Fisheries and Oceans Canada
Science

Pêches et Océans Canada
Sciences

C S A S

Canadian Science Advisory Secretariat

S C C S

Secrétariat canadien de consultation scientifique

Research Document 2002/117

Document de recherche 2002/117

Not to be cited without
permission of the authors *

Ne pas citer sans
autorisation des auteurs *

Fraser River Eulachon Biomass Assessments and Spawning Distribution: 1995-2002

Évaluations de la biomasse et répartition des lieux de reproduction de l'eulakane du fleuve Fraser de 1995 à 2002

D. E. Hay, P. B. McCarter, R. Joy, M. Thompson, K. West

Fisheries and Oceans Canada
Science Branch, Stock Assessment Division
Nanaimo, British Columbia V9T 6N7

ISSN 1480-4883

Canada

ABSTRACT

The eulachon (*Thaleichthys pacificus*) is a small anadromous smelt (Osmeridae) that spawns in the lower reaches of the Fraser River in April and May. In most years, modest catches were taken by First Nations, a small commercial fishery and a recreational fishery. Since the mid-1990's the many participants and observers of these fisheries have expressed concerns about the apparently declining spawning runs. To address some of these concerns we adapted marine ichthyoplankton survey methods and assessed eulachon spawning stock biomass (SSB) based on egg and larval production surveys. Eulachon deposit small adhesive, demersal eggs. At ambient temperatures, these eggs hatch into small (<7 mm) pelagic larvae that are rapidly advected downstream, at the same velocity as the river. We developed survey protocols that estimated larval density (n/m^3) at five different locations over a seven-week period. We use the measured river discharge (m^3/s) to estimate the total number of larvae discharged over specific periods of time. We convert this estimate of larval numbers into SSB from our measured estimates of relative fecundity (about 400 egg/g). The SSB estimated are presented with bootstrapped confidence limits for each area, and we discuss the sources of variability and error associated with this assessment method. By comparing the estimated spawning biomass among different areas of the river we can also comment on the general spawning locations each year. Since 1995, we estimate that SSB has varied from a minimum of about 100 tonnes (in 1997) to a maximum of 1600 tonnes (in 1996). The SSB for years 2001 and 2002 are between 800 and 1000 tonnes, but the 2002 samples analyses is not complete, because of budget constraints.

RÉSUMÉ

L'eulakane (*Thaleichthys pacificus*) est un petit éperlan (Osmeridae) anadrome qui fraye en avril et en mai dans le cours inférieur du fleuve Fraser. La plupart des années, un nombre modeste d'eulakanes sont capturés dans le cadre de pêches autochtones, d'une petite pêche commerciale et d'une pêche récréative. Depuis le milieu des années 1990, les nombreux participants et observateurs de ces pêches expriment leurs préoccupations au sujet des remontes de reproducteurs apparemment en déclin. Pour répondre à certaines de ces préoccupations, nous avons adapté des méthodes de relevé de l'ichtyoplancton marin et évalué la biomasse du stock reproducteur (BSR) de l'eulakane en fonction de relevés des productions d'oeufs et de larves. L'eulakane dépose des petits oeufs démersaux adhésifs. À température ambiante, ces oeufs éclosent et libèrent de petites larves pélagiques (<7 mm) qui sont rapidement transportées en aval par le courant fluvial. Nous avons élaboré des protocoles de relevé pour estimer la densité larvaire (n/m^3) à cinq emplacements différents sur une période de sept semaines. Nous avons utilisé le débit du fleuve (m^3/s) mesuré pour estimer le nombre total de larves charriées par le courant au cours de périodes précises. Nous avons converti ces estimations du nombre de larves en BSR à l'aide de nos estimations de la fécondité relative (environ 400 oeufs/g). Les estimations de la BSR sont présentées avec les limites de confiance obtenues par la méthode « bootstrap » pour chaque zone. Nous discutons des sources de variabilité et d'erreur liées à cette méthode d'évaluation. La comparaison des estimations de la BSR des différentes zones du fleuve nous permet également de discuter de la répartition générale des emplacements de frai chaque année. Nous estimons que, depuis 1995, la BSR a varié entre un minimum d'environ 100 tonnes (en 1997) et un maximum de 1 600 tonnes (en 1996). La BSR pour les années 2001 et 2002 se situe entre 800 et 1 000 tonnes, mais l'analyse des échantillons de 2002 n'est pas terminée en raison de restrictions budgétaires.

INTRODUCTION

Eulachon (*Thaleichthys pacificus)* spawn in the Fraser River in April and May (Ricker *et al*. 1954). Until a formal closure in 1997, a small commercial fishery occurred annually, probably since the 1930's or perhaps earlier. In the last 50 years, this commercial fishery has changed. In the earliest commercial fisheries, Fraser River eulachon were used for meal or animal feed for fur farms but in more recent years eulachon were sold fresh for human consumption. In addition to the commercial fishery there has been a recreational catch of uncertain size and a First Nations fishery, mainly for fresh food. Aside from some nominal seasonal openings and closures, there has been little regulation of the commercial fishery. Instead, the catch was regulated mainly by the market demand. Anyone with a commercial fishing license could participate and no quotas were set. In 1994, when participation in the commercial fishery was limited to about 20 participants, many fishers observed that the runs of eulachon were particularly low and the fishery was closed in mid-season. Subsequent meetings between the commercial fishers, Fisheries and Oceans (DFO) and First Nations followed in that year and a pilot research plan was developed to attempt to locate the major spawning areas and estimate the spawning biomass, based on egg and larval production surveys described in Pedersen *et al.* (1995) and Hay *et al*. (1997). In 1995, a small eulachon fishery continued, with a target of 20 tonnes. A similar catch target fishery was planned for 1996 but an unprecedented number of fishers (71) participated and landed a total catch of about 63 tonnes, more than 3 times the precautionary quota. In 1997 the commercial fishery was closed throughout the entire season because DFO was unable to regulate the catch of so many participants. Instead, DFO started discussions to introduce license limitation based on the number of participants in the fishery in the 1980's and 1990's, or about 10-20 vessels. The total catch of a small fleet of this size could be controlled by monitoring hailed catches of all licensed vessels.

In response to continued concerns in 1997 and 1998 about the apparently diminished spawning runs of eulachon in the Fraser and elsewhere (Hay and McCarter 2000) egg and larval surveys in the Fraser River continued into the year 2002. The objective of this paper is to describe the results of all survey work and make recommendations for future work. This paper is presented as an update of a previous paper on eulachon stock assessment in the Fraser River (Hay *et al*. 1997). The previous paper examined two approaches to assessments, both based on quantitative analyses of egg and larval surveys. Both approaches used the product of river discharge and larval eulachon density to estimate total egg and larval production for specific periods of time and both attempted to assess error in the biomass estimates. One approach, however, attempted to normalize the data (estimates of larval density in n/m^3) using log transformations and the other suggested techniques for transforming egg and larval survey data (Smith and Richardson 1977). The alternative approach was to analyze the data without transformations and use a bootstrap technique to estimate error. The PSARC subcommittee agreed that the bootstrap approach was preferable and we have again used that approach here, although we present two complementary variations to that approach.

The biology of eulachon along the Pacific coast of Canada was reviewed by Hay and McCarter (2000) in a report that included summaries of known and new information, so we provide only a brief summary in this paper. Also, we have recently completed a technical sampling manual, describing techniques of eulachon egg and larval sampling and laboratory analysis that can be applied to the Fraser and other rivers (McCarter and Hay 2002). In a later separate, report, we review other indices of eulachon stock abundance, such as Fraser River gillnet test fisheries and indices of offshore biomass from annual shrimp trawl surveys. Therefore we have confined the subject of this report to: (1) reporting and commenting on the results of egg and larval surveys, (2) describing the analytical methods we used and (3) commenting on sources of sampling error, based on biological assumptions. The report concludes with a brief discussion of implications of the results to: (1) historic run size estimates of eulachon in the Fraser River and (2) definitions and locations of Fraser River eulachon spawning habitat.

Biological Review

Eulachon are members of the smelt family, (Osmeridae) and are distributed from the southern Bering Sea to northern California, although no spawning runs have been observed in the most southern part of their range for more than 20 years (Hay and McCarter 2000). Eulachon spawn during the spring months and the earliest spawning occurs in the Columbia River in January and February (the largest run in the world), and the latest spawning in the Fraser in April and May (which may have been the second largest run in the world). Spawning in northern BC and Alaskan rivers usually takes place in March and April. There is no clear geographic pattern of spawning times with latitude, or other conditions. For instance, river temperatures vary widely, with spawning occurring in the Fraser at temperatures exceeding 6 or 7 ^{o}C whereas temperatures in northern rivers, which sometimes are ice-covered during spawning, are much lower. Also, there is little in common among many of the rivers, with some being small and clear (i.e. the Kemano River in northern BC) while others are large and turbid (i.e. the Fraser River). What most eulachon-bearing rivers do have in common, however, is that they all have predominant spring freshets, and drain major snowpacks or glaciers. For instance, there are no regular eulachon runs in rivers that drain coastal islands or peninsulas that have predominant fall freshets following rains in November and December.

