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by

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ABSTRACT

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The Upper Adams River has an estimated 1.25 million m^2 of spawning grounds and Adams Lake has the potential to produce 26 million sockeye salmon (*Oncorhynchus nerka*) smolts but blockages, including a splash dam on the Adams River (1907 to 1922) and a slide at Hell's Gate on the Fraser River in 1913 resulted in the total elimination of the Upper Adams River sockeye salmon stock. In light of the previous abundant run and the unused capacity of the system, a long term effort has been made to rebuild the sockeye run to the Upper Adams River. This included egg and fry transplants from 1949 to 1984 resulting in increasing run sizes every four years (most Adams sockeye mature at age-4) until 1988 (7,000). In 1992 the run was considerably smaller (3,000) and a renewed effort was made to enhance the offspring of the 1992 brood year.

Reduced exploitation rates (19%) in 1996 resulted in 25,000 sockeye spawners. Fish culture and fry release programs in 1992 and 1996 used native stock from both the Upper Adams River and nearby Momich River system, releasing fry into the river and after net pen rearing, into the north end of Adams Lake. In 1997, 1.3 million fry were released into the river and lake. In addition to the fry release project, the lake was fertilized in 1997 to promote the lake growth and subsequent survival of sockeye in the lake and marine environments. An average of 3 mg P/m^2/wk and 48 mg N/m^2/wk were added to the lake from May to September, using a "front end" loading regime where the nutrients were added at a higher rate in June than in September. We applied two agricultural fertilizers by boat, ammonium nitrate (28-0-0) and ammonium polyphosphate (10-34-0). Particulate C and P were higher in the fertilized year and the year following than in a reference year 1986. Chlorophyll concentrations were highest in 1997 but macrozooplankton showed no significant difference between years.

Our analysis, based on known sockeye escapements, length frequency analysis, and the levels of marine Sr in the otolith cores of juvenile *O. nerka*, determined that reference year samples were virtually all from lake resident kokanee, making between year size comparisons of trawl caught fall fry invalid. However, migrating smolts from the 1996 brood year were 1 g larger (3.6 g) than smolts from the 1992 brood year, which is expected to result in increase marine survival. Comparisons of adult returns to the Upper Adams River from the 1980 cycle brood years with co-migrating stocks to other nearby rivers, indicates increased abundance due to restoration efforts, although the sample size is insufficient for statistically significant comparisons.

RÉSUME

Hume, J.M.B., K.F. Morton, D. Lofthouse, D. MacKinlay, K. S. Shortreed, J. Grout, and E. Volk. 2003. Evaluation Of Restoration Efforts On The 1996 Upper Adams River sockeye salmon run. Can. Tech. Rep. Fish. Aquat. Sci. 2466: 57 pp.

On estime à 1,25 million m^2 la superficie des frayères du cours supérieur de la rivière Adams, et on considère que le lac Adams a le potentiel de produire 26 millions de smolts de saumon rouge (*Oncorhynchus nerka*), mais des blocages, notamment la présence (de 1907 à 1922) d'un barrage par éclusées sur la rivière Adams et un glissement de terrain survenu à Hell's Gate, sur le Fraser, en 1913, ont complètement éliminé le stock de saumons rouges du cours supérieur de la rivière Adams. Étant donné l'abondance historique de la remonte et la capacité inutilisée du système, on s'efforce depuis longtemps de rétablir la remonte de saumons rouges du cours supérieur de la rivière Adams. On a notamment transplanté entre 1949 et 1984 des œufs et des alevins, ce qui a fait apparaître une remonte plus abondante tous les quatre ans (la plupart des saumons rouges de l'Adams atteignent la maturité sexuelle à l'âge de 4 ans) jusqu'en 1988 (7 000 saumons). En 1992, la remonte a été considérablement plus faible (3 000 saumons), et on a renouvelé les efforts pour accroître la progéniture des reproducteurs de 1992.

La réduction des taux d'exploitation (19 %) en 1996 a permis la remonte de 25 000 géniteurs. Les programmes de salmoniculture et de lâchers d'alevins en 1992 et 1996 ont eu recours à des poissons indigènes du cours supérieur de la rivière Adams et du réseau voisin de la Momich; les alevins ont été lâchés dans la rivière après avoir été élevés en parcs de filet dans la partie nord du lac Adams. En 1997, 1,3 million d'alevins ont été libérés dans la rivière et le lac. Pour compléter le projet de repeuplement, on a fertilisé le lac en 1997 pour favoriser la croissance et la survie ultérieure des saumons rouges dans le milieu lacustre et le milieu marin. En moyenne, on a déversé dans le lac, entre mai et septembre, 3 mg P/m^2/semaine et 48 mg N/m^2/semaine, avec un pic dans le régime de charge, les quantités déversées étant plus fortes en juin qu'en septembre. Nous avons appliqué par bateau deux fertilisants agricoles, du nitrate d'ammonium (28-0-0) et du polyphosphate d'ammonium (10-34-0). Les formes particulaires de C et de P étaient plus abondantes l'année de la fertilisation et l'année suivante que l'année de référence, 1986. Les concentrations de chlorophylle étaient au maximum en 1997, mais on n'observait aucune différence notable dans le macrozooplancton d'une année à l'autre.

Notre étude, basée sur les échappées connues de saumons rouges, l'analyse de la fréquence des longueurs et les concentrations de Sr dans les centres des otolithes des *O. nerka* juvéniles, fait ressortir que les échantillons de l'année de référence provenaient presque tous de kokanis résidant dans le lac, ce qui invalidait toute comparaison interannuelle de la taille des alevins d'automne capturés au chalut. Toutefois, les smolts en migration de la classe 1996 étaient plus gros de 1 g (3,6 g) que ceux de la classe 1992, se qui devrait amener une hausse de la survie en mer. Des comparaisons des retours vers le cours supérieur de la rivière Adams d'adultes issus de la classe du cycle de 1980 avec des stocks co-migrants des rivières avoisinantes

révèlent une augmentation de l’abondance due aux efforts de rétablissement, mais la taille de l’échantillon est insuffisante pour permettre des comparaisons statistiquement significatives.

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INTRODUCTION

At the beginning of the 2Oth century, spawning sockeye salmon (*Oncorhynchus nerka*) were reportedly abundant in all tributaries of Adams Lake, a potentially major sockeye spawning and rearing area of the Fraser River. While stocks were not enumerated precisely at the time, J. P. Babcock (Commissioner of Fisheries for British Columbia) reported that in 1901, 1905 and 1909 every tributary to Adams Lake, including the 75 km of the Upper Adams River below Tumtum Lake, was crowded with spawning sockeye salmon (reported in Roos, 1991, Fig. 1). A subsequent series of impediments to fish passage resulted in the elimination of this run grouping. These impediments included a splash dam in the Adams River just below the lake (1907 to 1922) and the slides at Hell's Gate (1913 and 1914) caused by railway construction in the Fraser Canyon (Ricker 1987, Fig. 1). Thompson (1945) attributed most of the loss to the Hell's Gate slide as there were virtually no observed spawners in the Upper Adams River in that or subsequent years.

This report describes and evaluates the 1996 and 1997 fish culture and nutrient restoration efforts used to enhance and restore the Upper Adams River sockeye population. Evaluation of the releases and the nutrient additions were conducted by limnological sampling, acoustic and trawl surveys of the lake rearing fry, smolt sampling, and examining of freshwater growth patterns on the scales of returning adults. Results from the 1996 brood year are compared with information from other years to examine the effectiveness of the restoration techniques.

BACKGROUND

ADAMS LAKE SOCKEYE

Adams Lake sockeye spawn in the Upper Adams River, Momich River, Cayenne Creek, Pass Creek, and some lakeshore areas. The Upper Adams River is by far the largest with 1.25 million m² of spawning grounds in the 75 km of river below Tumtum Lake (Williams, 1987). There are spawning areas in about 0.5 km of the Momich River above Little Momich Lake and below Momich Lake and another 300 m in Cayenne Creek, a tributary to the Momich River above Momich Lake. Fry from Cayenne Creek may rear in Momich Lake as sockeye fry were reported there in the past (Mueller and Enzenhofer 1991). There are also limited spawning areas in Pass Creek and along the southern lakeshore near the outlet.

Sockeye fry from all of these spawning locations (except possibly Cayenne Creek) rear in Adams Lake for one year before smolting and migrating to the ocean. Adams Lake is large (129 km²) and is potentially a major juvenile sockeye nursery lake. Based on its current productivity and the primary production rearing capacity model of Hume et al. (1996) the lake has the potential to produce 26 million 4.5 g sockeye smolts, equivalent to the offspring of about 500,000 spawning adults (Shortreed et al. 2001).

Adams Lake sockeye spawning runs have returned in two timing groups. The "Early Summer run" spawns from late August to mid September while the "Late Shuswap" run spawned from mid October to early November (DFO data on file). The large runs of 1901, 1905 and 1909 were in the Early Summer group. From the start of numerical surveys in 1938 until 1953 there were no observed spawners in the Upper Adams River. Some late run sockeye were observed (including an extraordinary 200,000 shore spawners in 1942) but these were usually in the same year as the dominant late run to the lower Adams River (>1.5 million) and did not become established (Fig. 2). The Late Shuswap run is still less than 3,000 spawners in any of the tributaries and less than 7,000 lake spawners - even during the dominant spawning year on the lower Adams River. Due to restoration efforts, the early run Upper Adams River sockeye stocks have been slowly rebuilding and reached 71,000 spawners in 2000 (Fig. 2).

HISTORICAL REBUILDING EFFORTS

The International Pacific Salmon Commission (IPSFC) attempted to restore the early summer sockeye run to the Upper Adams River through a series of 14 egg transplants and 4 fry transplants from 1949 to 1984 (Roos, 1991). Almost 10 million eyed eggs and 271,000 fry were transplanted from the Seymour and Taseko river stocks between 1950 and 1976 (Williams 1987, Table 1, Fig. 1). None of these transplants resulted in substantial returns to the Upper Adams River (Fig. 3).

In 1980, sockeye spawners in Cayenne Creek were used as brood stock, and in 1981, a total of 772,000 fry from this stock were released in two groups into the Upper Adams River (Table 1). The 334,000 early emerging fry were 26.3 mm on release while the 393,000 later emerging fry were 27.5 mm (Williams 1987). An additional estimated 1,152,000 wild eggs were produced in the river. Total returns from these various egg sources were estimated to be 13,149 with 3,502 escaping the fishery to spawn.

In 1984, two groups of eggs were taken for release the following year. The larger group was a cross between eggs from Cayenne Creek females and sperm from Upper Adams River males. A smaller group of 48,000 eggs were taken from Upper Adams River spawners. Four hundred thousand of the hybrid eggs and all of the pure Upper Adams River eggs were placed into a prepared gravel bed in the Upper Adams River, at the eyed egg stage (Williams 1987) and were allowed to mature and emerge naturally. The remainder of the hybrid eggs were incubated in an upwelling gravel incubation box. A total of 393,000 fry were released from the incubation boxes. On emergence, 60,000 fry were released to the Upper Adams River and 33,000 were released into Adams Lake. The remaining 300,000 were reared for 28 days and released to the river at 28.7 mm. There was an estimated 12,378 returns in 1988 from these various releases with a spawning escapement of 7,169 (Table 1).

In 1988, just over 1.0 million sockeye eggs were taken from the Upper Adams River, along with 1.4 million eggs from the Momich/Cayenne river system (Table 2). They were placed into a new pilot facility the Department of Fisheries and Oceans (DFO) constructed near the mouth of the Upper Adams River. In hopes of matching

natural development rates, the facility operated on surface water from a river supply. Unfortunately, groundwater intrusion into a water collection point resulted in increased water temperatures and accelerated development and mid-winter ponding. Although 1.5 million, 0.2-gram fry were released in May of 1989, it was felt that unfavourable rearing conditions (very cold/silt laden water) resulted in poor quality fry that would have had limited survival potential.

In 1992, given concerns as to the suitability of the pilot site for future restoration, DFO's Clearwater Hatchery was used as the incubation/early rearing location. From an estimated combined escapement of just over 5,000 adults (Upper Adams River and Cayenne Creek), 750,000 eggs were collected. These eggs were incubated on virus-free groundwater at the Clearwater facility. Engineering modifications allowed for water recirculation through numerous outdoor rearing containers, resulting in winter cooling of the incubation supply and more suitable development rates. During primary incubation, severe problems associated with “soft shell condition” were experienced, resulting in a survival rate to ponding of only 47%. Soft shell is a bacterial infection of the egg shell that often results in premature "hatch" due to weakening/erosion of the outer membrane (Cousins and Jensen 1994). In early May of 1993, 105,000 - 1.9 gram fry were released into the Upper Adams River, while 211,000 were transferred to netpens in Adams Lake for final rearing. In late May, at an average weight of 2.5 grams, the net pen reared fry were released.

Reduced fishing effort was used as an additional attempt to improve spawning escapements to the Upper Adams River. Typically, the Upper Adams River sockeye was exploited at rates of 70 to 80%. Exploitation was reduced on the 1988 run to 42% of the total run, leaving 7,200 spawners. Unfortunately, the exploitation rate was considerably higher on the1992 run (82%) resulting in only 3,000 spawners (Fig. 3).

1996 RESTORATION EFFORTS

The low returns in 1992 resulted in a concerted effort to continue restoration of the stock by enhancing the offspring of this cycle year and subsequent adult returns through a combination of reduced fishing, restorative hatchery releases and nutrient restoration of the lake nursery area. The exploitation rate on the 1996 returns was kept very low at only 19%, leaving a spawning population of 25,000 sockeye in the Upper Adams River (PSC 1999). Further restoration activities were applied to the offspring of the 1996 spawners to increase the egg to fry survival and the growth and survival of the lake rearing fry. First, an egg-take/fish culture project used broodstock from the Upper Adams and Momich rivers to incubate and rear 1.3 million fry. Second, nutrient additions to Adams Lake were used to increase freshwater growth and/or survival. Increased smolt size has been shown to result in increased marine survival (Bradford et al. 2000, Koenings et al. 1993). Third, the exploitation rate was again low at 29% resulting in 72,000 spawners in 2000 (Fig. 3). This rest of this paper describes and evaluates these efforts.

STUDY LAKE

PHYSICAL DESCRIPTION

Adams Lake is located (51°15' N, 119°30' W) in the south-eastern portion of the Fraser River drainage basin, at an elevation of 407 m on the Shuswap Highlands of the Interior Plateau. It is oriented in a north-south direction with the Upper Adams River, the lake's largest tributary, at the northern end and the Adams River, the lake's outlet, at the southern end (Fig. 1). The lake also has two smaller tributary rivers. The Momich River drains three small lakes and enters the lake on the east shore approximately 10 km from the Upper Adams River. Pass Creek flows into the south-western side of the lake approximately 19 km from the lake outlet. The lake's drainage basin covers 3,080 km^2 in the interior western hemlock and interior Douglas fir biogeoclimatic zones of British Columbia. The climate is continental, with cool winters and warm summers. Mean annual precipitation ranges from 100 cm in the northern portion of the watershed to 40 cm at the south (outlet) end of the lake (Farley 1979). Adams Lake is large and deep with a surface area of 129 km^2, mean depth of 169 m and water residence time of 10 years. While no large residential developments occur adjacent to the lake, there is a small community and a commercial resort near the lake outlet. Substantial logging activity has occurred within the watershed with log dumping, storage and transport down the lake to a sawmill located at the outlet. Some agricultural activity occurs at the southern end of the lake, mostly along Pass Creek.

FISH COMMUNITY

Previous midwater trawls in Adams Lake from 1975 to 1978 captured only *O. nerka* and 2 unidentified juvenile fish (Mueller and Enzenhofer 1991). Besides sockeye salmon, the tributaries of Adams Lake support anadromous runs of chinook salmon (*O. tshawytscha*) and coho salmon (*O. kisutch*) which rear in the lake and its tributaries (NuSEDS V1.0 (http://sci.info.pac.dfo.ca/sein_prod/Default.htm)). There are few available reports on resident fish in Adams Lake but kokanee (*O. nerka*), mountain whitefish (*Prosopium williamsoni)*, and rainbow trout (*O. mykiss*) have been recorded (Fisheries Information Summary System (FISS), http://www.bcfisheries.gov.bc.ca/fishinv/fiss.html). One million rainbow trout eggs and 250,000 fry were stocked from 1939 to 1950.

In addition to these species, Shuswap Lake and the South Thompson River, downstream of Adams Lake, have records of pink salmon (*0. gorbuscha*), cutthroat trout (*O. clarki*), Dolly Varden (*Salvelinus malma*), lake trout (*S. namaycush*), lake whitefish (*Coregonus clupeaformis*), pygmy whitefish (*Prosopium coulteri*), prickly sculpin (*Cottus asper*), redside shiner (*Richardsonius balteatus*), northern pikeminnow (*Ptychocheilus oregonensis*), leopard dace (*Rhinichthys falcatus*), longnose dace (*R. cataractae)*, burbot (*Lota lota*), common carp (*Cyprinus carpio)*, largescale sucker (*Catostomus macrocheilus*), longnose sucker (*C. catostomus*), lake chub (*Couesius plumbeus*), peamouth chub (*Mylocheilus caurinus*), and white sturgeon (*Acipenser transmontanus*). Many of these species are likely to occur in Adams Lake.

METHODS

HATCHERY NET PEN REARING AND MARKING

The 1996 brood fish culture project collected 490 females from the Upper Adams River and 175 females from the Momich River, resulting in the placement of 1.98 million eggs into incubators at Clearwater Hatchery. Following the "soft shell" problems that were experienced with the 1992 brood, prophylactic treatments of both Cloramine-T and iodophor were applied to all 1996 brood eggs collected. Despite these treatments, significant mortalities still occurred, resulting in the ponding of only 1.36 million fry. During early rearing, mass marking of all fry was attempted through the use of strontium chloride (Sr/Cl) baths (Schroder et al. 1995). This entailed a four-hour soak in a 1,000 ppm Sr/Cl solution. In hopes of distinguishing differing strategies, fry destined for the "river release" received one mark, while fry destined for the "lake pen release" received two marks. At the end of April, 1997, 604,000 fry, weighing an average of 1.9 g, were released into the Upper Adams River. In late May, following four weeks of net pen rearing, 698,000 fry (mean = 2.3 g) were released into the northern end of Adams Lake (Table 2).

LIMNOLOGY

Limnological data were collected from Adams Lake in 1986 (Nidle et al. 1990), 1997 (the fertilized year), and 1998. We sampled the lake monthly from May to October (n = 6) during 1986 and 1998 and from April to October (n = 7) in 1997. Each year we sampled three locations along the lake's longitudinal axis (Fig. 1). Stations 1 and 2 were located within the fertilizer application zone and Station 3 was located 10 km down lake from the southern extent of the fertilized area.

Lake and watershed areas were calculated by digitizing the lake shoreline and watershed boundary from 1:50,000 topographic maps using a Kurta electronic digitizer (Model XLC 3648). Lake volume was determined by digitizing depth contours on a bathymetric map of the lake.

