (Bq/g)	Precision 1 SD (%)
0.0	0.089	3.6	0.0	0.126	3.4	0	0.112	4.6
3.5	0.068	3.8	5.0	0.100	5.4	4	0.079	4.9
8.0	0.099	3.8	8.0	0.044	7.3	8	0.052	7.2
11.5	0.094	5.9	12.0	0.041	8.6	12	0.055	8.2
15.5	0.055	7.3	16.0	0.030	5.6	16	0.045	7.9
19.5	0.054	7.4	20.5	0.021	7.4	20	0.026	7.3
23.5	0.058	6.2	24.0	0.020	7.9	24	0.026	8.0
27.5	0.052	7.1	28.0	0.025	6.5	28	0.025	8.0
30.5	0.052	6.2	32.0	0.024	6.1	32	0.029	8.0
35.5	0.052	6.2	36.0	0.017	9.2	36	0.025	8.0
39.5	0.046	7.3	40.0	0.021	7.9	40	0.028	7.2
48.0	0.050	8.0	44.0	0.018	6.6	44	0.025	7.9
56.0	0.048	6.7	50.0	0.015	7.5	48	0.027	7.5
64.0	0.041	8.0	58.0	0.021	6.6	52	0.024	8.6
172 [1/]	0.042	8.3	165.0	0.021	10.2	60	0.023	12.1
180 [1/]	0.050	11.9	170.0	0.023	10.0	161	0.018	8.8
--	--	--	--	--	--	178	0.018	15.3

1/ depths collected from Core 2

Appendix D.–Observed sockeye salmon wet weights from Canadian transboundary river and Alaskan lakes. (SD = standard deviation).

Lake	Geographic Location	Sampling year(s)	number of fish sampled (n)	mean weight (kg)	SD
Auke	SE-Alaska	1974–1975	726	1.98	0.93
Benzemen	SE-Alaska	1996, 1998	--	1.21[2/]	--
Chilkat	SE-Alaska	1997	3,017	2.40	0.82
Chilkoot [1/]	SE-Alaska	1997	2,162	3.39	0.60
Coghill [1/]	PWS-Alaska	1998–2005	--	2.91[3/]	--
Crescent [1/]	SE-Alaska	2007	131	2.66	0.89
Crescent [1/]	Cook Inlet-Alaska	1969–2006	--	2.79 [4/]	--
Falls	SE-Alaska	1981–1982	1,533	2.05	0.44
Hugh Smith	SE-Alaska	1980–1982	5,197	2.90	0.68
Kanalku	SE-Alaska	2007	207	1.73	0.42
Klag Bay	SE-Alaska	2001–2003	2,200	1.89	0.61
Kook	SE-Alaska	1994–1995	2,611	1.92	0.50
Kutlaku	SE-Alaska	2006	498	1.71	0.41
Little Trapper [1/]	Canada-Taku River	2005–2006	1,500	2.19	0.91
McDonald	SE-Alaska	1981	1,078	3.43	0.52
Redoubt	SE-Alaska	1980–1983, 1995	4,706	2.10	0.68
Sitkoh	SE-Alaska	1996	614	2.66	0.61
Speel	SE-Alaska	1996–1999	1,029	2.60	0.82
Tahltan	Canada-Stikine River	2006	400	1.63	0.54
Tatsamenie [1/]	Canada-Taku River	2005-2006	1,500	2.39	0.65
Tumakof	SE-Alaska	2002-2004	1,552	2.36	0.62
Windfall	SE-Alaska	1997	779	2.85	1.02

1/ Glacial lakes

2/ mean weight from Necker Bay commercial harvest data
(D. Gordon, ADF&G, personal communication)

3/ mean weights from Coghill commercial harvest data
(B. Lewis, ADF&G, personal communication)

4/ mean weights from Crescent commercial harvest data
(P. Shields, ADF&G, personal communication)

Appendix E.–Observed total spring phosphorus (CTPsp) and Total spring nitrogen (TNsp) lake concentrations, calculated phosphorus and nitrogen additions resulting from sockeye salmon escapement and carcass decomposition in Canadian transboundary river lakes and glacial sockeye nursery lakes in Alaska.

Lake	Location	CTP_{sp} [1/] (kg)	Total Fish P [2/] (kg)	Total Fish P / CTP_{sp}	TN_{sp} (kg)	Total Fish N [2/] (kg)	Total Fish N / TN_{sp}
Chilkoot	NSE	650	3,264	5.0	59,348	20,995	0.35
Coghill	PWS	999	1,797	1.8	58,809	11,561	0.20
Crescent (SE)	NSE	119	127	1.1	18,886	814	0.04
Crescent (CI)	Cook Inlet	833	2,146	2.6	114,935	13,804	0.12
Farragut	NSE	963	--	--	23,240	--	--
Little Trapper	Canada-Taku	49	250	5.1	--	1,608	--
Tahltan [3/]	Canada-Stikine	253	567	2.2	37,535	1,627	0.04
Tatsamenie	Canada-Taku	1,246	158	0.1	--	1,016	--
Trapper	Canada-Taku	634	--	--	--	--	--

1/ Corrected TP average values for glacial lakes (Edmundson and Carlson 1998).

2/ Average P value for adult sockeye 0.384 % TP/fish-wet weight, average N value for adult sockeye 2.47% TN/fish wet-weight (Barto 2004)

3/ measured TPsp value is not corrected for turbidity and inorganic phosphorus because this is a clear lake.