Eulachon appear to be semelparous (die after spawning) with most living for three years before spawning and dying (Hay and McCarter 2000). Probably some fish spawn at age two and others at age four or five. At lower latitudes (49^{o}-54^{o}, southern and central BC) post-spawning mortality seems to be the rule, although there may be some iteroparity (survive spawning) at higher latitudes, in Alaska or the Bering Sea. The evidence for semelparity in the Fraser, and other BC rivers, is strong. In the Fraser, and many other rivers, post-spawning mortality can be directly observed by floating and beached carcasses of spent fish. Also, we have confirmed that eulachon resorb teeth during spawning. All Fraser River fish that we have examined (several thousand) have evidence of substantial tooth loss. Furthermore, we observe only eulachon with well-developed teeth in the sea, after examining several thousand eulachon captured during offshore trawl surveys. Finally, the size (or standard lengths) of eulachon in the Fraser River constitutes the largest length groups of eulachon in BC, distinctly larger than any marine-captured eulachon. If any fish survived spawning, we would expect to observe a few, very large marine eulachon (which we do not), consistent with size distributions in rivers.

METHODS

Survey areas, times and vessels

From mid-April to mid-June, 1995 to 2002, we conducted plankton net surveys of the lower reaches and estuary of the Fraser River (Fig. 1). Originally we established 17 stations (or transects) from which samples were collected 1-2 times per week during the 7-8 weeks following the main run of spawning fish. In subsequent years we modified the sampling design to spend more effort sampling at lower Fraser River locations (Fig. 2) and stopped sampling most upriver locations.

Several vessels were used for this work. In 1995-1996 samples were collected from a 10 m launch (R/V REVISOR) for two days of each week (usually Monday and Tuesday) and a smaller 6 m whaler for 1-2 days per week, usually Thursday and Friday. Since 1997, we have used chartered, commercial gillnet vessels, and adapted the drum hydraulics to haul the plankton nets.

Key sampling stations

New Westminster is a key sample site because it is immediately upriver of the Fraser's divergence into the North and South Arms (Fig. 2). For this reason, all samples from the South Arm stations (***Tilbury and Deas Islands***) will tend to underestimate eggs and larvae production because some eggs and larvae will exit via the North Arm. On the other hand, the New Westminster site does not assess eggs and larvae from spawning downstream, in either the North, or South Arms of the Fraser River. ***Barnston Island***, the farthest upstream location, provides a biomass estimate of all eulachon spawning that occurred upstream of this location. The difference between biomass estimates at Barnston Island and New Westminster is an approximate estimate of the spawning that occurred between the sites, either in the Fraser River or the Pitt River, which enters the Fraser mainstem between the two sites. The difference in biomass estimates between Tilbury Island and New Westminster correspond to the biomass of spawning between those two locations. Similarly, the difference between Deas Island and Tilbury Island is an estimate of the spawning that occurred between those two sites within the South Arm. For 1995 and 1996, however, we did not take sufficient samples at Tilbury to calculate a biomass estimate. Similarly, in 2002 we collected samples, but lacked the resources to finish analysing Tilbury, Barnston Island and North Arm samples. Therefore for years 1995, 1996, and 2002 we pooled all the samples for the South Arm (***SARM***).

The collection of samples from the North Arm presented logistical difficulties, such that sampling effort was reduced relative to other locations. Still, by pooling samples from all North Arm locations (***NARM***), we estimated spawning biomass for all years, but caution that some locations were sampled relatively close to New Westminster. Such samples may contribute to an under-estimate of spawning biomass because they could miss spawning activity that occurred in downstream sites, within the North Arm.

Larval sampling: field methods

McCarter and Hay (2002) discuss and explain methods used to collect plankton net samples and conduct laboratory sorting and counting of larvae. Therefore the description of methods presented here is brief. Plankton samples were collected with small bongo nets, equipped with a General Oceanics© flowmeter. The nets were 1.5 m long with a mouth diameter of 19.5 cm and constructed of 350 μm Nitex mesh. The flow meter was mounted in the aperture of the net and was calibrated in order to estimate the total volume of water in cubic meters that was filtered through the net. The nets were deployed with a marked cable that indicated depth in metres. Where possible, samples were collected from fixed depth tows at the surface (0m), 5 m and 10 m depths and at three positions along cross river transects (north side, mid-river and south side) at each sampling site. At a few shallow stations we could only make surface and 3 m depth tows. Oblique tows were also conducted at each station and position on the river. These tows continuously sampled throughout the water column between the surface and 10 m depth. A minimum of 8 samples were collected from each area, each day, however, some areas (New Westminster and Deas Island) received maximum coverage of 12 samples per day. On retrieval of the nets from the water, the net's contents were collected in 1 litre bottles and fixed by adding formaldehyde to bring the total concentration to about five percent formalin. The samples were packed in boxes and stored until analyzed. Samples were analyzed at the Pacific Biological Station, Nanaimo (for the years 1995-1997 and 2001-2002) and at the Katzie First Nation (for the years 1998-2000).

In all years nearly all samples were collected during daylight, usually between 07:00 and 18:00 hours. We were concerned, however, that there may be a diurnal factor affecting eulachon egg and larval production, with either significantly more, or less production during dark, evening hours. For this reason we conducted a field experiment to assess the effect of time of day (or light vs dark) on estimated eulachon density. These tests were conducted over a 24-h period at the New Westminster sampling site. At each of four time periods (or 6-hour intervals) beginning at 24:00 (dark), 04:00 (dark), 10:00 (light) and 14:00 (light) we sampled at each depth (0, 5 and 10 m) at each of three positions (north, middle and south) in the river. Therefore with a combination of three depths and three positions, there were nine samples collected at each of the four sampling periods for a total of 36 samples. Using analyses of variance (ANOVA), we compared the estimated density of eggs and larvae in each sample to determine if there were diurnal differences in egg or larval density.

Larval sampling: laboratory methods

Detailed sample analysis methods are described in McCarter and Hay (2002). Therefore the description of methods presented here is brief. Excess sand and debris was removed from the samples by a set of fine-screen sieves (2 mm and 600 micron) that retained eggs and larvae. The concentrated remains of the samples consisted of various quantities of river debris (sand, small wood particles, fibers, insect parts, etc) in addition to eulachon eggs and larvae. Sometimes the larvae of other fish species were counted, especially starry flounders (*Platichthys stellatus*).

Both eggs and larvae of eulachon were collected (see Results and Discussion for more explanation) and some eggs were clearly dead, but most appeared to be alive and viable. Dead eggs were usually opaque, slightly shrunken, and without a clear periviteline space. In contrast, live eggs were translucent, larger and had a clear periviteline space. These characteristics of live and dead eggs were confirmed from photographs of eulachon eggs that were reared in the laboratory. For selected sub-samples from all years and most sampling areas, we attempted to quantify the approximate proportions of live and dead eggs.

Analyses of adult eulachon

Samples of spawning adults were collected in most years from the commercial gillnet fishery. After capture, eulachon were randomly assembled and frozen for later analyses. In the laboratory (PBS, Nanaimo) specimens were thawed and blotted dry. Data recorded included standard length, fork length, total body weight, fresh (wet) and preserved ovary weight, preserved egg weight and sex. Fish lengths were measured with calipers to the nearest millimeter. Weights were obtained to the nearest 0.1 gram using an electronic balance. The mean lengths and weights were compared among years by ANOVA. Linear regressions of the log-transformed standard lengths and weights were estimated and the residuals were compared among years. The value of the residual is a simple measure of 'condition': high residuals are indicative of fish that were heavier at a specific length, and low residuals indicate fish that were lighter. When compared among years, a lower mean residual may be indicative of fish that were in poorer condition.