We obtained 1986, 1997, and 1998 mean monthly air temperature and total monthly precipitation data for Kamloops (approximately 60 km south-east of Adams Lake) from Environment Canada's Climate Services, Vancouver, B.C. (data on file). We obtained 1986 and 1998 Adams River monthly discharge data from the Environment Canada, National Water Archive Hydat database. However, 1997 discharge data from the Adams River were not available so we calculated monthly rates using South Thompson River discharge (measured at Chase, Fig. 1). The South Thompson River drains the Shuswap watershed which includes the Adams Lake system. We used the regression of Adams River long-term discharge rates for years 1971 to 1995 on South Thompson River discharge rates ($y = 2.37x$; $r^2 = 0.98$; $P < 0.001$) to calculate Adams River 1997 monthly discharge (Fig. 4).

Temperature and conductivity profiles from the surface to 100 m were obtained on most occasions with an Applied Microsystems conductivity, temperature and depth

probe (Model STD-12). Otherwise, we used a Cole-Parmer hand-held thermistor to a depth of 30 m. Isolines were plotted by the SAS procedure Gcontour (SAS Institute Inc., 1990) from a grid of interpolated and smoothed unscaled data (Akima 1978). We calculate a modified Schmidt stability function (Costella et al. 1983) using temperature and conductivity data at each station to quantify water stability to 50 m depth. Li-Cor data loggers (model LI-1000) equipped with quantum sensors (model LI-192S) were used to measure photosynthetic photon flux density (PPFD: 400-700 nm) from the surface to below the euphotic zone (1% of surface intensity) and to calculate vertical light extinction coefficients. A 22-cm diameter white Secchi disk was used to measure water transparency.

We used an opaque Van Dorn bottle sterilised with 95% ethanol to collect all water samples. Water was collected at each station between 08:00 and 12:00 PST from three depths within the euphotic zone in 1986 and from 5 depths (which we mixed in a 20-L Nalge Lowboy carboy to provide an integrated sample) in 1997 and 1998. From the integrated samples (discrete samples in 1986), we carried out replicate analyses of nitrate, total phosphorus, particulate phosphorus, total dissolved solids, total chlorophyll, phytoplankton, picoplankton, and bacterioplankton. In 1998, phyto-, pico-, and bacterioplankton were sampled at station 2 only. During 1997 and 1998, we added replicate analyses of silica, particulate carbon, and particulate nitrogen. In addition to sampling the euphotic zone, we collected hypolimnetic water at each station from a depth of 40 m for chlorophyll, nitrate, and total phosphorus analyses.

Chemical analyses were carried out according to the methods given in Stephens and Brandstaetter (1983) and Stainton et al. (1977). For total phosphorus determination, clean screw-capped test tubes were rinsed with sample water, filled, capped, stored at 4°C, and later analyzed using a molybdenum blue method after persulfate digestion. Water samples for the remaining nutrient analyses and chlorophyll determinations were kept cool and dark and filtered within 2-4 h. Water for dissolved nutrient analyses was filtered through an ashed 47-mm diameter Micro Filtration Systems (MFS) borosilicate microfiber filter (equivalent to a Whatman GF/F filter). Each filter was placed in a 47-mm Swinnex filtering unit (Millipore Corp.), rinsed with distilled, deionized water (DDW), and then rinsed with approximately 50 mL of sample. An acid washed, DDW rinsed borosilicate glass bottle was rinsed and filled with 100 mL of filtered water, capped, stored at 4°C in the dark, and later analyzed for nitrate (Stainton et al. 1977). An additional 100 mL of sample was filtered into a clean, rinsed polyethylene bottle, stored at 4°C in the dark, and later analyzed for soluble reactive silicon and total dissolved solids. For determination of particulate phosphorus concentration, we filtered 1-L of water through an ashed 47-mm diameter MFS filter, placed the filter in a clean scintillation vial, and later analyzed it using the method of Stainton et al. (1977). For total chlorophyll analysis, we filtered 250 mL of water through a 47-mm diameter, 0.45-µm Millipore HA filter Filters were folded in half, placed in aluminium foil dishes, and frozen. They were later analyzed using a Turner fluorometer (Model 112) after maceration in 90% acetone.

Water for bacterioplankton enumeration was collected at all three stations in 1986 and 1997 but only at Station 2 in 1998. Samples were stored in sterile scintillation vials and preserved with two drops of formaldehyde. Bacterioplankton were counted using the DAPI method described by Robarts and Sephton (1981). Eight random fields were counted on each filter and the counts converted to numbers/mL. Occasional blanks were prepared to check for a significant background bacteria count in the staining solution and rinse water.

We collected water for nano- and micro- phytoplankton enumeration at all three stations in 1986 and 1997 but only at Station 2 in 1998. Samples were kept in opaque 125-mL polyethylene bottles and preserved with 1-mL of Lugol's iodine solution. A subsample was placed in a settling chamber of 7-, 12-, or 27-mL capacity and after settling overnight, cells were identified to genus or species and counted with a Wild M40 inverted microscope (187.5X and 750X magnification) equipped with phase contrast optics.

Phototrophic picoplankton (cyanobacteria and eukaryotic algae <2 µm in diameter) were enumerated using the method described by MacIsaac and Stockner (1985). We filtered 15 mL of sample water through a 0.2-µm Nuclepore filter counter-stained with Irgalan black. Filters were dried and store in the dark. After rehydrating the filters we enumerated the samples using a Zeiss epifluorescence microscope (1250X magnification) equipped with a 397-nm longwave-pass exciter filter and a 560-nm shortwave-pass exciter filter, a 580-nm beam-splitter mirror and a 590-nm longwave-pass barrier filter.

In addition to chemical analyses, we measured *in situ* photosynthetic rates (PR) at every station and sampling date in 1997 and 1998. We collected water from 5 depths within the euphotic zone and two below it. We filled two light and one dark 125-mL glass bottles with water from each depth. We then inoculated each bottle with approximately 137 kBq of a ^{14}C-bicarbonate stock solution, and incubated at the original sampling depth. Incubations lasted 1.5 - 2 h between 09:00 and 12:00. At the same time, we inoculated three scintillation vials containing 0.5 mL of Scintigest (Fisher Scientific) stock to determine activity of the stock solution. After incubation, bottles were placed in light-proof boxes and transported to the field laboratory where filtration started <2 h after incubation stopped. We filtered each PR sample through a MFS glass fibre filter (equivalent to a Whatman GF/F). Filters were placed in scintillation vials containing 0.5 mL of 0.5 N HCl and lids were left off the vials for 6-8 hr to release excess ^{14}C tracer. All samples were counted in a Packard Tri-Carb 4530 liquid scintillation counter after we added 10 mL of Scintiverse II (Fisher Scientific) to each scintillation vial. We determined machine counting efficiency with quench series composed of the same scintillation and filters used for our samples (Koenings et al. 1987) and calculated hourly PR with Strickland's (1960) equation. We converted PR from hourly to daily rates using light data collected with a Li-Cor Model LI-1000 datalogger and Li-Cor 190SA quantum sensors located near the lake.

Total alkalinity (mg $CaCO_3$/L) and pH of water collected along with PR samples was determined with a Cole-Parmer Digi-Sense pH meter (Model 5986-10) and Ross combination electrode following the standard potentiometric method of APHA (1980). We calculated dissolved inorganic carbon (DIC) concentrations indirectly from pH, temperature, total dissolved solids, and bicarbonate alkalinity.

In 1986, we collected replicate (n = 2) zooplankton samples at every station with a 100-µm mesh SCOR net (mouth area = 0.25 m^2) hauled vertically from 50 m to the surface. We collected replicate 30-m vertical samples at each station in 1997 and 1998 with a 160-µm mesh Wisconsin net (mouth area = 0..25 m^2). During these later years we collected SCOR net samples at Station 2 to compare sampling efficiency with 1986 data. All samples were placed in 125-mL plastic bottles and preserved in a sucrose-buffered 4% formalin solution (Haney and Hall 1973). Zooplankton (except rotifers) were counted, identified to genus or species using Balcer et al. (1984) and Pennak (1978), and sized with a computerized video measuring system (MacLellan et al. 1993). Measurement of body length was carried out as described by Koenings et al. (1987). Zooplankton biomass was calculated with species-specific length-weight regressions adapted from Bird and Prairie (1985), Culver et al. (1985), and Yan and Mackie (1987).

Seasonal averages of data collected at each station (with the exception of PR) were calculated as time-weighted means from the first sampling date in April or May to the final date in October. Total seasonal PR at each station was calculated by integrating under the curve of daily PR, with the growing season defined as May 1 to October 31 (we assumed that PR was 0 on the first and last days of the growing season). Seasonal average PR was calculated by dividing total seasonal PR for each station by the length of the growing season. Whole lake averages and total seasonal PR are simple means of the three stations. We tested whole-lake seasonal averages of various limnological variables for statistically significant differences between years using one way analysis of variance (ANOVA). We used the seasonal averages at each station as the sample data (n = 3 for each year).

FISH

Sockeye Escapement and Returns

Annual sockeye spawner abundances (escapements) are estimated throughout the Fraser River watershed by DFO, including the Adams Lake spawning areas (T. Cone, DFO, personal communications). Methodologies used in each spawning area vary depending on expected run size and are described in Schubert (1998). Estimates of the abundance of males, jacks and females are made for each stock as well as an estimate of effective female spawners (EFS, numbers of females that have successfully spawned). Escapements presented here are from NuSEDS V1.0 (http://sci.info.pac.dfo.ca/sein_prod/Default.htm). Adult catch data was supplied by the Pacific Salmon Commission (M. Lapointe, data on file).

A key question associated with restoration projects is whether there was a net increase in adult returns per spawner associated with the activity. However, effects of

restoration may be masked if restoration activities coincide with changes in survival associated with other unrelated environmental changes, such as marine survival. We controlled for unrelated environmental changes by comparing enhanced populations to non-enhanced populations with similar life histories. As a control, we devised the Early Summer Index comprised of the EFS to Fennell, Raft, Scotch and Seymour rivers. These stocks migrate with the Upper Adams River sockeye during the early summer period.

Given the relatively limited data for Upper Adams River sockeye it appeared unlikely that we could determine whether there was a statistically significant restoration effect. However, we estimated the total returns per EFS for Upper Adams River and the Early Summer Index for comparison purposes. In addition, we computed a time series of survival for the Upper Adams River population using a standard Ricker model:

$$(1)\quad \log\left(R_{it}/S_{it}\right)=a_i+b_iS_{it}+error$$

where R_{it} is the total abundance of returns from S_{it} effective female spawners from population i in brood year t; a_i and b_i are stock-specific intercept and slope parameters. The residual variation between the model fit and the observed log (R/S) indicates annual variations in survival (and also measurement error). Measurement errors are associated with difficulties in estimating recruitment of smaller runs because of errors in assigning fish caught in multi-stock fisheries. In addition, larger errors are associated with spawning escapement estimates for small runs because sampling programs for small runs are usually much less intense. For the Upper Adams River population, we only show the data points for the dominant 1996 cycle, because estimated escapements on the other cycles were very small. For the control stocks, we used weightings (see Bradford et al. 2000) to decrease the influence of potentially unreliable estimates associated with small run sizes.

For the control stocks, we computed a time series of survival using a modified Ricker model:

$$(2)\quad \log\left(R_{it}/S_{it}\right)=a_i+b_iS_{it}+C_t+error$$

where all parameters are defined as in (1) and C_t is a brood year survival deviate common to all stocks in the group. C_t (called the Early Summer Index) is an estimate of the annual variation in survival common to all of the stocks in the group. Common variation in survival in these stocks likely reflects processes that impact all of the stocks similarly, such as during smolt migrations in the Fraser River or marine residency. We compared the Early Summer Index to the time series of survival deviates for Upper Adams River to illustrate the potential benefits of restoration relative to variation common to all stocks. This approach removed the effect of spawner abundance on estimated survival and allowed comparisons to be made across stocks.

In Lake Fish Collection and Population Estimates

The limnetic fish populations of Adams Lake were surveyed using midwater trawling (1975 - 1978, 1997, and 1998) and hydroacoustics (1997 and 1998 only). Prior to the surveys, we divided the lake into 3 trawling sections. Within each section, 3 to 4 evenly spaced hydroacoustic transects were established for a total of 11 transects (Fig. 1). All sampling was done during the hours of darkness when fish were dispersed near the thermocline and within the working range of the trawl and hydroacoustic system (McDonald and Hume 1984; Burczynski and Johnson 1986; Levy 1990).

Midwater fish were collected with a 3 x 7-m midwater trawl to determine species and age composition of the limnetic fish community (Enzenhofer and Hume 1989). Trawls were from 5-30 minutes in duration and were made at locations and depths (11 - 35 m) suggested by fish targets on the chart recorder. In most years, all captured fish were anaesthetized and killed upon capture with an overdose of anaesthetic and preserved in 10% formalin. Fish were kept in formalin for at least one month before lengths and weights were recorded. Age composition of *O. nerka* was determined from scales and from length frequency analysis. Species, age and target strength information (1990's) were used to apportion the acoustic fish density for each transect. Stomach contents from up to 20 *O. nerka* per trawl were examined in 1997 and 1998. Thirty to 40 fish per survey were preserved in alcohol in 1997 and 1998 for the determination of anadromous origin by the detection of Sr in the otolith core.

In 1997 and 1998 acoustic survey was conducted using a Biosonics 105 dual beam echosounder with a 420 kHz transducer producing a 6°/15° beam. Data were digitally recorded for later echo integration and *in situ* target strength estimation (Burczynski and Johnson 1986) using a Biosonics Echo Signal Processor with a model 221 echo integrator and a model 228 dual beam processor. Target strengths and mean backscattering cross sections of fish were determined at each transect from data collected at 40 log R (distance to target) and target density was determined from echo integration of data collected at 20 log R. Target strength and equipment scaling factors were used to scale the echo integration to provide an estimate of fish density in each transect.

Data from each transect within a trawling section were averaged to provide a mean estimate of density for each section. Mean density was multiplied by the surface area of the section to provide a population estimate for the section and then summed to provide a total population estimate for the lake. Mean lake density was calculated by dividing the lake population estimate by the total surface area. Variances were calculated for the density of each section and were then weighted by the square of the section area. The sum of the weighted variances was divided by the square of the lake area to provide a variance for the lake population estimate. In this paper we report 95% confidence limits.

STOCK IDENTIFICATION AND AGING

Sockeye / Kokanee Identification

Three techniques were used to age and identify the stock origin of *O. nerka* captured in the midwater trawls; length frequency, age analysis from scales, and elemental analysis of the otolith origin. All *O. nerka* were initially assigned to preliminary age classes based on groupings determined from a simple length frequency analysis. It was apparent from the observed size distribution that most fish were young of the year (age-0) and up to 20 scales were randomly taken from this group to confirm this age classification. Scales were also taken from up to 20 of the larger fish to determine their age. Ages from scales were then used to confirm ages from the length frequency analysis. If any discrepancies were found (very rarely) the scale aging was used. All scale aging was done by modifications of the methods described in Clutter and Whitesel (1956) (Shayne MacLellan, DFO, Nanaimo, personal communication)

O. nerka in Adams Lake are either anadromous sockeye or non-anadromous kokanee. Based on scale analysis of returning adults, all sockeye migrate from Adams Lake after one winter as age-1 smolts (Pacific Salmon Commission, Vancouver, data on file). We therefore assumed that all age-1 and older *O. nerka* captured in trawls during July and October were kokanee. Other than possibly size, there are no readily distinguishable physical differences between age-0 sockeye and age-0 kokanee (Wood and Foote 1990).

In the fall of 1997 and 1998, we therefore used the strontium/calcium ratios in the otolith core to determine the stock origin of age-0 and some older *O. nerka*. This technique is based on the premise that Sr levels in seawater are much higher than typically found in lakes (Kalish 1990; Rieman et al. 1994) and this is reflected in the microchemistry of the otolith core of anadromous and non-anadromous salmonids. The general principle is that the disparate Sr concentrations found in fresh and sea water are incorporated into developing ova during yolk deposition and then deposited in the embryonic otolith which begins growing well before hatching. Sr and Ca were measured in the otolith origin and on the otolith rim using a four-spectrometer JEOL model 733-electron microprobe (Volk et al. 2000). We did not collect appropriate samples in July of 1997 for this analysis but instead applied the ratio of age-0 kokanee to sockeye determined in October 1997 to the July samples.

Sockeye Diet

Stomach contents from up to 20 *O. nerka* per midwater trawl sample were examined in 1997 and 1998. To minimize bias caused by different digestion rates of prey, only fish captured in trawls made within 3 hours after the onset of darkness (approximate start of the most intensive feeding period) were included in the analysis. Samples consisting of the contents of 10 pooled stomachs (two samples/tow) were subsampled with a Folsom plankton splitter and enumerated with a computerized video measuring system (MacLellan et al. 1993). Relative volume of prey types in the

stomachs and an index of stomach fullness expressed as a percentage by volume were estimated using a technique modified from Hellawell and Abel (1971).

Sockeye Smolts

In the spring of 1994, 1992 brood year sockeye smolts leaving Adams Lake were collected through the operation of an "inclined plane trap" (IPT). By fishing on eight evenings between April 20 and May 5, 1994, a total of 218 smolts were captured, from which a random sample of 123 were retained.

In the spring of 1998, in an attempt to measure enhanced contribution to the smolt stage for the 1996 brood year, a number of sub-samples were obtained from the smolt migration. By fishing an IPT on thirteen evenings between April 15 and May 9, nearly 3,500 smolts were captured. From this total, a random sample of 270 smolts were retained. Weights and lengths were obtained from these samples prior to lab examination for the presence or absence of otolith marks. Given cost considerations, a smaller random sample (50) of the smolt's otoliths were examined for Sr marks. We used the same techniques as those described above for sockeye/ kokanee identification except that a transect was taken from the otolith centre to the outer edge.

FERTILIZER APPLICATION

Adams Lake was fertilized for 18 weeks in 1997 from May 18 to September 15 in order to provide extra nutrients to the lake during the rearing period of the juvenile sockeye from the 1996 brood. Fertilizer was applied weekly, by boat, in the northern half of the lake (Fig. 1). We assumed the prevailing current towards the outlet would resulted in mixing throughout most of the southern portions of the lake.

On average we applied 3 mg P/m^2 and 28 mg N/m^2 weekly, based on the surface area of the whole lake. We used a N: P mass ratio of 9:1 in order to discourage the growth of large colonial nitrogen-fixing cyanobacteria and promote the growth of phytoplankton within an edible size range (1-40 μm) for herbivorous zooplankton (Stockner and MacIsaac 1996).

We skewed the rate of nutrient addition by adding more fertilizer in the late spring and reducing summer loads. The object was to match phytoplankton production to the seasonal patterns of macrozooplankton populations (Stockner and MacIsaac 1996). Planned weekly P loading rates were low in May (1.4 mg P/m^2), increased to a high in June (5.6 mg P/m^2) and then decreased in steps until mid-September (Fig. 5). Actual rates were less than target rates on three occasions July 14, Aug 11, and September 1 due to mechanical problems.

We used a mixture of two agricultural grade fertilizers, urea ammonium nitrate (28-0-0) and ammonium polyphosphate (10-34-0). The formulae designate, in order, the per-cent-by-weight elemental composition of nitrogen (as N), phosphorus (as P_2O_5) and potassium. The nutrient mixture was safe to handle as it is only slightly alkaline, non-flammable, and non-volatile. While it is very corrosive to brass, it is non-corrosive

to most other metals (including aluminium). The fertilizer was supplied by Agrium Inc., Calgary Alberta.