Estimating relative fecundity

Whole ovaries from unspawned females were removed, weighed and preserved by placing them into individually marked jars containing 10% formalin solution for at least 2-4 weeks to harden the eggs. After the hardening period, the ovaries were rinsed in clean seawater and dissected with forceps under a dissecting microscope. Exactly 100 loose, robust eggs were counted using a dissecting microscope and isolated. Robust, hydrated eggs were easily visible to the eye and were considered most likely to have survived. Three, 100-egg sub-samples were vacuum-dried for one minute in a Buchner funnel on damp filter paper and weighed separately to the nearest 0.l mg on a precision Cahn© Electrobalance. The preserved, whole ovaries (excluding sub-samples) were also vacuum-dried at the same time and weighed to the nearest 0.01 gram on an electronic balance. If any of the 100-egg sub-sample weights differed from the other by more than 10%, this sub-sample was returned to the ovary and the process was repeated. The mean weight of a preserved individual egg was estimated from the sum of the three, 100-egg sub-sample weights divided by 300. The fecundity (number of eggs per individual female) was estimated as the preserved ovary weight divided by the mean egg weight. The relative fecundity (number of eggs per gram of body weight) was then calculated as the fecundity divided by the body weight.

Estimating egg and larval production

The plankton nets captured both unhatched eggs and newly hatched larvae. For the purposes of estimating total egg and larval production (P) eggs and larvae were treated as numerical equivalents. For unknown reasons both larvae *and* eggs were captured frequently by the gear. The reason for the capture of eggs, which presumably originated from the bottom substrates, is uncertain but the same phenomenon is seen in the Kitimat and other rivers (Hay and McCarter 2000, Pedersen *et al*. 1995). We discuss the potential implications of this later. The cumulative number of eggs and larvae was estimated for each time period (t) as the product of the mean density of eggs plus larvae, or D (numbers/m^3) and the river discharge V (m^3/s) and the interval (I) or duration of the time period (t) in seconds:

$$P_t = D_t V_t I_t \qquad \textbf{(1)}$$

The discharge was available as mean daily estimates in m^3/s (Table 1). Usually larval densities were estimated 2 times per week at each major sampling location, thus we set the period *t* as always 7 days. The total egg/larval production for the spawning season is the sum of the estimates for each interval:

$$P = \sum_t D_t V_t I_t \qquad \textbf{(2)}$$

Theoretically, if all spawning occurred in one location, upstream of all sampling locations, then each location, at each time period, should be an independent estimate of P. Alternately, if spawning occurred throughout the sampling area, then the estimate of P should be highest in the most downstream locations and lowest in the most upstream. Samples were routinely collected bi-weekly from all sampling locations at several depth intervals and river positions, and particularly from the New Westminster and Deas Island stations which we consider most important.

Calculation of spawning biomass from estimates of egg and larval numbers

The estimate of the biomass of spawning females from a measure of the stock's annual egg and larval production is simply B = P/R , where B is biomass of spawning fish in the stock, P is the egg production of stock, R is the mean number of eggs/g/female. For eulachon in the Fraser River, we are interested in the biomass of spawning fish (males and females) so we modify this general equation as follows:

$$B_t = P_t / (R_t \cdot S_t) \qquad \textbf{(3)}$$

where B_t is the biomass of the spawning stock at time t, and R is the relative fecundity (eggs/g/spawning females) and S is the sex ratio (proportion female). This is a common equation and is the basis for estimation of spawning stock size for many fisheries, including the 'escapement' method used for Pacific herring (e.g. Schweigert *et al*. 1996). Specifically, for eulachon we estimate the biomass in grams or tonnes. To estimate P we need to estimate the number of eggs and larvae produced by the spawning stock. To estimate RS we require data on the number of eggs per gram of spawning females and the sex ratios. Most of the remainder of this paper is concerned with these estimates.

River discharge: data and sources

Daily discharge rates of the Fraser River were obtained from Inland Waters, Water Survey of Canada. The gauging station is located at Hope, BC. There are a number of sources of fresh water input between the Hope Station and our sampling locations and there are additional sources of freshwater input *within* the study area. Thomson (1981) estimates that the discharge in the vicinity of the study area is about 30% greater than the discharge at Hope. Therefore, the total estimates of P, using uncorrected flow rates from Hope, will underestimate total egg/larval production.

Data analyses: Bootstrap method #1 (cumulative weekly estimate)

We used a bootstrap method (Efron 1993) to estimate the mean and 95% confidence limits of egg and larval density measurements for each sampling area. We pooled all bi-weekly density measurements (oblique, surface, 5 m, 10 m sampling depths and north, mid-river and south river positions) into 7, one-week periods for each area. Annual egg and larval production was estimated in each sampling area by the cumulative total of each weekly estimate. For each bootstrap sample we let n = 1000. Bootstrap estimates (sampling with replacement) were generated from each sampling area during each of seven, one-week periods (from late April to mid-June) in each year (1995 to 2002). The bootstrap procedure estimated the confidence limits about the means (densities of egg plus larvae) for each week. The estimation of spawning stock biomass (SSB) was then calculated by multiplying by the respective cumulative weekly river discharge (m^3/s) and dividing by the relative fecundity (estimated as a constant 400 egg/g).

To estimate the cumulative mean biomass (and confidence limits) from consecutive sampling periods (week 1 to 7) we summed the individual bootstrap replicates: so that each of the 1000 bootstrap replicates from week 1 were added to the 1000 bootstrap replicates from week 2, and so on, for each successive period until week 7. For each bootstrap replication, the 95% confidence limits were estimated from the sample points representing the range between 2.5 and 97.5% of the bootstrap means. Approximately 12-24 field measurements were used to derive each weekly biomass estimate in each sampling area. Two additional bootstrap series (using 24-40 field measurements per week) were subsequently performed by pooling all South Arm sampling stations (Deas and Tilbury Islands) and pooling all North Arm sampling stations (Iona, Oak St Bridge and Pipeline). South Arm and North Arm pooled biomass estimates can then be summed and compared with those of New Westminster and Barnston Island that were conducted upriver of the north/south arm flow divergence.

Data analyses: Bootstrap method #2 (single annual estimate)

In a similar manner to method #1 (above) we estimated the total number of eulachon eggs and larvae produced in the Fraser River in a given year, by multiplying the density of eggs and larvae (n/m^3) by the river discharge (m^3/s) estimated at Hope. We then log-transformed these density data to stabilize the variance. The transformed data were assumed normalized by the log transformation such that a smoothed function passing through the median of the transformed data would also pass through the mean of the transformed data. We fit a non-parametric kernel smoother to the log-transformed data. This fit a smooth function to the expected number of eggs and larvae at any point in time. We chose a kernel bandwidth of seven days corresponding to a weekly sampling period. We then back-transformed the kernel-fit curve to the original scale. We adjusted the back-transformed mean function for non-linearity by using a Taylor-series first order correction (Casella and Berger 1990). We integrated the function using Riemann sums (Stewart 1995) to get a numerical approximation for the cumulative biomass.

This method provided a single annual estimate of the cumulative biomass of eulachon for each sampling station. In order to get confidence intervals and a measure of variability about this cumulative estimate, we ran a bootstrap simulation. For example, for any given day in one year, there were on average about 8 samples of egg and larvae density. We took "8" bootstrap samples for each of the sampled days in the year (the number actually varied according to how many samples were collected on a given day). We then followed the same methods as described above: we transformed the data, fit a curve, back-transformed the data, and numerically integrated the curve function to get one bootstrapped estimate of the cumulative biomass. We did this 1000 times to get 1000 bootstrapped estimates of biomass. To get a 95% confidence interval for the cumulative estimate, we calculated "Basic" intervals rather than the more widely used "Percentile" intervals (Efron and Tibshirani 1993). Because the distribution of the cumulative biomass estimates is asymmetrical, the Basic intervals are considered less biased as they do not rely on any underlying assumptions of normality (Efron and Tibshirani 1993). This method was used for two of the locations only: New Westminster and the South Arm (Deas and Tilbury Islands combined), and for the years 1995-2001.

RESULTS

Analysis of adult eulachon samples: inter-annual and sex differences

Based on analyses of 2672 fish collected between 1995 and 2001, fish weight increased exponentially with standard length (Fig. 3) as follows: log wt (g) = -4.50149 + 2.77424 log (standard length - mm), (r^2 = 73.3%). Length-specific weights varied among years (Fig. 4) and these differences, examined by ANOVA, were significant.

The mean length and weight of samples was still relatively consistent among years (Table 2). The mean female size for all years was: 157.8 mm standard length (SD = 11.24) and a mean wt of 41.4 g. Compared by a one-way ANOVA there were significant differences in mean weights among years both for males ($F = 8.11$, $p \ll 0.001$) and females ($F = 6.94$ and $p \ll 0.001$). These differences, however are relatively small, with a maximum female inter-annual differences in means of 7.7 mm (length) and 9.1 g (weight), and maximum male inter-annual differences of 5.7 mm (length) and 6.6 g. The major difference in size composition occurred in 1998, when most of the fish were smaller in length as well as weight (Fig. 4).

The sex ratio of samples collected in each year was approximately 50 % with some years slightly higher and other years slightly lower, except for 1998, when significantly more males were collected (Table 3). No samples were available for 1999 because the proposed gillnet test fishery was cancelled. The percentage of total weight, summed by sex for each year, was also approximately 50 percent for each sex. This indicates that the value 0.5 for S (equation 3) is valid, although the sex ratio in 1998 appears to be biased in favour of males. The deviation in sex ratio in 1998 could have several explanations. The samples were collected with gillnets, so it is possible that there could be some bias in the size composition of the samples. Also, we had no control over the timing of sample collections, so there could be some temporal variation in the sex ratio of spawners as the spawning season progresses (specifically larger eulachon may spawn earlier than smaller eulachon), as observed in herring and other species (Hay 1985). Therefore because the sex ratio was close to 1:1 in five of the six years we examined, and because there were reasons to occasionally expect some variability due to sample error, or within the spawning season, we conclude that the assumption of an equal sex ratio is valid.

Relative fecundity: measurements, calculations and inter-annual variation

Relative fecundity (eggs/g) was estimated for 521 females collected between 1995 and 1998. No samples were available for 1999 (samples collected in 2000, 2001 and 2002 remain unanalyzed because of budget limitations). In some sexually mature specimens there may have been some loss of eggs prior to estimation of fecundity, and in others there may have been some loss of somatic tissue, from tearing of operculums, heads or tails from the gillnets during capture. To reduce this error in fecundity estimation, we examined a subset of the samples that represents only females with a GSI (gonosomatic index) or percent gonad weight that was greater than 15 or less than 30. Low GSI values (i.e. << 15) would be expected among fish with excessive eggs loss, although few, if any, fully mature females with no egg loss would have a GSI less than 15. Similarly, a GSI > 30 would occur mainly in females that have intact ovaries and no egg loss but that have suffered significant loss of somatic tissue. Therefore to account for this possible source of error on fecundity we show the estimates of total and relative fecundity for all females (Table 4a, n = 521) and for a subset described above (Table 4b, n = 421). The differences between the two sets of data are small, and selection of data according to GSI has little effect on total estimates. There are, however, some significant inter-annual differences in total and relative fecundity. Small differences in total fecundity would be expected, because we already have noted that there are significant inter-annual differences in mean size (length and weight).

The frequency distribution of relative fecundity data (Fig. 5) was approximately normal (approximate P value of 0.09 from a Kolmogorov-Smirnov normality test). When relative fecundity was compared to length (mm) the slope was close to zero but; nevertheless, significant (Fig. 6). When relative fecundity was compared to length within individual years, however, there was no significant relationship except for 1998 (Table 5). Therefore for the subsequent analyses we have assumed that there is no meaningful effect of fish size. There are, however relatively small but significant inter-annual differences in relative fecundity. The annual differences in relative fecundity, examined by ANOVA are significant ($F = 95.98$, df = 3, 488, $P<<0.01$). Significant inter-annual differences in relative fecundity are a concern because this estimate is used for calculating spawning biomass (R_t in Equation 3).

The effect of an increase in relative fecundity will be to lower the estimate of spawning biomass. From Table 1, it is clear that the years with estimates of high relative fecundity (1997 and 1998) are also the years when general fish sizes were smaller. The estimate of relative fecundity is dependent on 'condition' or degree of fatness, and relative fecundity will be higher in low condition fish. A comparison of weight at length (Fig. 4) shows that years 1997 and 1998 were lower than other years. This was confirmed by examining the residuals in a regression of (log) length and (log) wt data. In such a regression a negative residual occurs in fish that, for a given length, had a lower body weight than the average. A comparison of the residuals, examined by ANOVA, indicates significant inter-annual differences between 1995 and 2001. For this reason, it would be desirable to use a year-specific estimate of relative fecundity but we have data only for four years, from 1995-1998. If and when the estimates of relative fecundity for other years (2000-2002) become available, then we could revise our biomass estimates accordingly.

As an alternative to year-specific estimates, we opted to use an approximate estimate of 800 eggs/g (or 400 egg/g for both sexes). This estimate is intermediate between the low values seen in 1995 and 1996 but lower than that seen in 1997 and 1998. It also is similar to the estimates used in a previous report (Hay *et al*. 1997) of 700 eggs/g (or 350 for both sexes). Although this estimate is very close to that shown in Table 3, we advise that the SSB estimates for 1997 and 1998 may be over-estimated. If the relative fecundity in 1997 was really about 900 eggs (450 for both males and females) then using an estimate of 800 would result in an over-estimate of about 11%. Similarly using an estimate 800 eggs/g instead of the observed 850 eggs/g in 1998, would over-estimate the SSB estimate by about 6%. On the other hand, if the actual fecundity were about 700 egg/g in 1995 and 1996, the estimate of 800 would underestimate SSB by about 14% in those years.

The potential for error caused by uncertainty about relative fecundity between 1999 and 2001 is uncertain, but probably it is well within the ranges shown above: that is, plus or minus 10-15%. This assertion is based on the observation that the distribution of residuals in years 1999-2001, from a regression of (log) wt by (log) length is approximately intermediate, between the highs of 1995-96 and the lows of 1997-98. Therefore, if the annual condition of a fish affects relative fecundity, then we would expect that the relative fecundity of eulachon in years 1999-2002 would be intermediate between those of years 1995 and 1997.

Analysis of plankton net samples:

(a) Estimates of live and dead eggs. It was impractical to closely examine every egg collected in the surveys, but we did examine over 11,000 eggs from 514 selected samples collected from 7 different sampling locations in the river in 1998 (251 samples) and 1999 (263 samples). For each sample we estimated the proportion of dead versus live eggs in addition to the number of larvae (Table 6). In both years (1998 and 1999) the percentage of eggs remained relatively high in all months (April: 54% and 95%; May: 52% and 14%, June: 73% and 29%). In both years, however, the percentage of live eggs was highest in April (54% and 76%), lower in May (49% and 64%) and lowest in June (10% and 62%). Although these may appear to be very high mortality rates, the percentage of viable offspring (live eggs plus larvae) was much higher and varied between 70% and 95%, except for 34% in June, 1999, but this low estimate probably reflects a small sample size. Although these results may warrant more future attention from the perspective of reproductive biology or ecology, the presence of live and dead eggs in the samples should not necessarily require any modification to the assessment methods, where a dead egg has equal value to a live egg.

(b) Factors affecting variation in egg and larval density: depth, position and time of day. Based on experimental analyses of samples collected on May 23-24, at New Westminster (Table 7) there were no significant differences in densities of eulachon eggs and larvae (n/m^3) either by depth ($F = 0.20$, $P > 0.8$) or time of day ($F = 0.22$, $P>0.8$). There were, however, significant differences among the three river positions: densities were significantly higher ($F = 12.78$, $P << 0.01$) on the north side of the river, intermediate in the middle and least on the south side (Table 7).

Spawning stock biomass estimation: Weekly method #1

Weekly and cumulative boxplots of bootstrapped biomass estimates were derived from egg and larval densities with 95% confidence intervals (Figs. 7a-f). The annual cumulative estimates (corresponding to the shaded bar in the far right of each panel in Fig. 7) are presented in Table 8 and show biomass estimates with upper and lower 95% confidence intervals derived from the 'cumulative weekly' (bootstrap method #1). In addition, geographically pooled samples from all South Arm (SARM) and North Arm (NARM) sampling stations were also run through bootstrap method #1 to produce combined estimates for each year. These estimates were based on 24-40 weekly field measurements as opposed to only 12-24 weekly measurements using the uncombined approach.

All boxplots with the exception of the 1996 South Arm, showed distinct, unimodal curves that differed only by the timing and magnitude of the runs. Corresponding weekly North Arm and South Arm boxplots showed remarkable similarities. The relative differences in egg and larval production between sampling areas in a particular year may reflect the locations where the majority of spawning occurred. Mean biomass estimates in the South Arm were always greater than or closely equal to those in the New Westminster area in 6 of the 8 surveyed years. This suggests spawning occurred to varying degrees above and below New Westminster (see Table 9, comments section). In 2001 and 2002, however, New Westminster egg plus larval production estimates have been greater than those in the South Arm. One possible explanation is the diversion of a large portion of eulachon larvae (perhaps as high as 30% and probably variable according to spawning distribution) down the North Arm (see Discussion). As of October 2002, all North Arm samples have not been processed to confirm this possibility but samples in 2001 did show relatively high larval densities (187 tonne spawning biomass estimate).