Nitrogen (N) in the fertilizer is extracted from the atmosphere manufactured into urea, ammonia, and nitric acid. Nitric acid is neutralized with ammonia to form ammonium nitrate. Urea, ammonium nitrate, and water are combined to form the liquid nitrogen fertilizer. In this fertilizer, 50% of the N is present as urea and 25% each is present as ammonium and nitrate. This process is very clean and the product is virtually free of impurities. The phosphorus for the 10-34-0 is extracted from rock, concentrated to phosphoric acid and reconstituted into polyphosphate. This process does not remove all other elements from the mixture and therefore contains a small amount of impurities, some of which, such as heavy metals, could be toxic in concentrated form. Studies on rainbow trout by the manufacturer found a 96-hr LC_{50} >100 mg/L for both fertilizers (Agrium, 2001a, b). Another study reported 96-hr LC_{50}'s of 585 mg/L for the 28-0-0 and 1342 mg/L for the 10-34-0 (MacKinlay and Buday, 2002). Toxicity to the cladoceran *Daphnia magna* (48-hr) and growth inhibition to the green alga *Selenastrum capricornutum* were both over 1200 mg/L in the same study. MacKinlay and Buday (2002) also evaluated the in-lake concentration after application and concluded that the nutrients were dispersed quickly enough to avoid any potential toxicity to aquatic life.

The premixed nutrient solution was stored in a 36,800-L capacity storage tank located on the shore of Adams Lake to the west of Transect 5 (Fig. 1). The tank was fitted with an exterior sight glass so that the level of nutrient solution could be seen during transfer to the application vessel. The fertilizer was transported and distributed by a 12 m aluminium herring skiff (4-m wide) powered by a 225-hp Yamaha marine outboard engine. The nutrient solution was pumped directly into the central hold of the skiff which had aluminium bulkheads designed to hold batches of herring. The bulkheads reduced excessive movement of the nutrient solution in rough weather. The skiff could carry approximately 7 tonnes of nutrient mix, enough for a single application at the lowest nutrient loading rate. Higher weekly loads required 2 trips in a single day and the highest loads required 2 trips on 2 days each, 3 or 4 days apart within a single week.

Nutrients were dispersed along a 24-km path while proceeding north at 12 km/hr by pumping the nutrient solution into the propeller wash behind the boat using a Prime 1500 bilge pump (at approximately 42 L/min) connected to a flexible 1" diameter plastic hose. If making a single application in one day, a track equidistant from the east and west shores was followed. For two applications in a day, tracks were equidistant from each other and one of the shores. Position and velocity were monitored using a Garmin 120 Global Position System (GPS) receiver.

RESULTS AND DISCUSSION

CLIMATE AND DISCHARGE

Annual variation in lake productivity is often the consequence of annual variations in climate, including solar radiation, air temperature, wind, and precipitation. Air temperature affects water temperature thermal stability and consequently affects lake productivity. Precipitation affects river discharge rates and consequentially a lake's flushing rate. Flushing rate influences lake physics and trophic status. Shortreed et al. (2001) observed that lower productivity was often associated with faster flushing rates in British Columbia sockeye lakes.

Seasonal average air temperatures in the Adams Lake area were higher in 1998 than in either 1986 or 1997 (Fig. 4a). Meteorological data from Kamloops, B. C., approximately 60 km from Station 3 indicates that the average summer (May to October) temperature in 1998 was 18.3 ^{o}C, 12% higher than the nearly identical means of 16.2 ^{o}C in 1986 and 16.4 ^{o}C in 1997 (Climate Services, Environment Canada, Vancouver, B.C., Data on file).

Total precipitation was lower in 1998 and 1986 than in the treatment year of 1997. Precipitation from January to September in 1997 was 291 mm. It was only 18% lower in 1986 (240 mm) but 39% lower in 1998 (178 mm, Fig. 4b).

In the 3 years of this study, Adams River monthly discharge was lowest from January to April and highest in June (Fig. 4c). Similarly to precipitation, mean monthly discharge from January to September was 40% lower in 1998 (79 m^3/sec) than in 1987 (165 m^3/sec). Mean monthly discharge was also lower in 1986 (120 m^3/sec) but by only 33%.

LAKE PHYSICS

Seasonal average surface temperatures were warm relative to other sockeye rearing lakes in B.C. (Shortreed et al. 2001), ranging from 14.3^{o}C at Station 3 in 1997 to 19.2^{o}C at Station 2 in 1998 (Table 3). Average thermocline depths, which ranged from 7.0 m at Station 2 in 1998 to 8.6 at Station 3 in 1997, did not vary significantly (ANOVA, $P > 0.05$). However, average epilimnetic temperatures (range: 12.3 °C at Station 3 in 1997 to 15.5 ^{o}C at Station 2 in 1998) were significantly warmer (ANOVA, $P < 0.05$) in 1998 compared with 1997. In 1998, thermal stratification developed earlier and persisted longer which resulted a significantly higher stability function that year than in 1997 or 1986 (ANOVA, $P < 0.05$, Fig. 6, Table 3). There was also a sustained period in 1998 when summer epilimnetic temperatures exceeded 20^{o}C.

Lake water clarity was relatively high with seasonal average Secchi depths ranging from 6.4 m at Station 1 in 1997 to 9.4 m at Station 3 in 1986 (Table 3). Values were generally highest in spring and lowest in summer (Fig. 7). Euphotic zone depth ranged from 10.6 m at Station 1 in 1997 to 14.5 m at Station 2 in 1998 (Table 3). Though Secchi and euphotic zone depths were slightly lower in 1997 than in 1998 and

1986, differences were not statistically significant (ANOVA, $P > 0.05$). Apart from a sustained period in 1998 when summer epilimnetic temperatures exceeded 20 ^{o}C, Adams Lake, with stable thermal stratification, a warm epilimnion, a cool deep hypolimnion and clear water, provides a good physical habitat for rearing juvenile sockeye. Water clarity was not reduced by fertilizer application in 1997.

CHEMISTRY

Average pH was significantly lower during 1998 (pH = 7.0) than in 1997 (pH = 7.3) and 1986 (7.3) *(*ANOVA, $P < 0.05$,Table 4). Values ranged from 6.9 at Station 1 in 1998 to 7.4 at Station 3 in 1986 and were highest during the summer. Total alkalinity, total dissolved solids and dissolved silicate showed little seasonal variation and differences between years were not statistically significant (ANOVA, $P > 0.05$) (Table 4). Total alkalinity, which indicates the lake's buffering capacity, was low relative to most interior Fraser sockeye lakes but higher than most coastal sockeye lakes for which we have data. Values ranging from 18.5 mg $CaCO_3$/L at Station 1 in 1997 to 22.9 mg $CaCO_3$/L at Station 3 in 1986 suggest that Adams Lake would be more susceptible to acidification than nearby Shuswap Lake with an average total alkalinity of 35.7 mg $CaCO_3$/L (Horne and Goldman 1994; Wetzel 2001).

Nitrogen loading was relatively high in all years with average spring overturn nitrate concentrations ranging from 111 μg/L in 1986 to 91 μg/L in 1998 (Fig. 8). Furthermore, there was no evidence of nitrogen depletion with seasonal minimum epilimnetic concentrations ranging from 30 μg/L in 1986 to 20 μg/L in 1997 and 1998. Seasonal mean epilimnetic nitrate was significantly greater *(*ANOVA, $P < 0.05$) in 1986 (average = 77.1 μg/L) than it was in 1997 (average = 61.6 μg/L) and 1998 (average = 51.0 μg/L) (Table 4).

In 1986, spring overturn total phosphorous (TP) concentrations averaged less than 2.0 μg/L (Fig. 9). Spring overturn in 1997 was only slightly higher at 2.2 μg/L, but was almost 3 times higher in 1998, averaging 6 μg/L. Seasonal epilimnetic concentrations averaged only 1.6 μg/L in 1986 but were significantly higher in 1998 at 4.2 μg/L (Table 4; ANOVA, $P < 0.05$). Seasonal TP was not measured in 1997. These TP concentrations indicate that the trophic status of Adams Lake shifted from ultra-oligotrophic in 1986 to the middle range of oligotrophy in 1998.

Concentrations of particulate C (PC), particulate N (PN), and particulate P (PP) were relatively consistent among stations but PC and PP were significantly greater (ANOVA, $P < 0.05$) in 1997 and 1998 compared with 1986 levels (Table 5). Ranges in seasonal average concentrations were 178 to 299 μg C/L, 21 to 32 μg N/L and 1.1 to 3.0 μg P/L.

Atomic ratios of the particular elements ranged from 7.7 to 12.4 C:N, 236 to 446 C:P and from 24 to 54 N:P (Table 5). N/P and C/P were significantly higher in 1986 than in 1997 and 1998, while C:N was significantly lower in 1986 (ANOVA, $P < 0.05$). Ratios of C, N, and P are useful for estimating the type and degree of nutrient limitation

in lakes (Redfield et al. 1963; Healey and Hendzel 1980; Hecky et al. 1993; Hassett et al. 1997). The extent of P limitation increases with increasing C:P and N:P ratios while co-limitation by N and P is indicated by low N:P ratios. The 1986 C:N:P ratio (413:51:1) was similar to the ratio of 473:45:1 reported for a range of severely P-limited coastal lakes in British Columbia (Stockner and Shortreed 1985). Lower C:N:P ratios in 1997 (266:24:1) and in 1998 (338:31:1) were similar to ratios in many sockeye producing lakes in the Fraser and Skeena systems (Shortreed et al. 1998). While C:N:P ratios indicate Adams Lake remained P-limited during fertilizer addition, the degree of this limitation was far less than was found in 1986, prior to fertilization.

LOWER TROPHIC LEVELS

Seasonal average epilimnetic chlorophyll concentrations (CHL) were relatively low (<1.1 μg/L) in all three years sampled, which is consistent with the lake being oligotrophic (Forsberg and Ryding 1980) (Table 6). Whole lake average CHL was substantially higher in 1997 (0.96 μg/L) due to elevated mid-summer concentrations at Stations 2 and 3 (Fig. 10). Lowest concentrations (average = 0.76 μg/L) occurred in 1998. While there was little variation among stations, CHL was consistently lower at Station 1 with the lowest seasonal average (0.66 μg/L) at Station 1 in 1998.

Numerically, picoplankton were 94 - 95% of the phytoplankton community, nanoplankton were <1 - 2% and microplankton comprised only 1 - 4%. Seasonal average picoplankton numbers ranged from 24.9 x 10^3/mL at Station 2 in 1997 to 94.2 x 10^3/mL at Station 2 in 1998 (Table 6). The whole-lake average for picoplankton in 1986 (65.1 x 10^3/mL) was significantly greater *(*ANOVA, $P < 0.05$) than the 1997 average (31.9 x 10^3/mL) but substantially lower than Station 2 seasonal average in 1998 (92.5 x 10^3/mL) (in 1998 only Station 2 was sampled).

Bacterioplankton abundance ranged 0.42 x 10^6/mL at Station 1 in 1986 to 1.77 x 10^6/mL at Station 3 in 1997 (Table 6). Whole-lake average abundance in 1997 (1.60 x 10^6/mL) was more than three times higher than the 1986 average (0.44 x 10^6/mL) and substantially greater than the 1998 (Station 2) average (1.23 x 10^6/mL). Bird and Kalff (1984) classified lakes having a bacterioplankton count of <1.7 x 10^6/mL as oligotrophic. Based on this categorization, Adams Lake was highly oligotrophic in 1986 but much less so in the fertilized year of 1997.

Seasonal photosynthetic rates (PR) were relatively low, consistent with the lake's oligotrophic status. Seasonal daily averages during the two years for which we have data ranged from 77 mg C/m^2 at Station 1 in 1998 to 161 mg C/m^2 at Station 3 in 1998 (Table 6). Seasonally, rates tended to be highest in early summer and lowest in spring (Fig. 11). There was little difference in whole-lake daily PR between 1997 (113 mg C/m^2) and 1998 (111 mg C/m^2) due to substantially elevated PR at Station 3 for a prolonged period mid-season in 1998. These rates were slightly higher than less productive sockeye lakes in the Fraser system (Quesnel Lake = 102 mg C/m^2, fertilized Chilko Lake = 98 mg C/m^2) but substantially less than other, more productive Fraser

sockeye lakes (Francios = 163 mg C/m^2, Shuswap = 171 mg C/m^2) (Shortreed et al. 2001).

MACROZOOPLANKTON

Seasonal average macrozooplankton biomass ranged from 515 to 709 mg dry wt/m^2 in 1986, 718 to 947 mg dry wt/m^2 in 1997, and from 738 to 1097 mg dry wt/m^2 in 1998 (Table 6). In 1986 and 1998 average biomass was highest at Station 3 but was highest at Station 2 in 1997. Whole-lake seasonal average macrozooplankton biomass estimates were not significantly different between years but were lowest (621 mg dry wt/m^2) in 1986 and highest (870 mg dry wt/m^2) in 1998 (ANOVA, $P > 0.05$). In 1986, prior to fertilization, Adams Lake macrozooplankton biomass was equivalent to levels in less productive sockeye lakes such as Harrison Lake (Shortreed et al. 2001) and Chilko Lake (unfertilized years, Hume et al. 1996). In 1998, the year following fertilizer application, seasonal average macrozooplankton biomass in Adams Lake was similar to zooplankton levels in more productive sockeye lakes such as Quesnel (829 mg dry wt/m^2), Shuswap (1,005 mg dry wt/m^2), and Chilko (during fertilized years) lakes (1,065 mg dry wt/m^2) (Shortreed et al. 2001).

Seasonal average diaptomid copepod biomass ranged from 296 to 308 mg dry wt/m^2 in 1986, 283 to 369 mg dry wt/m^2 in 1997, and from 255 to 336 mg dry wt/m^2 in 1998 (Table 7). Whole-lake seasonal average was lowest (303 mg dry wt/m^2) in 1986 and highest (313 mg dry wt/m^2) in 1997. Cyclopid biomass ranged from a seasonal average of 62 to 112 mg dry wt/m^2 in 1986, 164 to 212 mg dry wt/m^2 in 1997, and from 72 to 178 mg dry wt/m^2 in 1998.

Seasonal average *Daphnia* biomass ranged from 126 to 262 mg dry wt/m^2 in 1986, 240 to 304 mg dry wt/m^2 in 1997, and from 254 to 489 mg dry wt/m^2 in 1998 (Table 7). As with macrozooplankton, *Daphnia* biomass was highest at Station 3 in 1986 and 1998 while greatest concentrations occurred at Station 2 in 1997. Whole-lake seasonal average was lowest (172 mg dry wt/m^2) in 1986 and highest (377 mg dry wt/m^2) in 1998. Season maxima occurred several weeks earlier in 1997 and 1998 (June-July) than in 1986 (August-September, Fig. 12) which in 1997 could indicate some degree of top-down predator control of late season *Daphnia* abundance by the higher densities of *O. nerka*. *Daphnia* biomass found in Adams Lake in 1986 was comparable to less productive interior sockeye lakes. In 1997 and 1998 *Daphnia* biomass was similar to or slightly greater than that found in several large interior sockeye lakes Francois (356 mg dry wt/m^2), Quesnel (237 mg dry wt/m^2), Seton (219 mg dry wt/m^2), and Trembleur (231 mg dry wt/m^2) lakes (Shortreed et al. 2001).

ZOOPLANKTON AND SOCKEYE DIET

Diet is a direct indicator of food resource availability and as such can be used to assess the success of lake fertilization if comparative data are available. Juvenile sockeye selectively graze large cladocerans and if available may feed exclusively on *Daphnia (*Narver 1970; Goodlad et al. 1974; Morton and Williams 1990; Shortreed et al. 1996). High grazing pressure can reduce the relative abundance of *Daphnia* while

increasing that of less productive predator resistant copepods (Kyle et al. 1988). During our study, the relative abundance of *Daphnia* ranged from 30% to 45% indicating that there was an ample food supply for sockeye densities rearing in the lake in 1997. However, strong persistent thermal stratification at Station 2 in 1998 that could have contributed to elevated PR and zooplankton biomass, also likely reduced access of juvenile *O. nerka* to food resources within the epilimnion.

Stomach samples collected in the summer of 1997 averaged 70% full. Fall samples collected in 1997 and 1998 were only about 45% full (Fig. 13). *Daphnia*, the preferred prey of age-0 sockeye, was the major dietary component averaging >80% of the stomach contents. *Daphnia* along with other cladocerans comprised >90% of the diet. Despite their abundance in Adams Lake, predator resistant copepods (Cyclopidae and Diaptomidae) were rare in stomach contents.

The large proportion of *Daphnia* in the summer and fall diets confirms that an amply supply of quality prey items was available for the sockeye rearing in Adams Lake during fertilized and post-fertilization years. Sockeye diet was very similar during the fall of these two years, but, without pre-treatment data, we could not determine effects of the fertilization experiment on sockeye diet.

IDENTIFICATION OF JUVENILE SOCKEYE AND KOKANEE

Examination of the elemental composition of the otolith core from trawl caught juvenile *O. nerka* in 1997 and 1998 allowed us to determine the proportion of sockeye and kokanee in the lake during these years as well as to determine if there was any differences in length or weight of the two populations. Other studies have found that when strontium and the Sr:Ca ratio are much lower in the rearing lake than in seawater, the otolith core of known freshwater resident kokanee also have a Sr/Ca ratio much lower (< 0.001) than that from anadromous sockeye (Rieman et al. 1994, Volk et al. 2000). In Adams Lake the mean concentrations of Sr (0.044 mg/L) and Ca (6.15 mg/L) result in a Sr:Ca ratio of 0.003. This is similar to other lakes where the technique was successfully applied (Rieman et al.1994) and well below those found in seawater (Sr concentrations of 7.8 mg/L and a Sr:Ca ratio of 0.009, Nozaki, Y.1997).

Analyses conducted at the otolith margins of all *O. nerka* reflect freshwater chemistry during juvenile lake residence, regardless of maternal origin. These values therefore represent a basis for comparison against core values to assign maternal life history to individuals. From a relationship developed by Volk (Wash. Dept. Fish Wildlife, Olympia, personal communication) between Sr:Ca ratios in lake water and observed freshwater zones of otoliths (Y = 0.37 x -0.41), we expected a Sr:Ca ratio of 0.0008 in the margin of all otoliths as well as in the core of the offspring of kokanee. In 1998, we examined the Sr:Ca ratios in the otolith margins of 22 age-0 and 5 age-1 *O. nerka*. Sr:Ca ratios on the margin of all fish examined averaged 0.00074 and all ratios were less than 0.001 (Fig. 14). These are very close to the values expected from the lake water Sr:Ca ratios and validates the methodology for detecting freshwater origins.

Otolith core samples from age-0 *O. nerka* captured in the fall of 1997 (offspring of the 1996 brood year) were distributed in two groups (Fig. 14). Thirty nine fish, 31 to 64 mm in length, had otolith core Sr:Ca ratios ≤ 0.0008 (mean 0.00048) indicating that they were the offspring of resident kokanee. Four samples (9%) had values between 0.0010 and 0.0016 indicating that they were the offspring of anadromous sockeye. Three of these fish were greater than 70 mm but one was only 43 mm, in the middle of the low ratio samples. We conclude that most trawl caught age-0 *O. nerka* were the offspring of non-anadromous kokanee.

Otolith core Sr:Ca ratios for the 22 age-0 and 5 age-1 *O. nerka* in 1998 were <0.0007 and the mean ratio was 0.00048, indicating that all fish examined were offspring of non-anadromous kokanee. This is consistent with the very low sockeye spawning escapement (35 EFS) in 1997.

Based on the above results and reasoning, we assigned the trawl captured fish to one of three categories. In October 1987, *O. nerka* greater than 63 mm were assumed to be age-0 sockeye, while smaller fish (< 58 mm) were assumed to be age-0 kokanee (Fig. 15). There is undoubtedly some overlap in the length distributions between these two morphs, as indicated by the one apparent sockeye found in the smaller size class. However, the break in the length-frequency distribution between 57 and 62 mm appears to be a reasonable distinguishing point. There were no older kokanee captured in 1997, as all fish > 54 mm were aged and all were young of the year. From the otolith evidence in 1998 and the low sockeye escapements in all years except 1986, we assigned all *O. nerka* from 1975, 1976, 1978, and 1998 to kokanee and used scale ages to determine the age structure each year.

We also did a summer survey in July of 1997 in addition to the fall survey. All fish > 57 mm and most of the smaller fish were aged from scales but none of the otoliths were examined for Sr. Scale analysis determined that there were 4 age classes captured (Fig. 16). In the age-0 group there was a considerable range in size (24 - 58 mm) and an indication of bimodal distribution but we were unable to distinguish between kokanee and sockeye in this age category.

Kokanee spawners have not been enumerated but trawl catches indicate that they were abundant in some of the early sample years. EFS in these years were 100 or less. Making assumptions about fecundity (3,200 eggs/female), egg to fry survival (15%), and emergent to fall fry survival (55%) we estimate that sockeye fall fry densities would be < 2 fry/ha in the 1970's. Densities this low result in trawl catches that are close to zero sockeye/hr (J. Hume, unpublished data). Thus, the relatively high trawl catches of 36 - 1,200 age-0 fish/hr of trawling indicate that the lake density of kokanee was also relatively high and that the vast majority of age-0 *O. nerka* caught in Adams Lake in 1975, 1976, 1978, and 1998 were kokanee (Table 8).

In comparison, the EFS of 13,610 in 1996 would theoretically produce a fall fry density of 280 fry/ha in 1997. Again, assuming a kokanee spawning population similar

to the other study years the trawl catch of *O. nerka* in 1997 would be a mix of kokanee and sockeye fry.

SOCKEYE AND KOKANEE ABUNDANCE AND DISTRIBUTION

Using the proportions of sockeye and kokanee determined from the trawl catch, scale ageing, Sr:Ca ratios in the otolith core and target strength information in 1997 and 1998, we apportioned the total hydroacoustic estimate into age-0 kokanee, age-0 sockeye and large fish. Acoustic target strength information can not distinguish between small differences in fish size and therefore can not easily distinguish between age-0 and age-1 *O. nerka*. The age-0 groups will therefore include some age-1 fish but based on the trawl data, these are a small proportion. The large fish group are probably mostly older kokanee but may also include other species in the limnetic region.

Age-0 *O. nerka* were distributed more or less evenly throughout Adams Lake during the hydroacoustic surveys conducted in 1997 and 1998 (Table 9). The observed densities of < 200 *O. nerka*/ha each year are low when compared to other lakes in the Fraser River system. For example Shuswap and Quesnel lakes have had fall sockeye fry densities in excess of 4,000 and 2,500 fry/ha respectively (Hume et al.1996). Such low fall fry densities in these lakes have only been observed in years when the escapement was less than 2% of the observed maximum escapements. A lake capacity model that uses primary production (PR) to predict the rearing capacity of the limnetic region of sockeye lakes was developed by Hume et al 1996. It estimates that Adams Lake could produce about 2,000 smolts /ha. This is about 10 times the observed fall fry density and is similar to that of Quesnel Lake (Shortreed et al. 2001).

SOCKEYE SIZE AND SURVIVAL

In 1976, age-0 kokanee captured in the fall averaged 1.6 g but in all other years fall age-0 kokanee averaged < 1.0 g (Fig. 17, Table 10). In the fall of 1997, age-0 sockeye were considerably bigger (4.0 g). As age-0 sockeye were not captured in the lake in other years we can not determine the effects of fertilization on the size of fall fry by direct comparisons. The fall fry in Adams Lake are about the same size as observed in Shuswap Lake, an adjacent productive sockeye nursery lake, at similar densities (Hume et al. 1996).

Smolts from the 1992 brood year (unfertilized) were significantly smaller than those from the 1996 brood year (fertilized)(Table 11, ANOVA, $P < 0.05$). There were only 265 EFS in 1992 which produced smolts that averaged 2.6 g in the spring of 1994. Four years later the 13,610 EFS produced 3.6 g smolts. Although the density of juvenile sockeye in the lake from the 1996 brood year was still low, we expected it to produce smaller smolts than did the 1992 escapement. This has been observed in a number of other sockeye rearing stocks (Hume et al. 1996). Instead the larger sized smolts in the higher density, but fertilized, year suggests that fertilization increased the productivity of planktonic prey items.

A total of 1.3 million fry were released from the hatchery and net pen facilities in April and May 1998. This is about 20% of the 5.8 million fry we estimate entered the lake from natural spawning (assuming 3,200 eggs/female and 15% egg to fry survival). Mean size of the hatchery released fry were 1.9 and 2.3 g, considerably bigger than the emergent fry which would have been between 0.1 and 0.3 g on lake entry (Burgner 1991). Marine survival of sockeye smolts has been shown to be related to size and presumably this would be the same in the lake as well, although no studies have been done.

We examined 50 smolts for evidence of Sr marks applied in the hatchery but no marks were found on any of the samples examined. Although our sample size was low, we expected around 10 of the smolts to be marked. It is reasonable to assume that effective marking with SrCl is partially dependent on the concentration of strontium used and the metabolic uptake rate of the fish, which is in turn dependent on water temperature. Subsequent results from other strontium marking events infer that the 1992 water temperatures (4.5-6.0 ^{o}C) were too low to place a persistent mark with the concentration (1,000 ppm) and duration (4 hr) used (D. Lofthouse, data on file).

THE EFFECTIVENESS OF RESTORATION ON ADAMS LAKE SOCKEYE

We have attempted to assess all aspects of the restoration activities applied to the Adams Lake sockeye and although in some cases we were unable to do so, there is enough lines of evidence to reach conclusions on both the effectiveness of lake fertilization and the rearing activities. A limitation to our assessment of fertilization effects is that we only had data from one reference year (limnology, 1986; smolts, 1992). This effectively removed our ability to separate treatment effects from interannual variation. Increased data from more reference years should provide more defensible conclusions.

In many other sockeye nursery lakes, the addition of N and P during the growing season has resulted in increased primary, secondary and tertiary productivity (Stockner and Hyatt 1984; Hume et al. 1996; Bradford et al. 2000). To assess the effectiveness of nutrient additions in Adams Lake we compared several limnological variables, often used to estimate lake productivity, from the treatment year (1997) with those from an untreated reference year (1986).

Although we measured these same variables during the year following treatment, we did not consider this a valid reference year because of carry-over effects from the treatment and substantial climatological differences between years. First, precipitation and lake discharge during 1988 were substantially less than 1997 rates. Second, seasonal air temperature and epilimnetic temperatures were warmer in 1998 than in 1997. Third, thermal stratification was much stronger and persisted for a longer period in 1998 than in1997. Since all of these factors are primary influences on lake productivity, discerning any effects of nutrient addition based on 1998 data is difficult. In addition, Adams Lake has an average water residence time of 10 years, and carry-over effects are more of a factor affecting evaluation than in treated lakes with faster flushing rates. Elevated spring overturn total phosphorus levels in 1998 were likely a

carry-over from the 1997 treatment and likely influenced post-treatment biological activity in the lake.

Compared to 1986, the measured limnological variables indicate that the addition of fertilizer in 1997 resulted in increased lake productivity. The average spring overturn concentration of total P in the year following fertilization was more than 3 times greater than occurred in the reference year, indicating a carry-over of phosphorus from the fertilized year. In addition, a lower C:N:P ratio in 1997 indicated that although Adams Lake productivity remained P-limited during the addition of fertilizer, it was far less so than during the reference year. Chlorophyll concentration has been used as an analogue for primary productivity and higher average chlorophyll concentration during the treatment year in Adams Lake suggests that fertilization was responsible for increased primary productivity (Forsberg and Ryding 1980; Stockner and Shortreed 1985; Shortreed and Morton 2000). Finally, a 30% increase in macrozooplankton biomass and 45% increase in *Daphnia* biomass compared to the reference year suggests fertilization successfully increased secondary production.

Although we are able to show positive effects of nutrient addition in key chemical and biological variables at lower trophic levels, the effects on sockeye fry are not easily detectable due to the lack of sockeye samples from unfertilized years. Our analysis of juvenile *O. nerka* collected in the years other than 1997 indicate that the vast majority of these fish are kokanee. Studies have shown that kokanee in other Fraser system lakes are typically 25 - 30% smaller than cohabiting sockeye (Wood and Foote 1990; Wood et al.1999; data on file). Thus, meaningful comparisons of the size of juvenile lake resident sockeye fry in the fertilized year with other years within Adams Lake is not possible.

Comparisons between the size of migrating sockeye smolts that reared in Adams Lake during fertilization and on the previous cycle year (unfertilized) do show evidence of the effects of fertilization. Smolts from the fertilized year were 1 g bigger than in the previous unfertilized cycle year (Table 11). Smolt size is strongly related to smolt to adult survival (Koenings et al. 1993; Bradford et al. 2000). In Chilko Lake, an increase of 1 g in smolt weight resulted in a smolt to adult survival increase of 14% (Bradford et al. 2000).

In 1980 and 1984 extensive fish culture activities were undertaken with considerable success in rebuilding the Upper Adams River stock (Williams 1987). Subsequent egg take operations were sometimes less successful. Incubation and rearing problems in 1988 resulted in the release of poor quality fry with limited survival potential, while incubation problems in 1992 resulted in early egg loss but the 312,000 fry released from this group in 1993 appeared healthy. The 1996 egg take also suffered early survival problems but in the end 1.3 million healthy short-term reared fry were released. No attempt was made to directly evaluate the freshwater or marine survival of earlier releases and our initial attempts at marking the 1996 brood year were unsuccessful. However, examination of the adult return data provides evidence that

both the 1992 (fish culture) and 1996 (fish culture and lake enrichment) restoration efforts were successful although the data is insufficient to test for significance.

Restoration efforts associated with these two brood years appear to have produced dramatic increases in returns per EFS relative to non-enhanced stocks (Table 12). Suspected poor ponding conditions associated with the 1988 brood year are supported by productivity estimates similar to other non-enhanced stocks. In years with no restoration activities, productivity of Upper Adams River sockeye was similar to the non-enhanced stocks in 1984, but considerably higher in 1980. However, there may be considerable error associated with the estimated productivity of Upper Adams River in 1980 given the small run size.

Survival of Upper Adams River sockeye in the 1992 and 1996 brood years relative to the Early Summer Index suggests that restoration had a net positive effect on survival (see vertical arrows in Fig. 18). The R/S from the 1992 brood year was considerably higher than from the 1996 brood year. However, the Early Summer Index shows that survival for all early summer stocks was much higher for the 1992 brood than for the 1996 brood. The larger incremental effect on survival of Upper Adams River in 1996 relative to 1992 may be the result of the combined effect of fish culture and lake fertilization. Survivals of the Upper Adams River population in the non-enhanced brood years and the failed 1988 restoration year were consistent with the variation in survival common to all stocks. While restoration does appear to have a promising effect on the survival of Upper Adams River sockeye salmon relative to other Early Summer stocks, more years of restoration data will be necessary to determine if restoration effects are statistically significant.

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Table 1. Sockeye transplants and adult returns (catch and escapement) to the Upper Adams River from 1949 to 1984.

	Eggs (thousands)				Fry (thousands)		
Br. Year	Est. natural eggs	Seymour	Taseko	Adams / Cayenne	Seymour	Adams / Cayenne	Resultant adult returns
1949	0	158			84		0
1950	0	667					194
1951	0						0
1952	0				187		9
1953	0						291
1954	304	495					291
1955	0	780					0
1956	13	253					0
1957	467	520					0
1958	467	483	850				79
1959	0	900	600				5
1960	0		702				162
1961	0						0
1962	128						63
1963	6						0
1964	269						0
1965	0						0
1966	102						4
1967	0						0
1968	0						31
1969	0						0
1970	6						13
1971	0						23
1972	58						40
1973	0						0
1974	22	1,374					0
1975	32	2,140					0
1976	77						2,774
1977	0						0
1978	0						425
1979	0						0
1980	1,152					772	13,149
1981	0						83
1982	214						2,431
1983	0						2
1984	5,971			448		393	12,378
Total	9,290	7,770	2,152	448	271	1,165	

Table 2. Sockeye culture in 1988, 1992, and 1996.

Brood year	Source	Females	Eggs (millions)	Ponded (millions)	Date released	Size (g)	Released (thousands)
1988	Upper Adams River		2.40		May, 1989	0.2	1,500
1992	Upper Adams & Momich rivers	271	0.75	0.35	May, 1993	1.9	105
						2.5	211
1996	Upper Adams & Momich rivers	665	1.30	1.36	April, 1997	1.9	604
					May, 1997	2.3	698

Table 3. Variation in physical characteristics of Adams Lake. Data are seasonal averages with two standard errors shown in brackets.

Station	Year	Surface temp. (^{o}C)	Thermocline depth (m)	Mean epil. temp. (^{o}C)	Stability (kg/s^{2})	Secchi depth (m)	Euphotic zone (m)	Extinction coeff. (/m)
1	1986	15.9	7.9	13.9	2700	7.1	11.2	0.42
2		16.7	7.2	14.8	3054	7.7	12.0	0.41
3		16.1	7.2	13.8	2766	9.4	14.1	0.30
Mean (2SE)		16.2 (0.5)	7.4 (0.5)	14.2 (0.7)	2840 (217)	8.1 (1.4)	12.4 (1.7)	0.38 (0.08)
1	1997	14.7	7.8	12.8	3027	6.4	10.6	0.44
2		15.6	7.6	12.9	2900	6.8	12.0	0.35
3		14.3	8.6	12.3	2456	6.6	12.3	0.38
Mean (2SE)		14.9 (0.8)	8.0 (0.6)	12.7 (0.4)	2794 (346)	6.6 (0.3)	11.6 (1.0)	0.39 (0.05)
1	1998	18.4	7.1	14.9	3972	6.5	11.7	0.36
2		19.2	7.0	15.5	4492	8.5	14.5	0.29
3		17.5	8.4	14.7	3567	8.5	13.2	0.31
Mean (2SE)		18.4 (1.0)	7.5 (0.9)	15.0 (0.5)	4010 (536)	7.8 (1.3)	13.1 (1.6)	0.32 (0.04)

Table 4. Variation in seasonal average epilimnetic chemical variables at Adams Lake. Two standard errors are shown in brackets.

Station	Year	pH	T.D.S. (mg/L)	Total alk. (mg $CaCO_3$/L)	Silicate (mg Si/L)	Nitrate (µg N/L)	Total P (µg/L)	Tot. diss. P (µg/L)
1	1986	7.20	34	19.8		75.4	1.5	
2		7.26	44	21.5		75.3	1.6	
3		7.41	40	22.9		80.6	1.6	
Mean (2SE)		7.29 (0.12)	39 (6)	21.4 (1.8)		77.1 (3.5)	1.6 (0.1)	
1	1997	7.32	43	18.5	2.17	55.1		5.9
2		7.35	48	20.4	1.70	64.9		5.2
3		7.37	40	21.7	2.06	64.9		4.7
Mean (2SE)		7.34 (0.03)	44 (5)	20.2 (1.9)	1.98 (0.29)	61.6 (6.6)		5.3 (0.7)
1	1998	6.91	33	19.3	2.15	50.0	4.3	3.3
2		7.00	37	20.8	2.45	52.1	4.0	3.3
3		6.99	37	22.7	2.58	50.9	4.2	3.4
Mean (2SE)		6.97 (0.06)	36 (3)	20.9 (1.9)	2.39 (0.26)	51.0 (1.2)	4.2 (0.2)	3.3 (0.1)

Table 5. Variation in seasonal averages of epilimnetic concentrations of particulate elements and atomic ratios. Two standard errors are shown in brackets.

		Particulate mass (µg/L)			Atomic ratio		
Station	Year	C	N	P	C/N	C/P	N/P
1	1986	202	27	1.4	8.6	382	45
2		178	27	1.1	7.7	410	53
3		182	26	1.1	8.2	446	54
Mean (2SE)		187 (15)	27 (1)	1.2 (0.2)	8.2 (0.5)	413 (37)	51 (6)
1	1997	278	32	3.0	10.1	236	24
2		299	31	2.9	11.2	268	24
3		260	24	2.3	12.4	293	24
Mean (2SE)		279 (22)	29 (5)	2.7 (0.5)	11.2 (1.4)	266 (33)	24 (0)
1	1998	189	21	1.9	10.4	251	24
2		236	25	1.6	11.1	389	35
3		224	24	1.5	10.9	374	34
Mean (2SE)		216 (28)	23 (2)	1.7 (0.3)	10.8 (0.4)	338 (87)	31 (7)

Table 6. Variation in seasonal averages of biological variables in Adams Lake. The value of two standard errors is shown in brackets.

Station	Year	Bacteria (#x10^6/mL)	Chlorophyll (µg/L)	Daily PR (mg C/m^2)	Phytoplankton #x10^3/mL			Macrozooplankton biomass (mg/m^2)
					Pico.	Nano.	Micro	
1	1986	0.42	0.81		60.7	1.6	2.8	515
2		0.51	1.00		69.7	1.3	3.5	640
3		0.39	0.81		64.9	1.0	2.2	709
Mean (2SE)		0.44 (0.07)	0.87 (0.12)		65.1 (5.2)	1.3 (0.3)	2.8 (0.8)	621 (113)
1	1997	1.42	0.86	107	39.7	0.5	1.2	718
2		1.60	1.03	112	24.9	0.4	1.4	947
3		1.77	1.02	121	31.2	0.4	0.7	722
Mean (2SE)		1.60 (0.20)	0.97 (0.11)	113 (8)	31.9 (8.6)	0.4 (0.1)	1.1 (0.4)	796 (151)
1	1998		0.66	77				774
2		1.23	0.80	96	92.5	0.5	1.5	738
3			0.83	161				1097
Mean (2SE)			0.76 (0.10)	111 (51)				870 (228)

Table 7. Variation in average biomass of major zooplankton groups. Two standard errors are shown in brackets. Daphnia are *Daphnia thorata* and *D. longiremis*, Bosminidae are primarily *Eubosmina longispina*, Cyclopidae are mainly *Diacyclops thomasi* and the most common Diaptomidae are *Leptodiaptomus ashlandi.*

		Zooplankton biomass (mg dry wt/m^2)			
Station	Year	Daphnia	Bosminidae	Cyclopidae	Diaptomidae
1	1986	126	2	62	304
2		128	1	189	296
3		262	2	112	308
Mean (2SE)		172 (90)	2 (1)	121 (74)	303 (7)
1	1997	240	5	164	283
2		304	5	212	369
3		208	10	141	288
Mean (2SE)		251 (56)	7 (3)	172 (42)	313 (56)
1	1998	389	4	72	255
2		254	5	119	307
3		489	34	178	336
Mean (2SE)		377 (136)	14 (20)	123 (61)	299 (47)

Table 8. Trawl catch effort and catch per unit effort for fish captured in Adams Lake.