Spawning stock biomass estimation: Annual method #2

As an illustration, the smoothed expected number of eggs and larvae, by time, is shown relative to observed data for Deas-Tilbury Island (1995) in Fig. 8a and the log-transformed data are shown in Fig. 8b. The numerical approximation of the mean cumulative biomass for all years from 1995-2001, with 95% confidence intervals, is shown in Table 9a (Deas-Tilbury Island) and Table 9b and for New Westminster. The estimated means of the cumulative spawning biomass estimates are nearly identical (Fig. 9) for the two sampling stations of New Westminster and South Arm (Deas and Tilbury Island pooled) and have r^2 correlation coefficients of 99 and 98 percent, respectively. These estimates of the means of spawning biomass are very similar between the two methods, but the confidence limits are much tighter for method #2 (Fig. 10).

Larval data as indicators of spawning sites

As indicated in Table 7 for experimental sample collections, larval densities from sampling sites on the north bank of the Fraser River were significantly higher than those from mid-river sites or sites near the south bank. It is likely that spawning occurs more frequently on the north side of the Fraser River or from major tributaries (i.e. Pitt River) that join the Fraser mainstem from the north side. Cross-river dispersal and mixing is minimal and very gradual in the lower 50 km of the Fraser River because of river channelization and limited meander. An example of this north and south side difference in larval densities is shown for Deas Island, in 2001 (Fig. 11). This tendency to favour the north side of the river is shown by mean egg plus larval densities compared between the north, middle and south positions at Barnston Island, New Westminster and Deas Island sampling stations (Tables 11a-c).

DISCUSSION

The sampling design

In the first year of this work we had little *a priori* basis for the survey design. From earlier work concerned with the identification of spawning areas (Samis 1977) we knew that some eggs were found as far upstream as Mission, and that eggs were found both in the North and South Arms. It was unclear if those eggs had been spawned there or had advected downstream from upstream areas. We also knew that a considerable part of the small commercial fishery occurred upstream from New Westminster so we set New Westminster as the main sampling area. This site has the advantage of being located immediately above the river divergence into the North and South Arms (a factor that complicates the abundance analyses).

Operational limitations also affected the study design. Initially we attempted to sample with a small trailered-vessel, but we found that there are a limited number of launching sites and few safe moorage sites that are convenient to the main sampling areas. For this reason, from 1995-1997 we used a relatively high velocity 10 m DFO launch, the R/V REVISOR, that allowed us to work along the entire length of the river, from Steveston to Mission, over a period of 2 days. After 1997, this vessel was no longer available, so we chartered slower-velocity (~10 m) salmon gillnet vessels. These vessels could deploy the sampling gear with equal efficiency but took longer to run between sampling locations. Therefore beginning in 1997, we altered the survey to concentrate sampling to fewer locations but we increased both the number of samples at each site and the sampling frequency at each site.

Sampling methods: comparison with other study conditions

The methods and sampling equipment used here follow the general recommendations made by Smith and Richardson (1977) and are consistent with egg and larvae surveys conducted for other species in marine areas. The main difference is that we did not conduct a broad, 2-dimensional survey over a short time interval. Instead, we conducted a survey in a single direction (i.e. a river) over a broad range in time. We used temporal variation in river flow (m^3 per unit time) as the equivalent of spatial variation. As a consequence, instead of having a larvae number of single point estimates of larval density, we have a fewer number of estimates based on many repeated samples.

There are three major concerns when egg and larval surveys are used to estimate fish biomass: (i) rapid dispersion and advection of eggs and larvae from spawning areas (ii) egg and larval loss (mortality) prior to the survey and (iii) the relationship between egg production and spawning biomass, that can be complicated by repeated spawning (over a period of days to months). These factors can confound biomass estimations (e.g. Ultang 1977, Priede and Watson 1993).

Dispersion and advection. In contrast to marine studies, the theoretical basis for riverine eulachon surveys are simple and sampling error associated with dispersion and advection is reduced. Theoretically, only one sampling site on the river is required, preferably as far downstream as possible. All larvae must pass that site, so if one knows the river flow and the larvae density, then the estimate of biomass should be a straightforward matter. In practice, there are some technical complications, but these are mainly imposed by operational limitations and not theoretical or biological. A problem would arise if the hatching of all eulachon eggs were synchronous, or nearly synchronous, perhaps occurring over a period of several hours. In this case a large 'pulse' of larvae could hatch, be advected downstream, and go undetected by our surveys that operate only 3-4 days per week. For several reasons, however, we do not think this is a problem. For instance, the duration of the spawning run, as indicated by the commercial fishery, is several weeks or longer (Ricker *et al*. 1954). Also, the duration of the run, as observed in other rivers, is usually a number of days or weeks (Pedersen *et al*. 1995). These observations indicate that the spawning period, and presumably, the hatching period, also is protracted. Further, in other similar fishes such as herring, hatching usually occurs over a number of days. This is known exactly in laboratory studies where artificially fertilized eggs of exactly the same age hatch over a period of several days, or longer (i.e. Alderdice and Velson 1971). Variation in hatching time may be associated with micro-climatic differences in incubation sites. For these reasons, we do not think that significant numbers of eulachon eggs hatch at one time and are flushed downstream undetected, between our sampling periods.

Egg and larval loss prior to the survey. If eggs died and disintegrated in the river during incubation, prior to the survey, or if eggs and larvae were eaten by predators, we would not know. Therefore, reduction of egg and larval numbers before the survey will result in lower biomass estimates and this is a concern of our analyses. Incubating eulachon eggs, however, may have fewer predators than eggs of similar size and incubation requirements such as herring (*Clupea pallasi*). Estimates of egg mortality for Pacific herring, during the two week incubation period, can exceed 50% (Haegele and Schweigert 1991). Based on the approximate similarity of egg sizes, this estimate may be similar for eulachon. We note, however, that the number of potential predators in the river probably is lower than most marine areas and, indeed reduced predation during early life stages is a general explanation for the evolution of anadromy in most fishes. Mortality associated with pollution or other habitat impacts (dredging) also could lower the egg and larval survival prior to the survey, but at the present time, we do not know if this is a problem. We do not think there is a substantial loss to predation, between hatching and when they are captured in our surveys. Once hatched, most larvae will be advected downstream very rapidly, usually within a few hours. The total loss during this short time would be small.

Conversion of egg and larval production to spawning stock biomass - relative fecundity. When examined at various stages of development, egg maturation in eulachon is synchronous in all parts of the ovary. Within individuals, there only is one stage of egg development at any single time. In this regard eulachon are similar to other small pelagic fishes in temperate climates, that produce only one clutch of eggs and spawn once per year. This simplifies the relationship between egg production and spawning fish biomass, relative to multiple spawning fish, such as anchovies (*Engraulis mordax*). To further simplify the biomass:egg number relationship, we use an estimate of relative fecundity, or the number of eggs/g. Although this estimate is variable among individuals, the estimate of the mean (about 700 eggs/g/female or 350 g/spawning fish) was consistent between two years (1995 and 1996) and is not markedly different than the relative fecundity for Kitimat River eulachon (502 eggs/g/female, Pedersen *et al*.1995).

Biomass estimation: confidence limits and estimation of error

The two approaches used in this study provide very similar estimates of mean spawning biomass but the estimates of confidence limits are closer to the mean (or more precise) for most estimations from method #2 (single annual method). This gain in precision, however, occurs at the cost of other useful information such as the seasonal variation in spawning biomass (or egg and larval production) that is derived from method #1. Such temporal information is useful for a number of purposes, including the analysis of factors affecting spawning distributions, and also comparison with other temporally based measures of abundance (such as gillnet test fishery data, that are not examined in this paper. Probably the differences in methodology are less important than the variations related to sampling protocols and natural variation in local distribution. For instance, it is clear that in some years a significant number of larvae leave the Fraser River via the North Arm. Therefore the error associated with infrequent samples in this area probably exceed the small differences in estimation between the two methods. Similarly, there clearly is a tendency for more eggs and larvae to occur on the north side of the river, so there is a potential for sample bias if the collection of samples do not represent a reasonable cross section of the river. In this regard, for all of our estimates we have assumed that all parts of the river where we sample (i.e. surface, 5 and 10 m depths and north, middle and south positions) move at the same velocity. Probably this is not correct, and the velocity at which eggs and larvae are advected out of the river will vary substantially in time and space. We note, however, that comparisons of biomass between two adjacent sampling areas of the river, made at the same times, are often very similar. Specifically, the weekly estimations of spawning biomass (or egg and larval density) measured at Tilbury Island, were often nearly identical with those measured at Deas Island, immediately downstream. This can be seen by a year-by-year comparison of panels in Fig. 7c and Fig. 7d. The frequent similarity between these two independent estimates is, in our opinion, evidence that the measured egg and larval densities are a reasonable representation of the actual densities in the river.

Spawning Times, Areas and Movement of eggs and larvae

Since 1996 we concentrated our sampling effort at four major locations: Barnston Island, New Westminster, Tilbury and Deas Island on the South Arm and three minor locations: Iona Island, Oak St. Bridge and Pipeline station on the North Arm. In 2000 and 2001, we focussed principally on three sites: New Westminster, Tilbury and Deas Islands.

We captured both eggs and larvae at most sampling locations, river positions and depths. The occurrence of embryonic eggs required more detailed explanation. A fundamental assumption of this survey work is that eggs and larvae will be advected, unidirectionally, from upstream to downstream areas. If eggs or larvae could resist this advection, and somehow stay near their spawning sites, during and after hatching, then these analyses would be confounded. We have found no evidence, however, for retention of eggs or larvae ***within*** the river. Although the flow rate varies with the tidal state at most of the sampling sites, below New Westminster the movement of water is always downstream during sampling times, usually at a velocity of about 4 knots - or about 2.5 m/sec -and may reach 7 knots (Canadian Hydrographic Service 1982). These rates exceed the ability of eulachon larvae to swim upstream. Small pelagic larvae such as herring usually have a maximal burst swimming velocity of not more that 10 body lengths/sec (Fuiman 1993). With an average length < 7 mm, most eulachon larvae could not swim faster than 0.1 m/sec, much less than the river velocity.

If eggs and larvae move, unidirectionally, downstream, then their numbers at downstream areas should represent cumulative totals from upstream spawning areas. In general, this appears to occur but an important exception concerns the flow divergence into the North and South Arms. In some years, the SSB estimates for the South Arm locations are less than those from New Westminster. The North Arm receives about 25 % of the total Fraser River flow discharge at New Westminster (Thomson 1981) so in general, if eulachon eggs and larvae were uniformly (or randomly) distributed throughout the water column and assuming no additional spawning in the South Arm, then the South Arm sampling locations should have about 75 % of the eggs and larvae observed at upstream locations (i.e. New Westminster). In 2001 and 2002, there were only about half as many eggs and larvae seen in the South Arm locations as we estimated at New Westminster. Probably the explanation for this is that a disproportionate number exited via the North Arm, because many were incubated and hatched on the north side of the river, where eulachon spawned. Apparently, the relatively straight path followed by the Fraser River, in regions upstream of New Westminster, does not promote much lateral (i.e. north side versus south side) mixing, so the lateral position of eggs and larvae would remain consistent (M. Foreman, Pers. comm.). Therefore if there were more eggs and larvae on the north side of the river, at the point of divergence into the North and South Arms, above New Westminster, then more would flow down the North Arm.

An observation made elsewhere (Hay and McCarter 2000) and confirmed here is that eulachon embryonic eggs as well as larvae are commonly collected in riverine plankton nets. From microscopic analysis we determined that some eggs were dead, but most were alive at the time of capture. The high incidence of live eggs in the Fraser River, as well as from other eulachon-bearing rivers is a puzzle, and to our knowledge, such observations have not been described for other species. Probably this occurrence is so widespread that it is not evidence of some unknown pathology, but rather a natural occurrence, and may represent a life history trait. That is, eulachon eggs appear to be able to incubate and develop while mobile. This mobile incubation (or 'tumble' incubation) may even have a selective advantage because it may spread the eggs over a broad space, thereby reducing predation and optimizing environmental conditions. This is speculation, however, and an important consideration is that eulachon appear to use a very broad area of the river as incubation sites, and therefore probably also as spawning sites. In other river systems, eulachon are known to frequent very shallow areas along the shore, within meters of the river edge and sometimes within only a few centimeters of water depth. This very nearshore occurrence is consistent with observations that eulachon are often easily captured with dip nets held by fishers standing on the shore. Therefore, from a perspective of attempting to identify and protect eulachon spawning habitat, we tentatively conclude that, based on observations from 1995-2002, eulachon spawn in different parts of the river among years, between areas as far downstream as Deas Island, (perhaps even closer to tidal areas) and upstream as far as Mission or further. We speculate that within these areas most of the actual spawning activity will occur in very shallow water, and perhaps concentrate on the north side, or in the vicinity of tributaries entering the Fraser River. From the perspective of attempting to protect (or mitigate) habitat loss, it seems clear that the nearshore shallow areas are important, but that more investigation is required to confirm this.

The river as a spawning and egg incubation habitat

The lower Fraser River might appear as a harsh place for spawning habitat for eulachon, with small, delicate eggs. Further, the area has been impacted through anthropogenic changes in the physical habitat (such as dikes, dredging and landfills) and chemical habitat (Rogers *et al*. 1990). In some ways, however, this area may be very good habitat. Relative to marine areas, there are fewer invertebrate predators that can feed on incubating eggs. For example, predation rates on herring eggs can exceed 50% during the incubation period, mainly from a resident invertebrate fauna, consisting of crabs, molluscs and starfish (Haegele 1993). Probably predation rates on eulachon eggs are lower, although scavenging fish such as starry flounder (*Platichthys stellatus*), sculpins and sturgeon (*Acipenser*) might consume eulachon eggs. Predator consumption of eulachon eggs would depend on the extent to which eulachon eggs are clumped and the amount of physical debris that adheres to the egg. Eulachon eggs have stocky mantles that provide an anchoring device, that adheres to sand grains (Hart and McHugh 1944). If the ratio of debris to eggs is high, this may deter some predators.

The organic debris in samples consists of a mixture of small woody chips, fibres and insect parts, mainly various shades of grey and black. Against this background, the translucent eulachon larvae are barely visible. Consequently predation during the early larval stage may be low because the combination of the high sediment load and organic debris in the river would probably reduce the impact of visual predators, such as small fish. In contrast, predation rates on similar pelagic larvae (e.g. herring in marine waters) can be very high, up to 10%/day (Arai and Hay 1991). Therefore, in terms of reduced predation risk, the lower Fraser River may be a good, but temporary, habitat for larval eulachon.

The distribution of larvae in downstream waters may be complex and some may concentrate in side channels and sloughs. We have observed larval eulachon in the Gardner Canal, near the eulachon-bearing Kitlope River, concentrated in the freshwater-seawater interface during ichthyoplankton surveys (McCarter and Hay 1999). In the lower Kitimat River, we found high numbers of larvae in a brackish estuary adjacent to the mouth of the river. Once in seawater, however, dispersal appears rapid. Based on 1994 surveys in Bute and Knight Inlet, conducted several weeks after eulachon hatched and emerged into marine areas (McCarter and Hay 1999), larvae of variable size were dispersed throughout the full extent of the inlet or fjord.

Spawning sites: inter-annual differences

It is clear that eulachon spawn in various parts of the river. In some years most of the spawning was upriver of New Westminster, and in other years, most spawn was below, in either the South Arm, North Arm or in both arms. We have no explanation for this variation in spawning location, but we also noticed that there is a tendency for more larvae to be captured on the ***north*** side of the river. Apparently, most of the recreational fisheries also occurs on the north side (D. Stacey, pers. Comm.), which indicates that eulachon probably favour that side for spawning. One feature of the north side that may attract eulachon is the influx of local drainage from lakes and small rivers, such as the Pitt River, Allouette River, Whonnock River and other small tributaries. In some years this water may have some unique characteristics, and is perhaps clearer or colder than the mainstem of the Fraser River. If so, eulachon may be attracted (or repelled) from water from local sources. If so, it follows that inter-annual differences in the regional composition of water from different sources could affect the distribution of spawning sites. Of course, these factors, if significant, would occur in the context of many other factors that could affect eulachon spawning sites, including river discharge, velocity, turbidity, temperature and tidal state (spring versus neap tides) relative to the states of sexual maturation and spawning readiness of eulachon when they enter the river.

The significance of biomass estimates and changes in abundance in the Fraser River

The importance of eulachon exceeds their value in the small commercial fishery on the Fraser River. Eulachon are an important species to First Nations throughout all coastal areas of British Columbia and Alaska and parts of Washington, Oregon and California (Stewart 1975, Kuhnlein *et al.* 1982). Eulachon populations in the Fraser, Columbia and Klinaklini rivers, and perhaps others declined in 1993 and 1994 (Hay *et al*. 1997). The causes of the declines are uncertain. Eulachon abundance is closely monitored in the Columbia River (Anon. 1993) where there is a substantial commercial fishery. Remarkably, in 1993 there was an unprecedented eulachon spawning in the Chehalis River system (Hay *et al*. 1997). Therefore, part of the apparent decline may involve a shift in spawning areas. This may also occur in the Fraser River where it appears that the spawning areas may vary among years, with some years spawning above, and others below New Westminster.