Section	Taxa	Duration (min)	Catch	Catch/hour
October 6, 1975				
1	Age-0 *O. nerka*	5	97	1,164
	Age-1 kokanee	5	1	12
October 20, 1976				
3	Age-0 *O. nerka*	30	49	98
	Age-1 kokanee	30	2	4
October 16, 1977				
2	Age-2 kokanee	10	7	42
October 18, 1978				
1	Age-0 *O. nerka*	20	8	24
2	Age-0 *O. nerka*	20	15	45
	Unident. Cyprinid	20	1	3
	Unidentified	20	1	3
3	Age-0 *O. nerka*	20	13	39
	Age-2 kokanee	20	1	3
Lake	Age-0 *O. nerka*	60	36	36
July 23, 1997				
1	Age-0 *O. nerka*	30	8	16
	Age-1 kokanee	30	1	2
2	Age-0 *O. nerka*	20	53	159
	Age-1 kokanee	20	2	6
	Age-2 kokanee	20	1	3
3	Age-0 *O. nerka*	20	45	135
	Age-1 kokanee	20	7	21
	Age-2 kokanee	20	3	9
Lake	Age-0 *O. nerka*	70	106	91
	Age-1 kokanee	70	10	9
	Age-2 kokanee	40	4	6
October 21, 1997				
1	Age-0 *O. nerka*	30	26	52
2	Age-0 *O. nerka*	50	110	132
3	Age-0 *O. nerka*	30	24	48
Lake	Age-0 *O. nerka*	110	160	87
November 10, 1998				
2	Age-0 *O. nerka*	60	35	35
	Age-1 kokanee	30	2	4
3	Age-0 *O. nerka*	30	200	400
	Age-0 *O. nerka*	60	40	40
	Age-1 kokanee	30	6	12
Lake	Age-0 *O. nerka*	150	275	110
	Age-2 kokanee	60	8	8

Table 9. Acoustic population estimates of fish in Adams Lake. Species, morph and age class are based on trawl catches and analysis of otolith origins (see text for explanation). Larger fish were primarily determined by target strength information and are most likely older kokanee.

			Age-0 kokanee			Age-0 sockeye			Large fish		
Trawl Section	Surface Area (ha)	N	Density (N/ha)	N	±95% C. I. (%)	Density (N/ha)	N	±95% C. I. (%)	Density (N/ha)	N	±95% C. I. (%)
July 19, 1997											
1. South End	4,860	5	120	583,366	66	13	63,381	66	30	145,457	82
2. Middle	4,729	3	94	442,859	35	23	110,715	35	16	76,463	94
3. North End	3,418	3	209	714,821	44	42	143,307	44	31	105,308	16
Total	13,007	3	134	1,741,046	19	24	317,403	14	25	327,228	28
October 20 , 1997											
1. South End	4,860	5	219	1,063,825	42	24	115,582	42	11	52,846	126
2. Middle	4,729	3	140	663,406	33	35	165,851	33	15	70,953	157
3. North End	3,418	3	167	571,503	116	34	114,575	116	25	86,121	189
Total	13,007	3	177	2,298,733	20	30	396,008	19	16	209,919	49
November 11, 1998											
1. South End	4,860	5	33	160,019	83				0	0	
2. Middle	4,729	3	58	274,852	67				3	12,931	117
3. North End	3,418	3	119	405,764	44				3	11,837	99
Total	13,007	3	65	840,636	18	Undetectable			2	24,768	36

Table 10. Midwater trawl catch and size statistics for Adams Lake. Where possible *O. nerka* have been characterized as either sockeye or kokanee. See text for explanation.

		Weight (g)						Length (mm)					
Section	Taxa	N	Mean	+-95% C.I.	SD	Min.	Max.	N	Mean	+-95% C.I.	SD	Min.	Max.
October 6,1975													
1	Age-0 kokanee	97	0.75	0.05	0.26	0.12	1.43	97	47.0	0.8	4.1	35	56
	Age-1 kokanee	1	8.56			8.56	8.56	1	97			97	97
October 20,1976													
3	Age-0 kokanee	49	1.55	0.15	0.51	0.61	2.95	49	53.0	1.8	6.2	38	66
	Age-1 kokanee	2	12.24	28.21	3.14	10.02	14.46	2	106.0	114.4	12.7	97	115
October 16,1977													
2	Age 2+ kokanee	7	72.63	5.40	5.84	60.96	77.72	7	184.0	5.5	6.0	173	190
October 17,1978													
1	Age-0 kokanee	8	0.36	0.13	0.16	0.18	0.68	8	31.0	3.7	4.4	25	38
2	Age-0 kokanee	15	0.48	0.10	0.18	0.22	0.74	15	36.0	2.9	5.3	28	42
	Unident. Cyprinid	1	2.08			2.08	2.08	1	56.0			56	56
	Unidentified	1						1	762			762	762
3	Age-0 kokanee	13	0.62	0.12	0.20	0.43	1.00	13	38.0	2.7	4.5	33	46
	Age 2+ kokanee	1	48.48			48.48	48.48	1	165			165	165
Lake	Age-0 kokanee	36	0.51	0.07	0.20	0.18	1.00	36	36.0	1.9	5.5	25	46
July 21,1997													
1	Age-0 *O. nerka*	8	1.03	0.35	0.42	0.13	1.42	8	45.0	7.7	9.2	24	52
	Age-1 kokanee	1	10.43			10.43	10.43	1	97			97	97
2	Age-0 *O. nerka*	53	0.95	0.11	0.41	0.14	1.78	53	43.0	2.1	7.5	25	56

Table 10 (Cont.). Midwater trawl catch and size statistics for Adams Lake. Where possible *O. nerka* have been characterized as either sockeye or kokanee. See text for explanation.

		Weight (g)						Length (mm)					
				+-95%						+-95%			
Section	Taxa	N	Mean	C.I.	SD	Min.	Max.	N	Mean	C.I.	SD	Min.	Max.
	Age-1 kokanee	2	6.90	4.76	0.53	6.52	7.27	2	84.0	25.4	2.8	82	86
	Age 2+ kokanee	1	182.			182	182	1	232.			232	232
3	Age-0 *O. nerka*	45	1.56	0.25	0.84	0.10	5.95	45	51.0	2.4	8.0	24	80
	Age-1 kokanee	7	8.15	2.90	3.14	4.85	13.52	7	89.0	8.9	9.6	78	103
	Age 2+ kokanee	3	34.33	22.48	9.05	26.88	44.40	3	143.0	25.5	10.3	134	154
Lake	Age-0 *O. nerka*	106	1.22	0.13	0.69	0.10	5.95	106	47.0	1.6	8.5	24	80
	Age-1 kokanee	10	8.13	1.96	2.74	4.85	13.52	10	89.0	6.2	8.6	78	103
	Age 2+ kokanee	4	71.2	118.	74.2	26.88	182.	4	165.0	72.3	45.4	134	232
October 20, 1997													
1	Age-0 sockeye	5	3.82	1.01	1.15	2.78	5.79	5	72.6	5.2	5.9	66	82
	Age-0 kokanee	21	0.65	0.10	0.23	0.32	1.26	21	40.4	2.1	5.0	32	52
2	Age-0 sockeye	14	4.33	0.95	1.82	2.47	10.00	18	74.6	4.0	8.6	64	101
	Age-0 kokanee	53	0.78	0.08	0.29	0.35	1.56	92	43.7	1.1	5.2	31	57
3	Age-0 sockeye	10	3.50	0.48	0.78	2.45	4.75	10	70.6	3.7	5.9	62	78
	Age-0 kokanee	14	0.81	0.12	0.23	0.40	1.16	14	43.2	2.6	4.9	33	49
Lake	Age-0 sockeye	29	3.95	0.52	1.44	2.45	10.00	33	73.1	2.6	7.5	62	101
	Age-0 kokanee	88	0.75	0.06	0.27	0.32	1.56	127	43.1	0.9	5.2	31	57
November 11, 1998													
2	Age-0 kokanee	25	0.67	0.08	0.21	0.31	1.07	32	41.2	1.8	5.1	30	52
	Age-1 kokanee	NS						2	79.0	2.0	1.4	78	80
3	Age-0 kokanee	200	0.97	0.04	0.27	0.38	1.75	224	45.7	0.6	4.8	32	57
	Age-1 kokanee	NS						6	84.7	3.6	4.5	79	91
Lake	Age-0 kokanee	225	0.93	0.04	0.28	0.31	1.75	256	45.2	0.6	5.1	30	57
	Age-1 kokanee	NS						8	83.3	3.2	4.7	78	91

Table 11. Size and catch of smolts caught in the Adams River in 1994 and 1998.

		Weight (g)						Length (mm)					
Section	Taxa	N	Mean	+-95% C.I.	SD	Min.	Max.	N	Mean	+-95% C.I.	SD	Min.	Max.
1992 brood year (EFS = 1,462)													
April 20 - May 6, 1994		118	2.64	0.17	0.83	1.30	6.70	118	78.10	1.06	5.80	45	98
1996 brood year (EFS = 13,610)													
April 14 - May 6, 1998		273	3.58	0.12	1.00	2.64	7.94	273	80.10	0.50	4.21	70	109

Table 12. Recruits per effective female averaged over non-enhanced Stocks and for the enhanced Upper Adams River sockeye population.

Brood Year	Upper Adams River Returns per EFS	Non-enhanced Stocks (Raft, Fennell, Scotch, Seymour) Mean Returns per EFS	Min Returns per EFS	Max. Returns per EFS
1980	36.5	17.4	25.2	8.2
1984	6.6	7.2	9.9	3.9
1988	4.3	3.8	5.5	1.4
1992[a]	21.0	6.9	13.9	1.7
1996[b]	7.5	3.1	5.3	0.9

[a] 0.3 million fry released.
[b] 1.3 million fry released and lake fertilized.

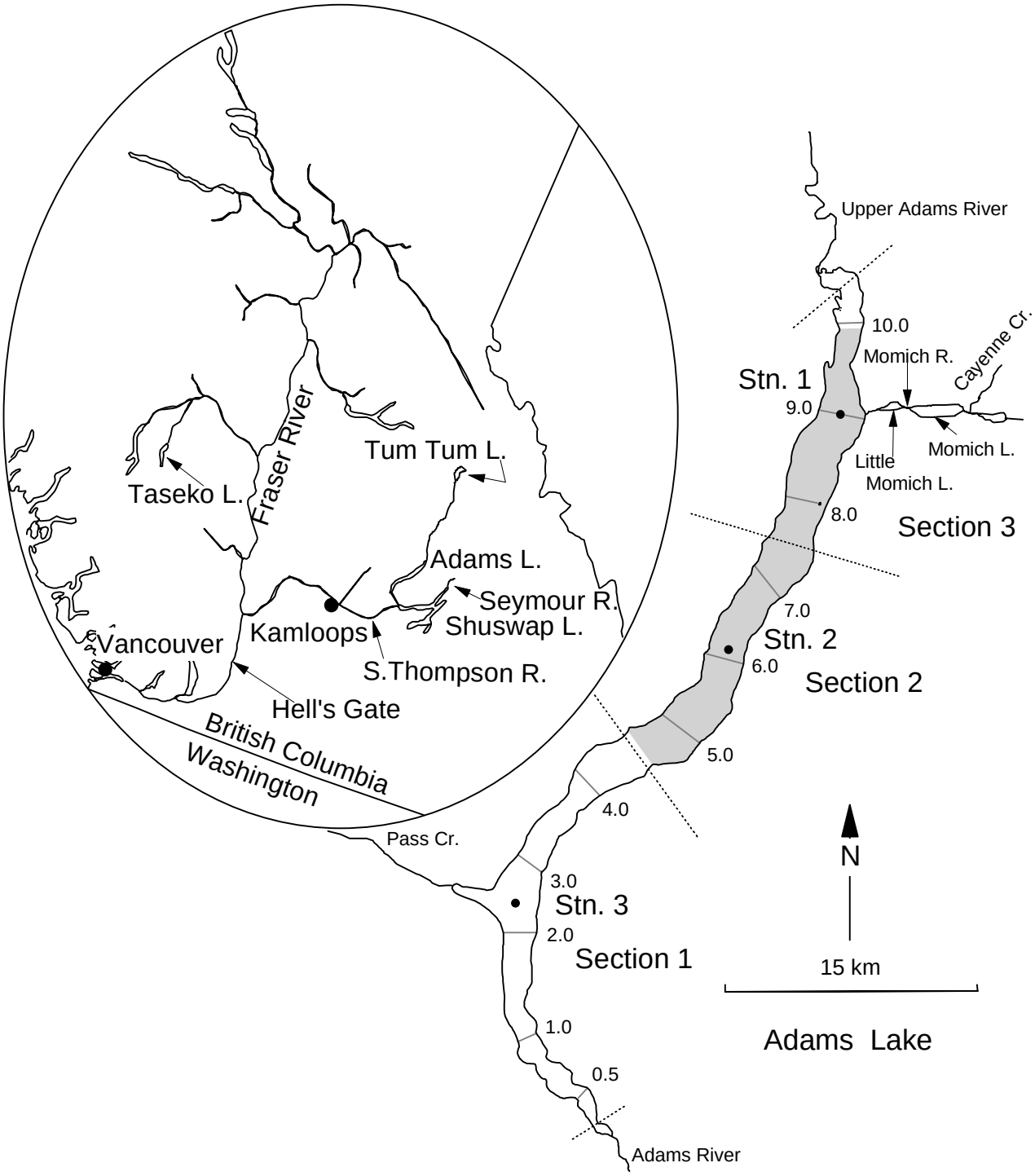


Fig. 1. Adams Lake and location maps showing spawning tributaries, the area fertilized (shaded), acoustic transects (solid lines), trawl sections (between dashed lines) and limnology stations (solid circles).

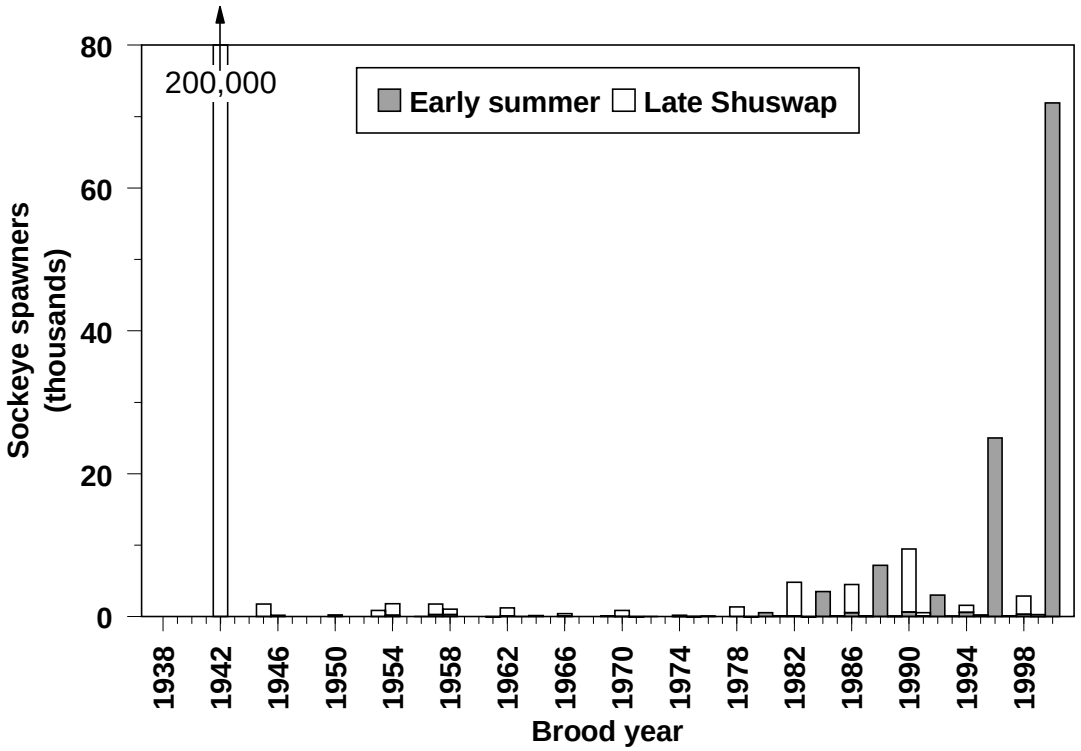


Fig. 2. Early summer and late Shuswap escapement to Adams Lake watershed.