Although there was a sudden decline in the early 1990's, Fraser River eulachon appear to have been declining for some time. In the 1950's, annual total catches of several hundred tonnes were taken each year. Such catches would be impossible today. Long-time residents indicate that they do not see eulachon spawning in the locations that were once utilized for spawning in the upper areas of the Fraser River and that eulachon availability for recreational catches has been relatively low in recent years. These observations support the view that there has been a general decline in their abundance, and that this decline preceded the sudden population decline in 1994. Such a general decline also has been observed in California (Moyle 1994) although not in the Columbia River where catches were close to historical averages until 1993 (Hay *et al*. 1997). In California, some of the decline in eulachon has been attributed to changes in the lower parts of the Klamath River (the main eulachon river in California). There may be similar problems with eulachon habitat in the Fraser River, including the possibility of toxic chemical changes (Rogers *et al*.). Other frequently suggested 'within-river' explanations for the decline include high predation rates by marine mammals and dredging. In addition, there are concerns about factors external to the river, including general changes in ocean climate and bycatch of eulachon in other fisheries. These issues and concerns will not disappear unless eulachon abundance is somehow restored. Monitoring eulachon abundance in the Fraser River will not necessarily assist with the restoration of the eulachon population, but it would be required to confirm the event, if it happens.

Egg and larval surveys provide only 'after-the-fact' assessment of spawning biomass and provide no basis for estimating future returns by forecasting recruitment. Data on egg and larval abundance does not provide a reliable basis for forecasting recruitment in Pacific herring (a species where a lot of information is available) so it is unlikely that data on larval abundance would provide useful forecasts for eulachon. Also, it appears that most, if not all of the spawning eulachon die after spawning (Hay and McCarter 2000). Therefore, there is little or no continuity of spawning fish between years (i.e. repeat spawners) so the biomass assessment in year n will have little predictive value for year $n+1$. At best, larval surveys can indicate where and when eulachon spawn and the approximate size of the spawning run. Even with this uncertainty, estimation of the approximate size of the spawning run in the previous year provides a quantitative reference point for management decisions.

SUMMARY

Anadromous eulachon (*Thaleichthys pacificus,* family: Osmeridae) have supported First Nations, commercial, and recreational fisheries for over a century. Until 1994, these fisheries were essentially unregulated and only cursory monitoring activity occurred. In 1994 there was concern from the commercial fishery participants about drastically declining catches and changes in spawning distribution and habitat. This concern prompted research to estimate the spawning stock biomass (SSB) and determine the approximate spawning locations. Prior to this research, spawning locations were uncertain but anecdotal reports from earlier years, however, indicate occasional spawning above Chilliwack (about 100 km upstream). Results of our surveys from 1995-2002 indicate that most spawning occurs in the lower 50 km of the river. Adult eulachon enter the Fraser River in late March and April to spawn. At ambient temperatures, the small (~0.8 mm) eulachon eggs incubate for three to four weeks on sand grains in the river substrate. Immediately after hatching, small larvae (4.0-6.5 mm) and some embryonic eggs are rapidly advected downstream.

The Fraser River diverges into the North and South Arms near the city of New Westminster. Our major sampling locations were at Deas Island (South Arm, a few km upstream from tidal waters), Tilbury Island, (South Arm, about 15 km upstream), New Westminster, (a few km above the North/South Arm divergence) and Barnston Island (about 60 km upstream of tidal water). Occasionally minor sampling was conducted in other locations, in the North Arm and Pitt River and sites between Mission and the Port Mann Bridge. Fine-mesh plankton nets equipped with flow meters to estimate density (n/m^3) were used twice a week throughout a seven-week period following spawning. The material collected from the nets consisted of small quantities of eulachon eggs and larvae (cumulative wt 1 to 3 g) mixed with much larger quantities (100 g to 2 kg) of river mud, sand and debris. All sample material was fixed in five percent formalin for later analysis in the laboratory. Sample analyses followed established analytical routines (McCarter and Hay 2002). Often, eulachon material consisted of small (~5 mm) recently-hatched larvae and considerable numbers of live, viable, unhatched eggs, and sometimes smaller numbers of dead or moribund eggs. The reason for the capture of eggs is uncertain, but it is known to be common in surveys of other eulachon rivers. Each sample was collected from plankton net tows of about 6 minutes duration, and in this time approximately 20 m^3 of water was filtered. Longer tow durations were impractical, because nets became clogged with debris. In the first survey in 1995, we sampled many locations on the river from the Hatzic Slough to Sand Heads (Fig. 1). In subsequent years, we focused our efforts on four, lower river sampling locations and attempted to examine spatial variation at each of these locations (Fig. 2). To do this, we established cross-river transects and on each transect we sampled at three sites: north side, south side and mid-river. At each site we towed the net at fixed depths of 0, 5 and 10 m. In addition, 'oblique' tows were conducted at 10 m and slowly raised to the surface over a 6-minute period.

In principle, the estimation of spawning stock biomass (SSB) can be calculated from an estimation of the total egg and larval production. In the case of eulachon we can assume that each recently hatched larva represents an egg, so an estimate of the production of eggs and larvae (from river samples) can be converted to biomass based on estimates of relative fecundity of about 400 eggs/g (for males and females). Relative fecundity does not vary with female size, but there is some small, inter-annual variation, and we discuss the effects of this on our estimates (i.e. plus or minus 10%). Estimates of larval production (or SSB), for any period (duration) can be calculated at any location in the lower river as the product of larval density (D) and river discharge (V). The total river discharge, in m^3/s, is estimated daily for the Fraser River at Hope, about 100 km upstream. Therefore, for any period (t) and location, SSB can be estimated as the product of discharge and larval density ($V_t \cdot D$). Within each year, SSB can be estimated for different periods within the sampling schedule, or at different locations, or both. The main limitation of the analysis is the relatively small number of samples available for estimates at specific periods and locations. For instance, downstream sampling locations (below most spawning sites) should have the highest estimates of larval production and spawning biomass, and the upstream locations (above most spawning sites) the least. Therefore variation in SSB, compared among different sampling sites, provides a basis for calculating the approximate spawning locations within and among years. Although estimates of SSB for short periods (i.e. a week) and specific locations have relatively large estimates of error, they are useful for analyses of temporal variation of larval production and SSB. This is important for comparison with other temporally based data (i.e. annual eulachon gillnet test fishery data, or temporal changes in river discharge or river temperature). Pooling data over longer duration's (i.e. 7-8 weeks) provides less spatially detailed but more precise (i.e. smaller Standard error) estimates of SSB spawning biomass for each sampling site. Therefore we present two slightly different, but related approaches for estimating biomass: (1) one method estimates a single, overall annual spawning biomass at each location without reference to weekly samples, and (2) another method estimates biomass at each site on each week. Estimates of total spawning biomass range from a peak of nearly 1600 mt in 1996 to less than 100 mt in 1997 and 2000. Spawning biomass was distinctly higher in 2001 and 2002, and was at least 800 mt in each of these years. Our surveys corroborated other independent observations (i.e. gillnet test fisheries) that there was relatively low spawning biomass in most years except 1996. We suggest that these surveys may be an approximate but reliable indicator of spawning biomass and spawning locations, but they are not useful for predicting spawning biomass in future years.

Eulachon spawning areas are not static and change among years. Probably the explanation for such change is related to variation in river conditions (temperature, discharge, etc) as well as the date of sexual maturity of eulachon. There are significant differences in fish size and weight among years, and this may affect spawning dates. Also in sampling stations upriver of New Westminster, there is a clear pattern of higher egg and larval abundance on the north side of the river. The explanation for this is uncertain, but in other parts of their range there appears to be an association of eulachon with rivers that have strong spring freshets and drain major glaciers or snowpacks. Most Fraser River tributaries enter on the north side, and some also drain glaciers and snowpacks, so perhaps there is some unknown attraction for eulachon to these conditions. For example, sometimes eulachon spawn in the lower reaches of the Pitt River, possibly attracted by infusions of water entering the north side of the Fraser River.

Although there are large annual fluctuations in recent years, the abundance of Fraser River eulachon may be significantly lower than what it was during the early and middle years of the twentieth century, when several hundred tonnes were captured annually. Recent information indicates that the unreported non-commercial catches also may have been substantial, perhaps equivalent to the commercial catches. If Fraser River eulachon runs have declined, then there are a number of potential explanations, including changes in the offshore environment, where eulachon spend over 95 percent of their lives. Spawning biomass also may reflect deleterious changes in habitat in the Fraser River, particularly in the shallow reaches. Based on observations of other rivers, eulachon appear to spawn in very shallow water, sometimes only a few centimeters in depth. This observation is consistent with independent observations, on the Fraser River and elsewhere, that spawning fish can be captured from the river bank in large quantities with simple dipnets. It is precisely such shallow water habitats that might have been subjected to the greatest habitat impacts, or lost, with the creation of dykes for flood control, or other shoreline installations. In a separate report the results of these plankton net surveys will be compared with three other, independent indices of eulachon abundance: (1) the annual (since 1995) Fraser River gillnet test fishery; (2) an index of eulachon abundance estimated during annual (since 1975) offshore shrimp surveys, (3) Columbia River eulachon spawning escapements.