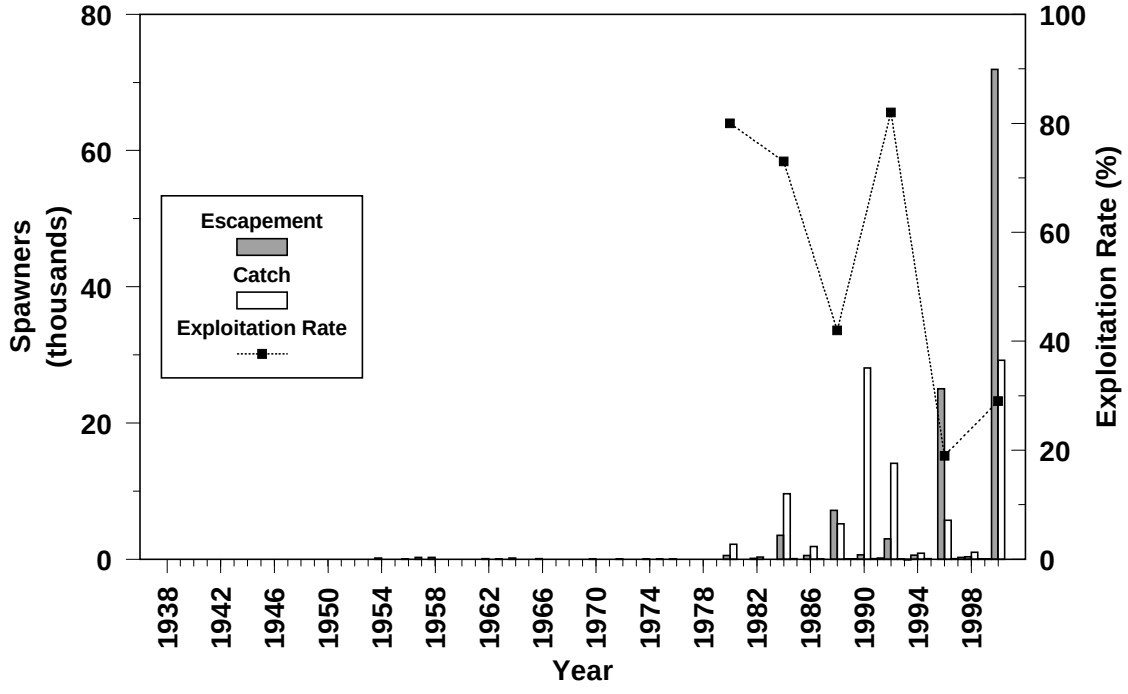
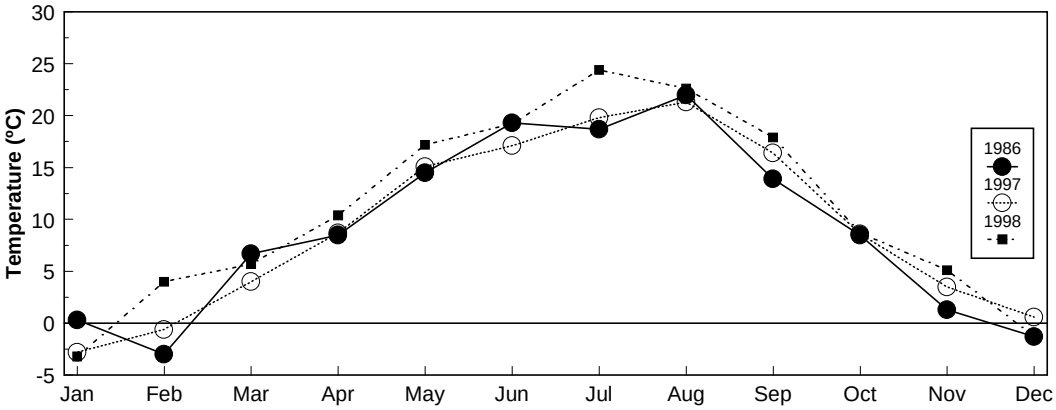
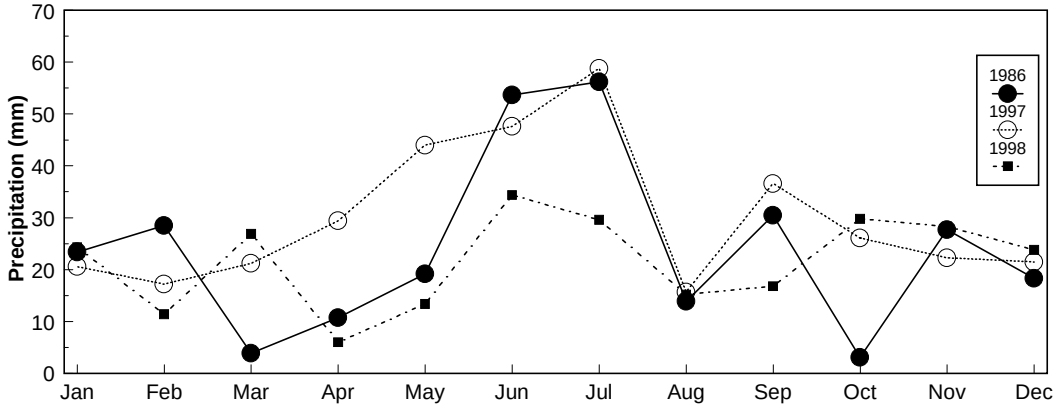


Fig. 3. Returns (catch and escapement) to the Upper Adams River and exploitation rate on the dominant runs.

A. Kamloops mean monthly air temperature



B. Kamloops total monthly precipitation



C. Adams River mean monthly discharge

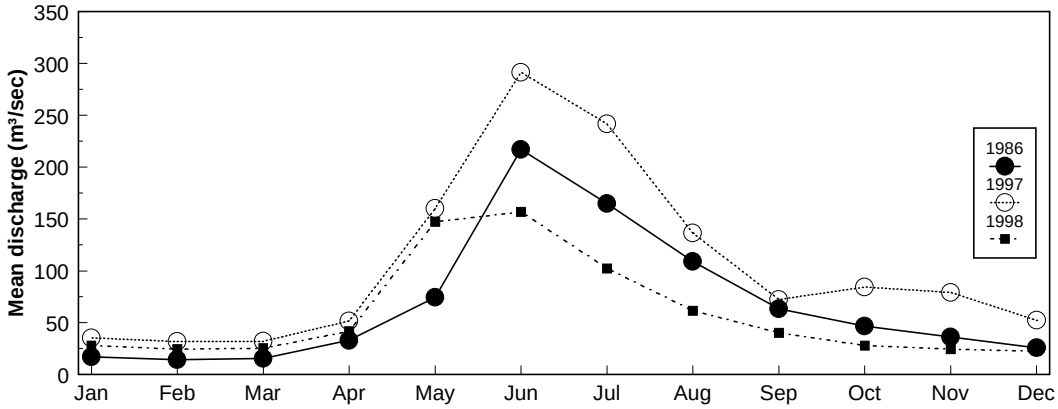


Fig. 4. Kamloops mean monthly air temperature (A), total monthly precipitation (B), and Adams River mean monthly discharge (C) for 1986, 1987, and 1998.

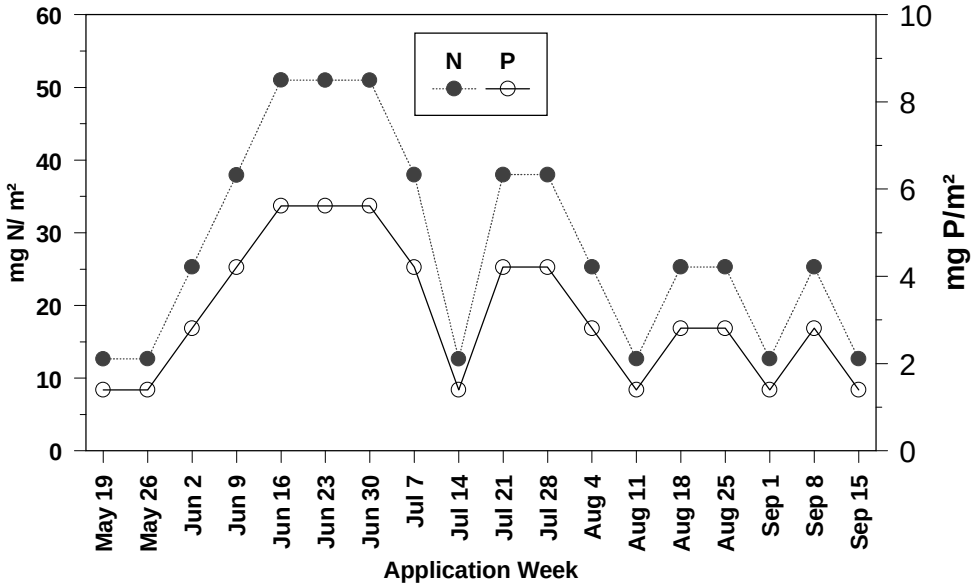


Fig. 5. Weekly application rates of N and P to Adams Lake In 1997.

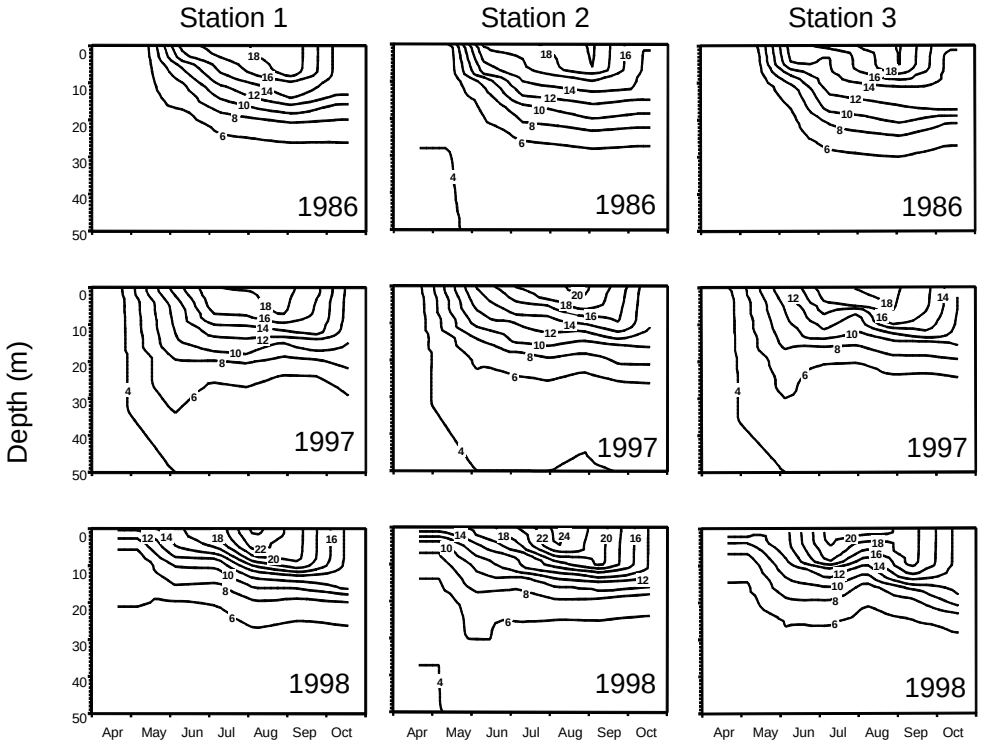


Fig. 6. Seasonal isotherms for stations 1 - 3 in 1986, 1997, and 1998.

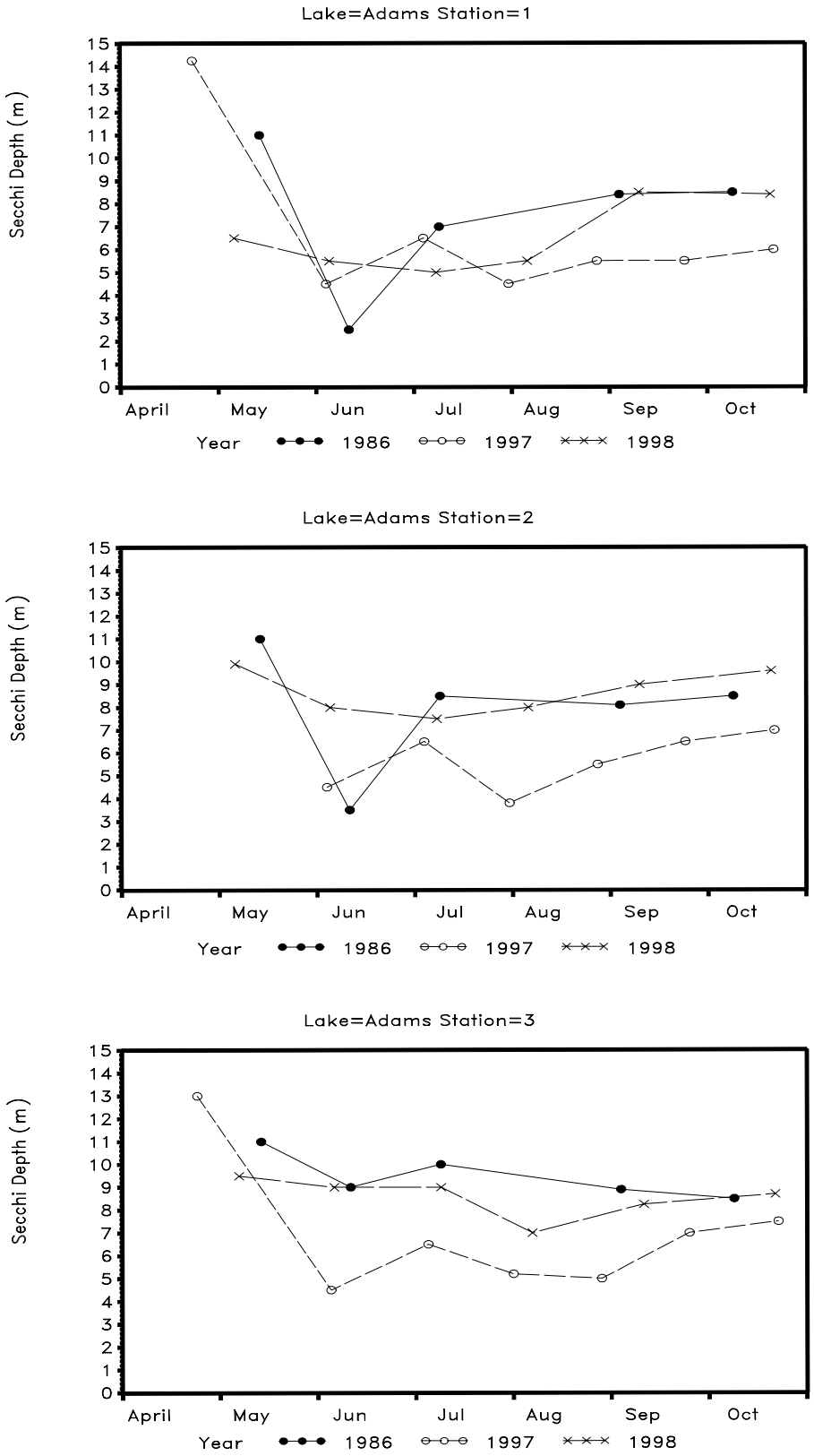


Fig. 7. Variation in Secchi depths for stations 1 - 3 in 1986, 1997, and 1998.

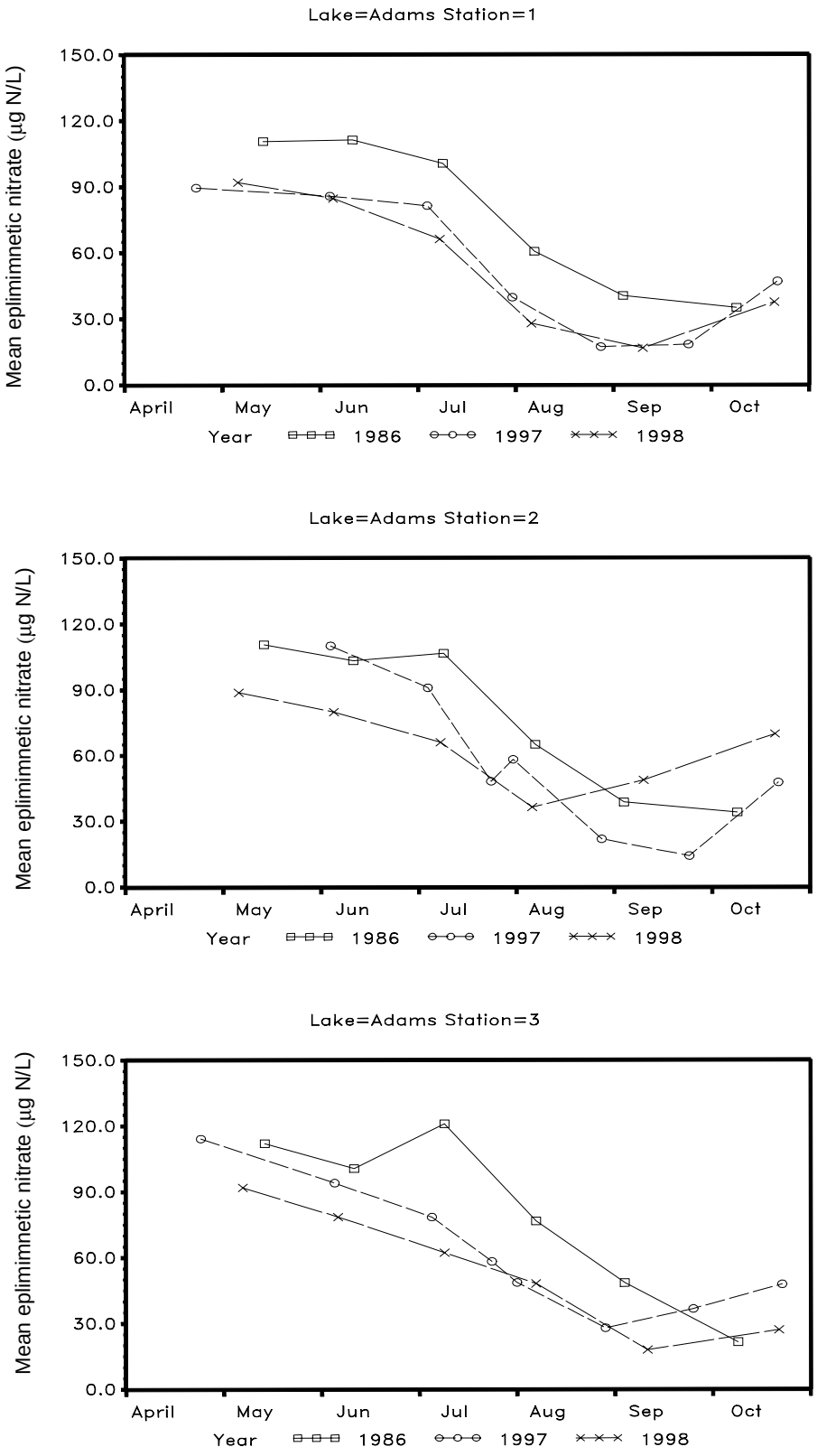


Fig. 8. Variation in epilimnetic concentrations of nitrate for stations 1 - 3 in 1986, 1997, and 1998.

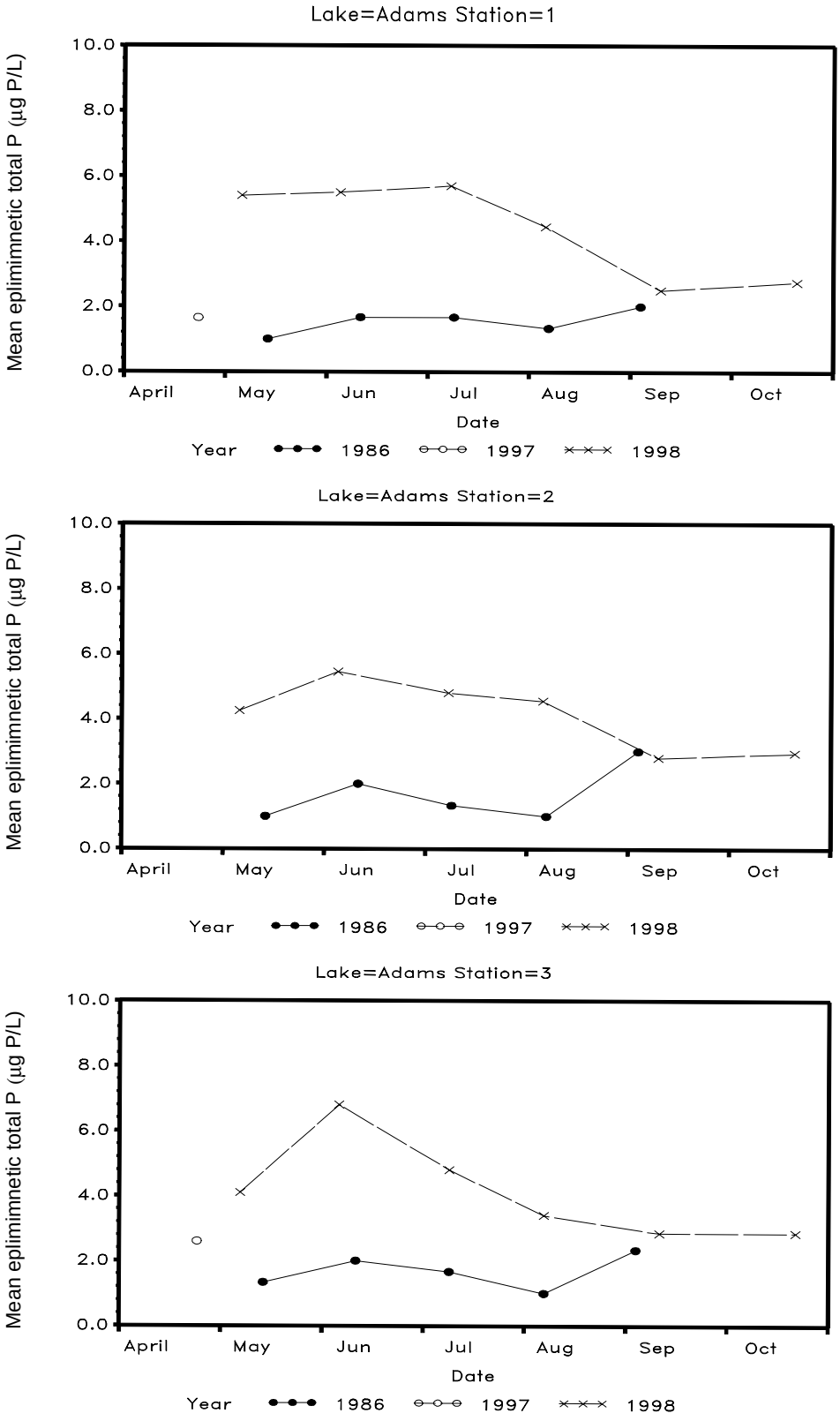


Fig. 9. Variation in epilimnetic concentrations of total P for stations 1 - 3 in 1986, 1997, and 1998.

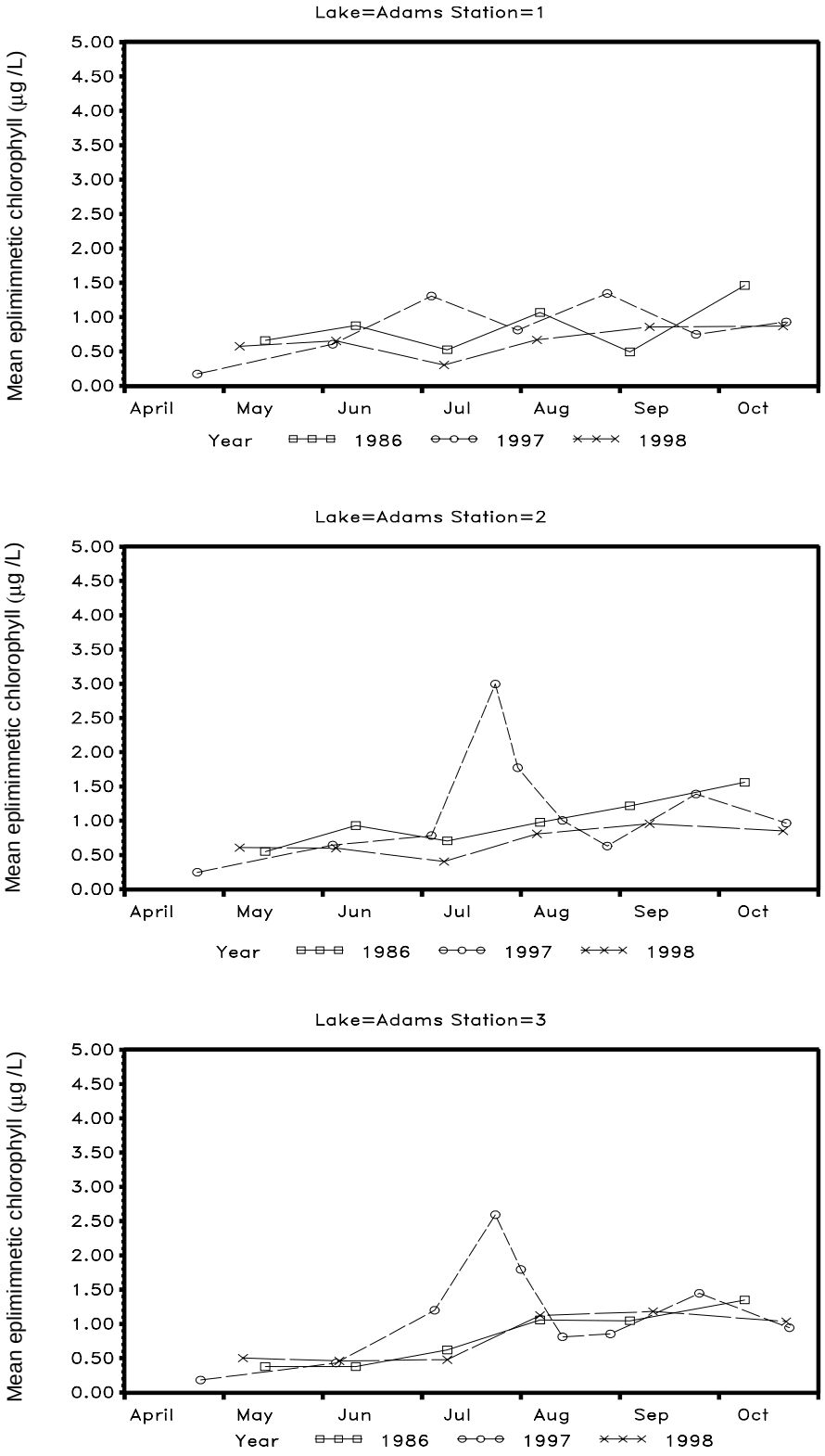


Fig. 10. Variation in epilimnetic concentrations of Chlorophyll for stations 1 - 3 in 1986, 1997, and 1998.

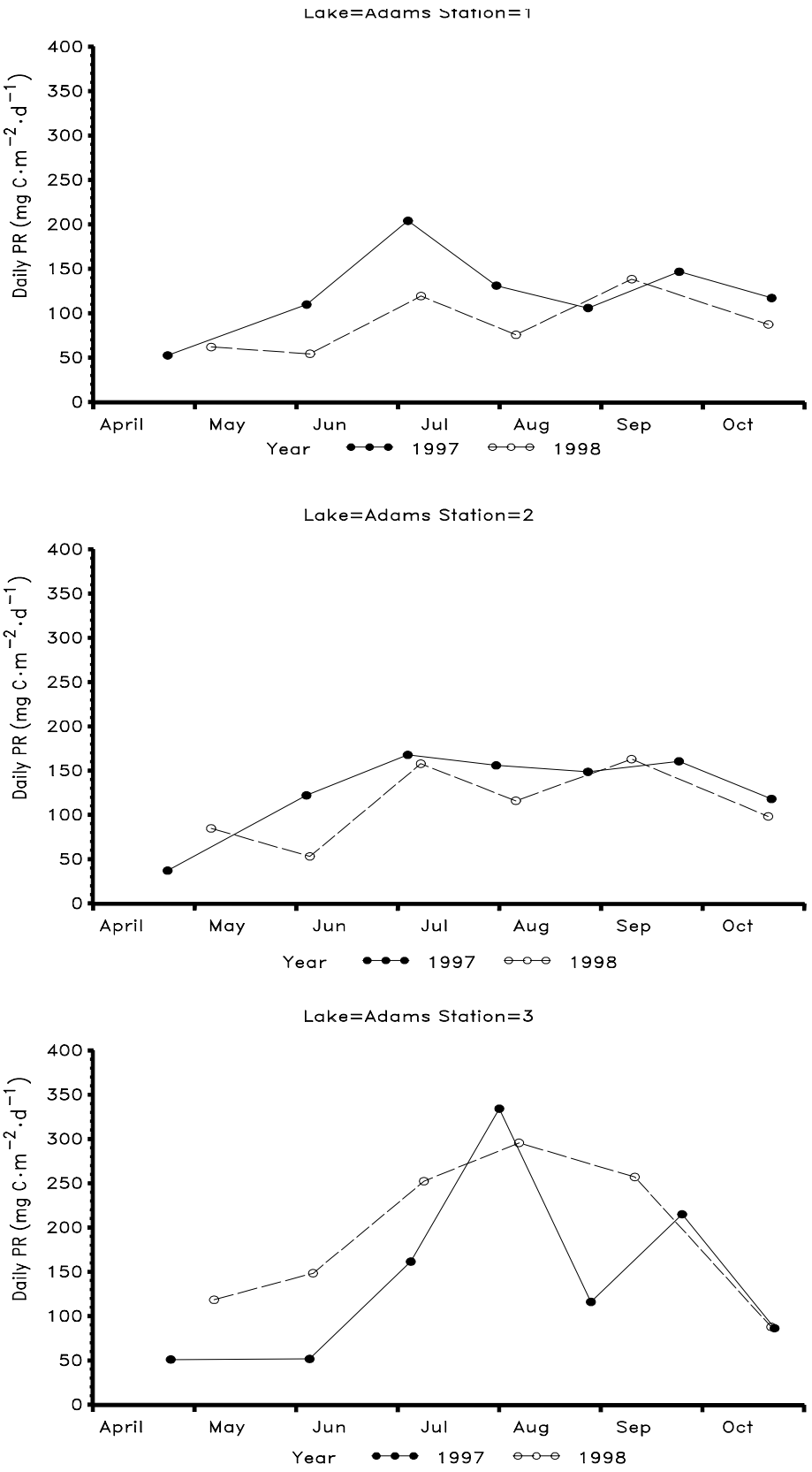


Fig. 11. Variation in epilimnetic concentrations of Daily PR for stations 1 - 3 in 1997, and 1998.

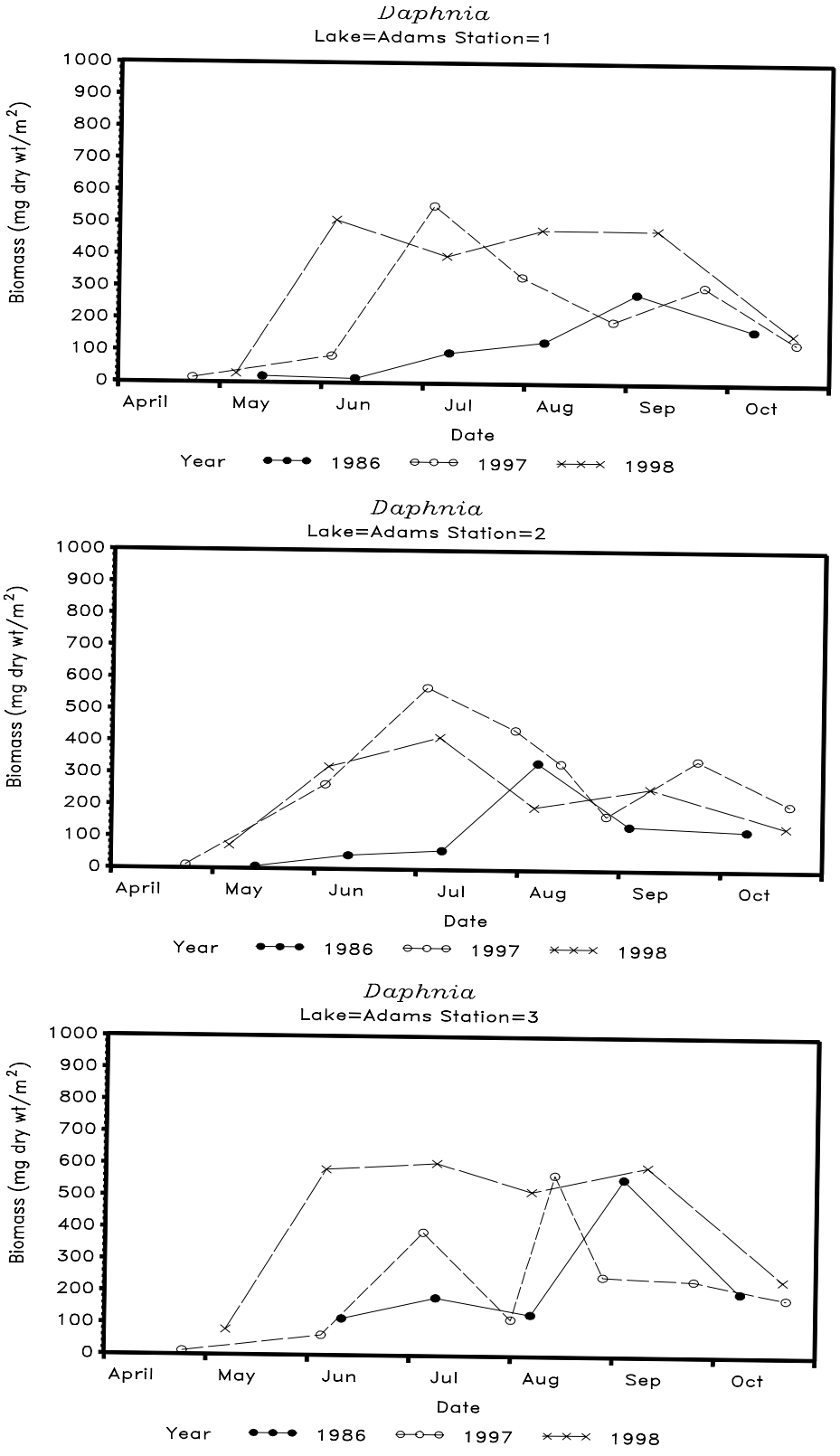


Fig. 12. Variation in Daphnia biomass for stations 1 - 3 in 1986, 1997, and 1998.

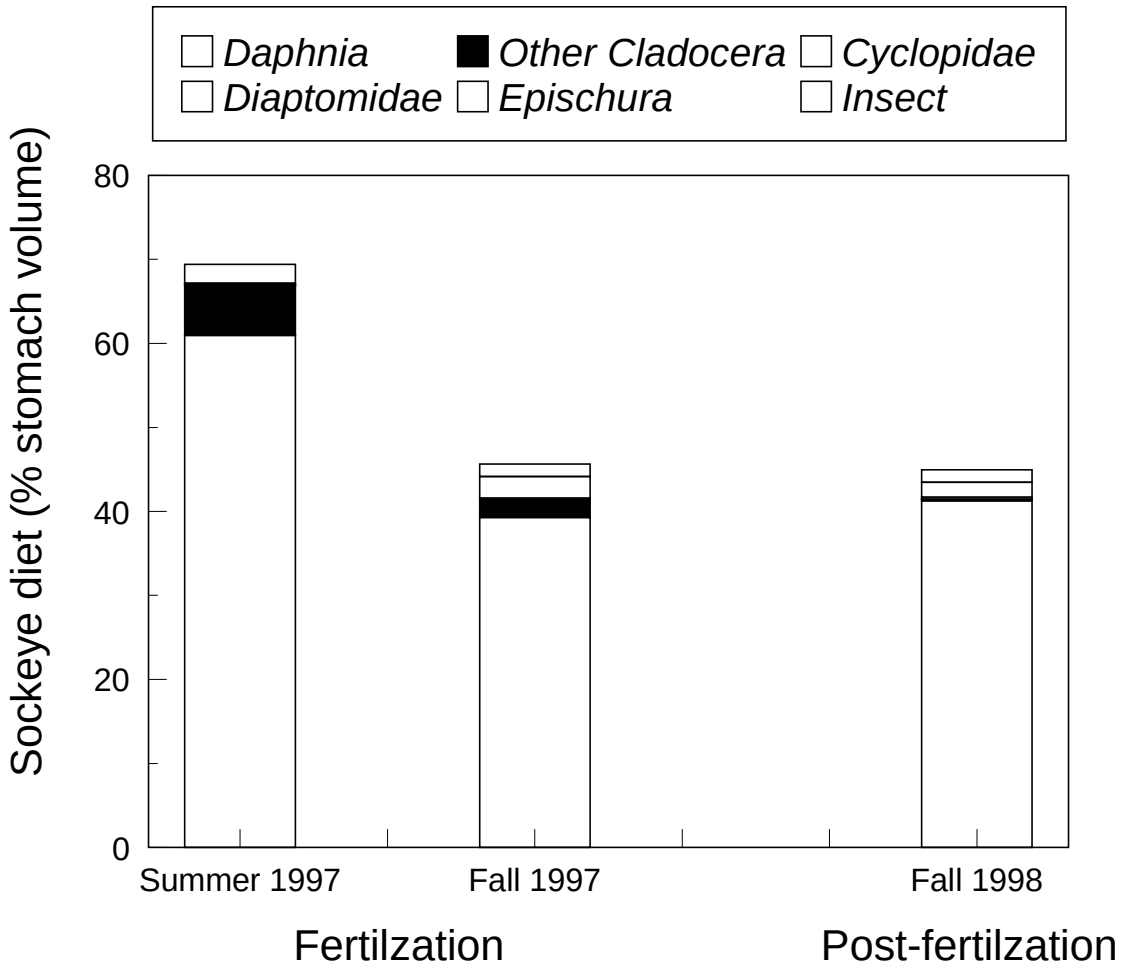


Fig. 13. Stomach fullness and composition of stomach contents for Adams Lake age-0 *O. nerka* from Adams Lake in 1997 and 1998.

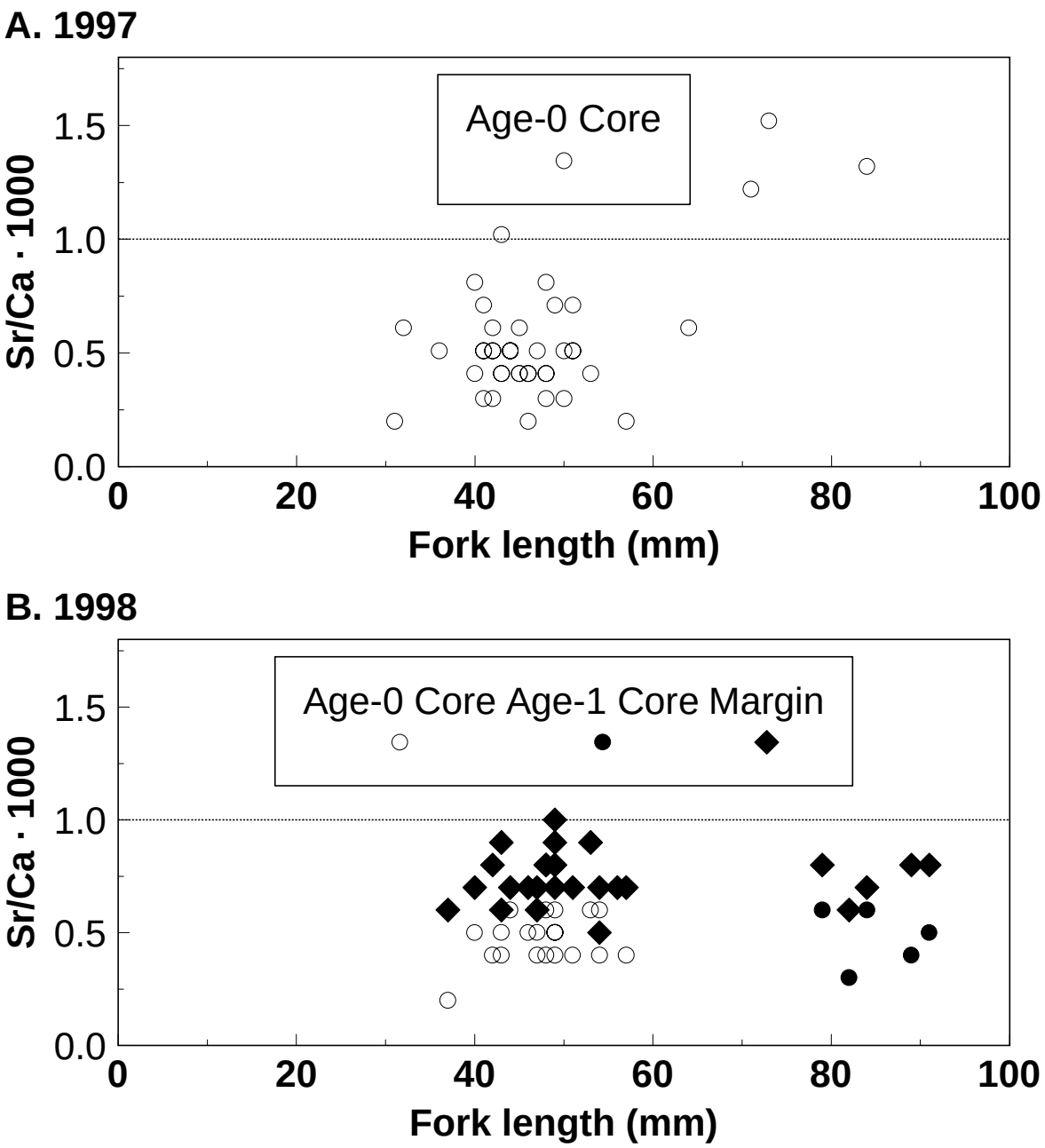


Fig. 14. Sr:Ca ratios in otoliths taken from juvenile Adams Lake *O. nerka* in 1997 and 1998. Ages in 1997 were determined from length frequency histograms and scales analysis of fish caught in the same trawls. Ages in 1998 were determined from scale analysis of the same fish used in the otolith analysis.

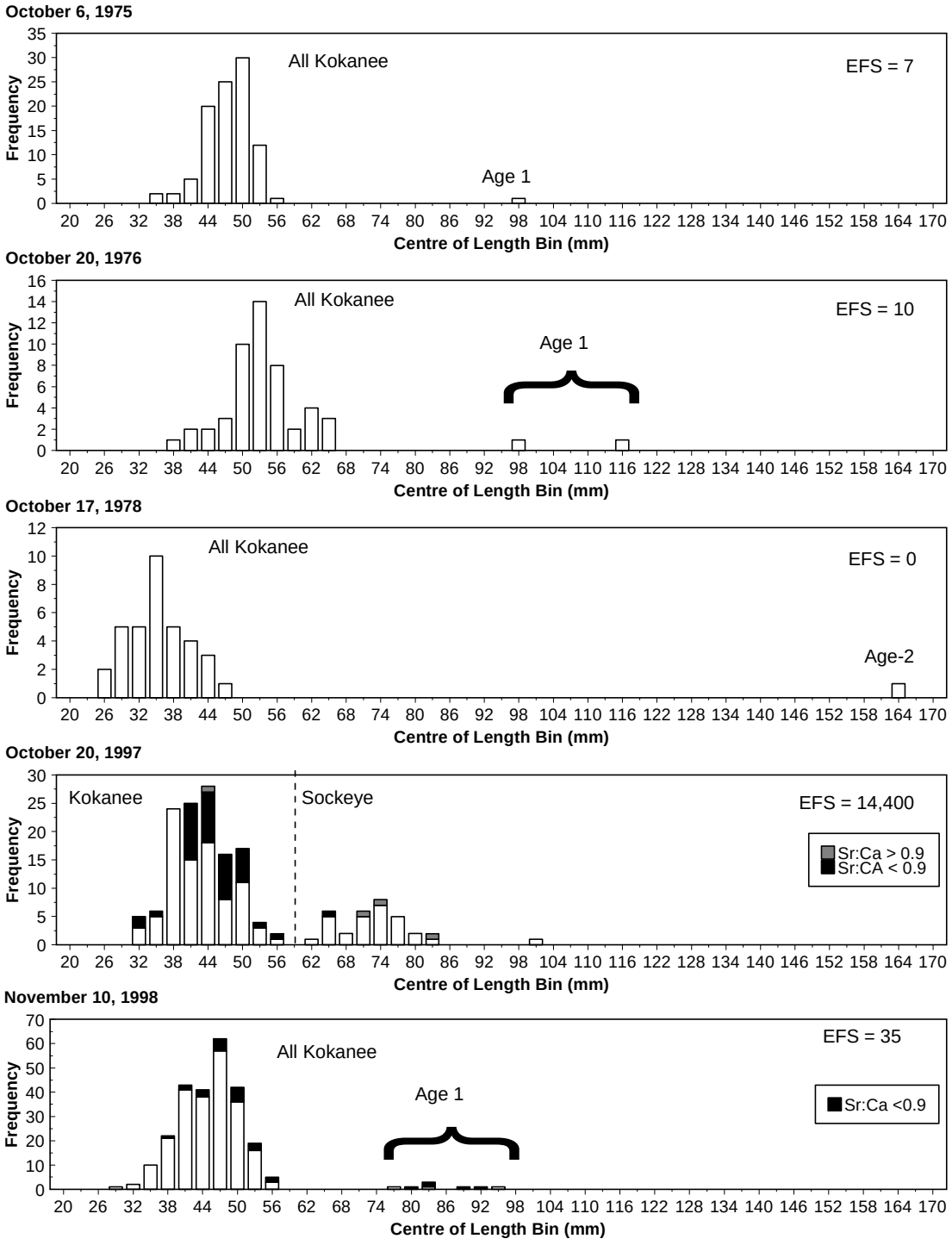
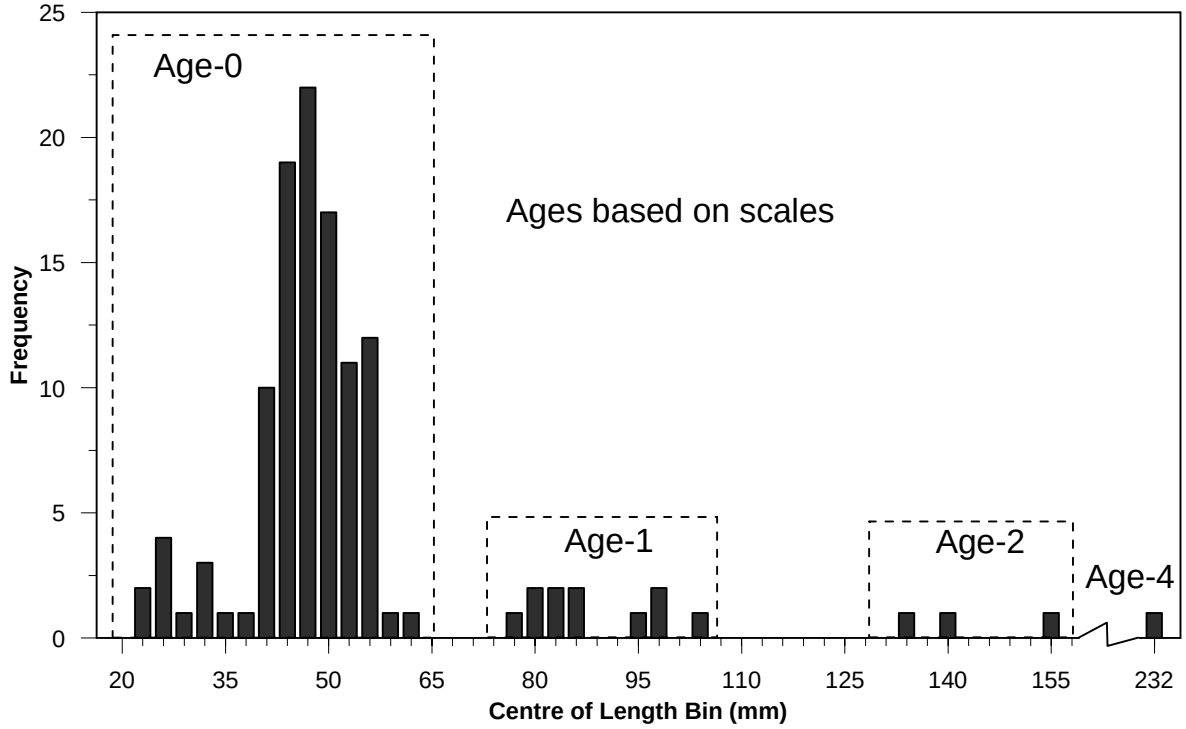


Fig. 15. Length frequency of trawl caught *O. nerka* during the fall in Adams Lake from 1975 to 1997. Ages are based on scale analysis. All fish are age-0 unless labelled otherwise. Stock origin is based on known sockeye spawning numbers and Sr/Ca ratios in 1997 and 1998.

July 19, 1997



October 20, 1997

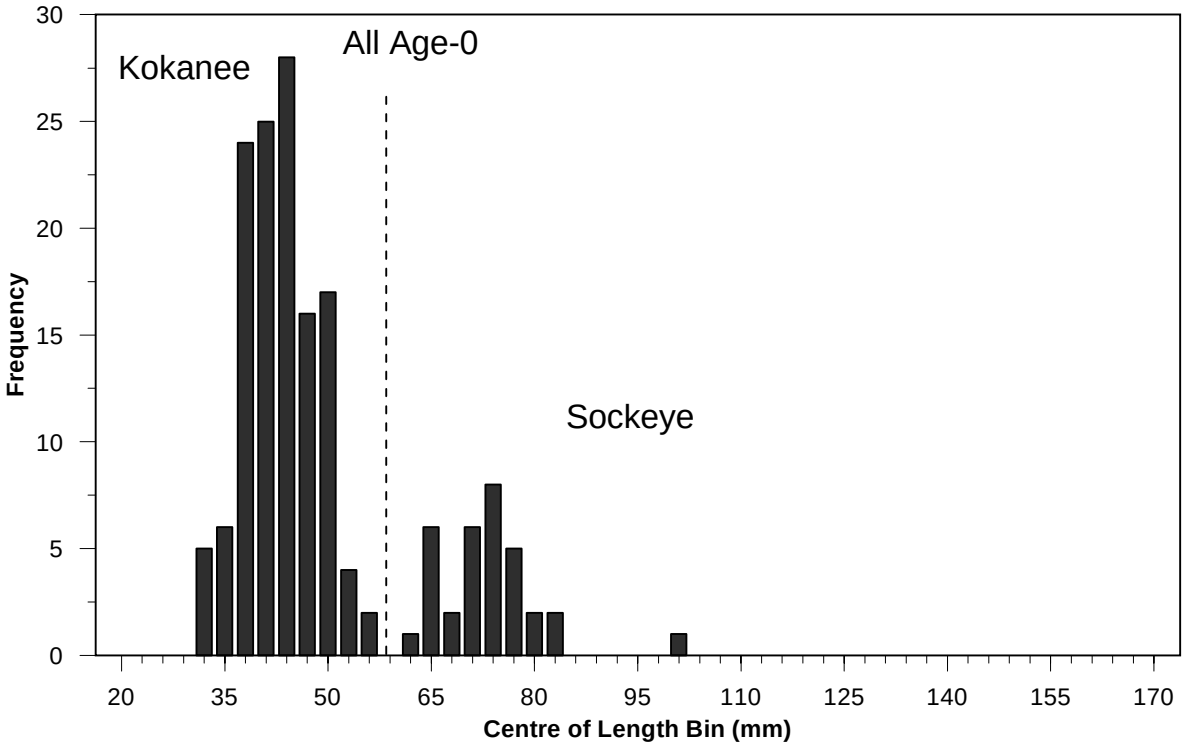


Fig. 16. Length frequency of trawl caught *O. nerka* in Adams Lake during 1997

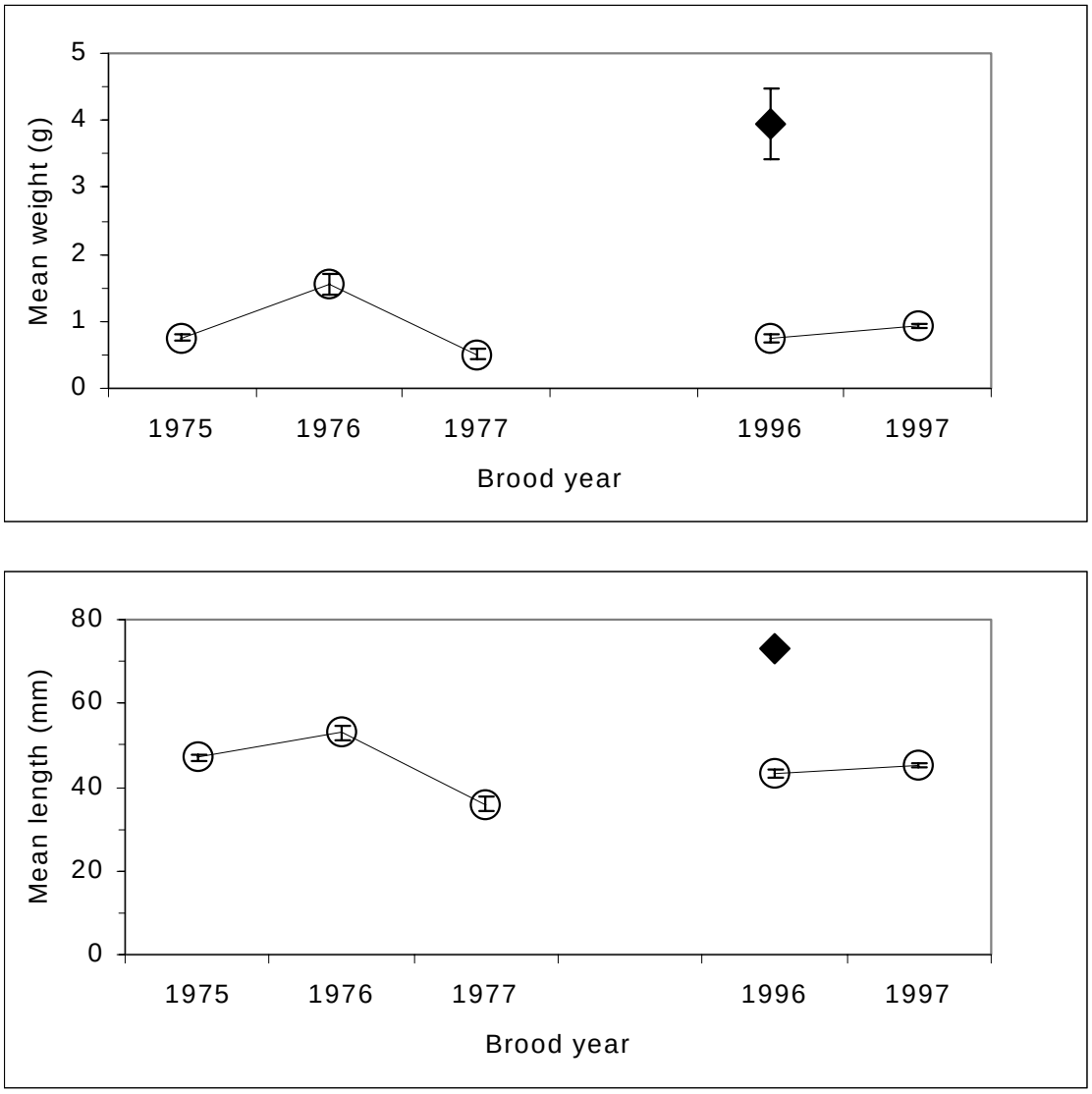


Fig. 17. Mean length and weight of Adams Lake age-0 kokanee and sockeye captured in the fall.

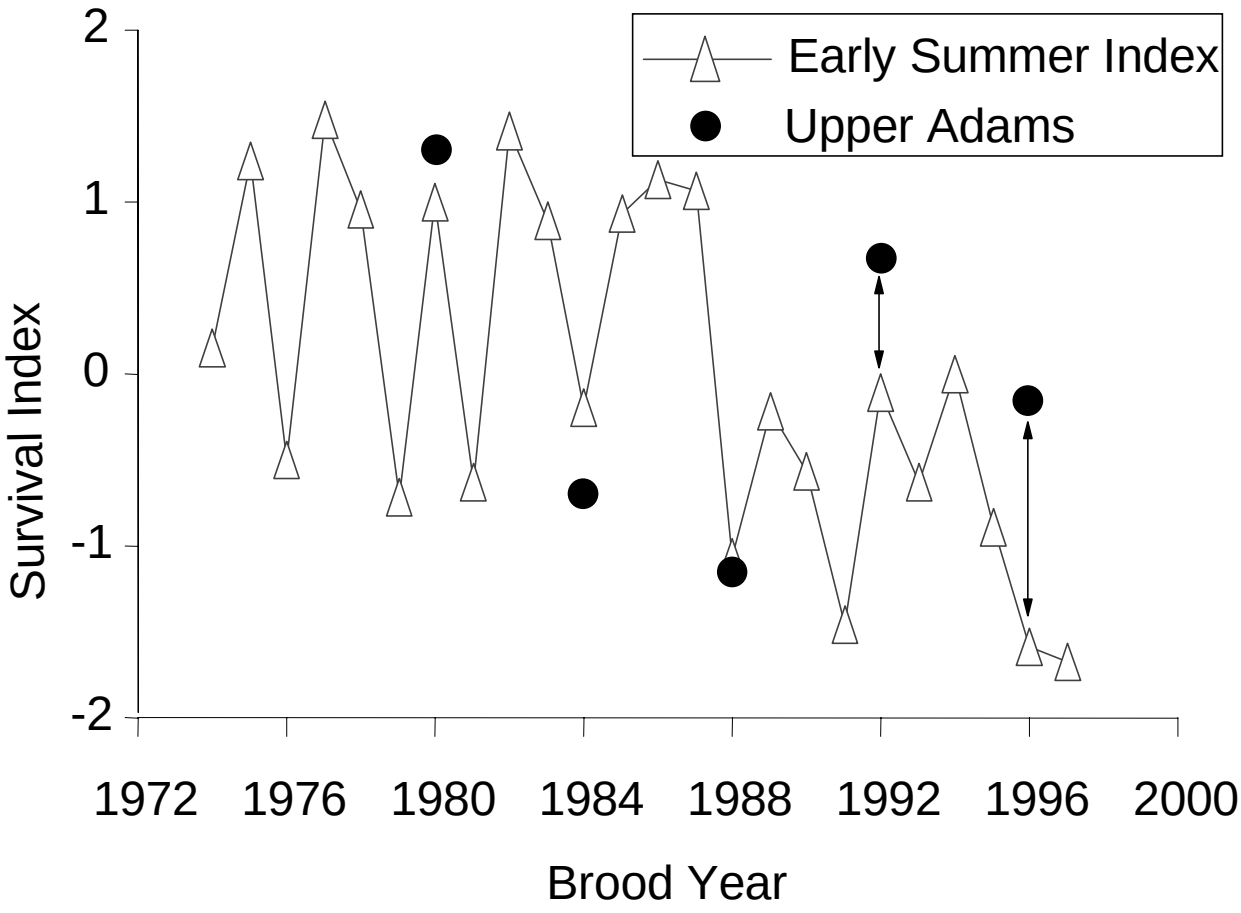


Fig. 18. Early Summer Index (survival index) calculated from Fennell, Raft, Scotch and Seymour populations by brood year; and survival index for 1996 cycle of Upper Adams River sockeye. Vertical arrows indicate potential effect of enhancement projects.