CONCLUSIONS

Egg and larval surveys, conducted for a 7-8 week period in the lower Fraser River, provide conservative estimates of eulachon spawning biomass. The biomass estimates exhibit striking annual differences but probably all are conservative because they do not account for mortality between the time of spawning and the time of capture, as eggs or larvae. The relatively high frequency of viable eggs in the samples, captured throughout the survey, however, is evidence that pre-hatching mortality is not profoundly high.

The survey design provides independent, spatially-referenced estimates of spawning biomass that allow an approximate estimate of the spawning areas within the river, and inter-annual changes in spawning distribution. For eulachon it appears that the location of egg incubation is not confined to the spawning site, because we capture significant numbers of live eggs downstream. For this reason, eulachon may utilize a much larger part of the river for early development (egg incubation) than the specific spawning sites alone.

3. In principle, to be fully effective as a stock assessment technique, egg and larval samples on the Fraser River must be collected at least in two major locations: the lower reaches of the North Arm and in the South Arm, in the vicinity of Deas Island. In theory, these key stations will encounter every egg or larvae produced in the Fraser River (unless they die or are preyed upon prior to being advected down river). In practice, however, we suggest that sampling should also occur at New Westminster, because there may be uncertainties about the dispersal of eggs and larvae in the river, especially where the salt wedge backs into the lower Fraser. During some tidal conditions, there may be a reversal of flow, and this could affect larval abundance estimates, although we understand that the river flow is mainly unidirectional seawards during the time of the freshet (Thomson 1981), which is exactly the same time that we conduct the surveys.

4. The biomass estimates determined on the lower Fraser River exhibit striking annual differences. We suggest that they provide a conservative but reasonable estimate of the spawning biomass at different locations in the river. This estimate is a significant reference point that can be compared with others, including estimates of offshore biomass (obtained from shrimp trawl surveys) and in-river, gillnet test fisheries but we have not included such comparisons in this paper.

RECOMMENDATIONS

We recommend that egg and larval surveys be continued, but suggest that it may be possible to reduce their scale. For the past 4-5 years we have collected about 500-600 samples from several locations, but the analyses time has been substantial, requiring in excess of four months of dedicated laboratory technician time. Although a reduction in the number of samples would result in a decrease in the precision of the estimates, such a loss may be small relative to the observed inter-annual variation. Therefore a slightly reduced field sampling effort, and a commensurate reduction in laboratory analysis would still produce useful results. The cost savings for sample collection would be minimal but the laboratory analyses costs could be reduced to the equivalent of about 16-18 weeks of technician time.

REFERENCES

Alderdice, D.F. and F.P.J. Velsen. 1971. Some effects of salinity and temperature on early development of Pacific herring (*Clupea pallassi*). Can. J. Fish. Res. Bd. Can 28:1545-1562.

Anonymous. 1993. Status Report - Columbia River fish runs and fisheries, 1938-1992. Joint Publication of the Oregon Dept. of Fish and Wildlife and the Washington State Dept. of Fisheries. 257 pp.

Arai, M.N. and D.E. Hay. 1991. Predation by medusae on Pacific herring. Can. J. Fish. Aquat. Sci. 39: 1537-1540.

Canadian Hydrographic Service. 1982. British Columbia coast (south portion). Volume 1. Dept. Fisheries and Oceans. Institute of Ocean Sciences. Sidney, B.C. 523 pp.

Casella, G. and R.L. Berger. 1990. Statistical Inference. Duxbury press.

Efron, B and R.J. Tibshirani. 1993. An Introduction to the Bootstrap. Chapman & Hall. NewYork. 436 pp.

Fuiman, L.A. 1993. Development of predator evasion in Atlantic herring, *Clupea harengus* L. Anim. Behav. 45:1101-1116.

Haegele, C.W. 1993. Epibenthic invertebrate predation of Pacific herring *Clupea pallasi*, spawn in British Columbia. Can. Field-Naturalist 107: 83-91.

Haegele, C.W. and J.F. Schweigert, 1991. Egg loss in herring spawns in Georgia Strait, British Columbia. Proc. Int. Herring Symposium. Alaska Sea Grant College Program 91-01: 309-322.

Hart, J.L. and J.L. McHugh. 1944. The Smelts (Osmeridae) of British Columbia. Bull. Fish. Res. Bd. Canada. 64. 27 pp.

Hay, D. E. 1985. Reproductive biology of Pacific herring (*Clupea harengus pallasi*). Can. J. Fish. Aquat. Sci. 42 (Supplement 1):111-126.

Hay, D.E. and J. Boutillier, M. Joyce, and G. Langford. 1997. The Eulachon (*Thaleichthys pacificus*) as an Indicator Species in the North Pacific. 509-530. *In:Forage Fishes in Marine Ecosystems*. Wakefield Fisheries Symposium. Alaska Sea Grant College Program 97-01. Anchorage, Alaska.

Hay, D.E. and P.B. McCarter. 1997. Larval distribution, abundance, and stock structure of British Columbia herring . J. Fish Biology. Vol. 51 (Supplement A):155-175.

Hay, D.E. and P.B. McCarter. 2000. Status of the Eulachon *Thaleichthys pacificus* in Canada. Can. Stock. Assessment. Sect. 2000/145. 92 pp.

Kuhnlein, H.V., A.C. Chan, J.N. Thompson and S. Nakai, 1982. Ooligan Grease: a nutritious fat used by Native people of coastal British Columbia. J. Ethnobiol. 2:154-161.

McCarter, P.B., and D.E. Hay. 1999. Distribution of Spawning Eulachon Stocks in the Central Coast of British Columbia as Indicated by Larval Surveys. Can. Stock Assessment Secretariat Res. Doc. 99/177.

McCarter, P.B., and D.E. Hay. 2002. Eulachon Embryonic Egg and Larval Outdrift Sampling Manual for Ocean and River Surveys. Can. Tech. Rep. of Fish. and Aqua. Sci. *In Press*

Minitab. 1997. Reference Manual. Minitab Inc.

Moyle, P. 1994. The Decline of Anadromous Fishes in California. Conservation Biology. 8:869-870.

Pedersen, R.V.K., U.N. Orr and D.E. Hay. 1995. Distribution and Preliminary Stock Assessment (1993) of the Eulachon, *Thaliechthys pacificus*, in the lower Kitimat River, British Columbia. Can. Man. Rep. Fish. Aquat. Sci. 2330. 20 pp.

Priede, I.G. and J.J. Watson. 1993. An evaluation of the daily egg production method for estimating biomass of Atlantic mackerel (*Scomber scombrus*). Bull. Mar. Sci. 53:891-911.

Ricker, W.E., D.F. Manzer and E.A. Neave. 1954. The Fraser River eulachon fishery, 1941-1953. Fish. Res. Bd. Canada. MS Rept. Biol. Sta., No. 583. 35 pp.

Rogers, I.H., Birtwell, I.K. and G.M. Kruzynski. 1990. The Pacific eulachon (*Thaleichthys pacificus*) as a pollution indicator organism in the Fraser River estuary, Vancouver British Columbia. Science of the Total Environment. 97/98. 713-727.

Samis, S.C. 1977. Sampling eulachon eggs in the Fraser River using a submersible pump. Dept. Fisheries and Environment Tech. Rep. Series PAC/T-77-18. 10 pp.

Schweigert, J.F., C. Fort and L. Hamer. 1996. Stock assessment for British Columbia herring in 1994 and forecasts of the potential catch in 1997. Can. Tech. Rep. Fish. Aquat. Sci. 2089. 66 pp.

Smith, P.E. and S.E. Richardson. 1977. Standard techniques for pelagic fish egg and larva surveys. FAO Fisheries Technical Paper No, 175. Food and Agricultural Organization of the United Nations. Rome. 100 pp.

Stewart, 1975. The seasonal availability of fish species used by the coast Tsimshians of northern British Columbia. Syesis 8: 375-388.

Stewart, J. 1995. Multivariated Calculus, 3rd Edition. Brooks/Cole.

Thomson, R.E. 1981. Oceanography of the British Columbia coast. Can. Spec. Publ. Fish. Aquat. Sci. 56. 291 pp.

Ulltang, O. 1977. Methods of measuring stock abundance other than by the use of commercial catch and effort data. FAO Fish Tech. Paper. 176. 23 pp.

Table 1. Fraser River discharge (m3/s) by year (1995-2002) and day of the year (DOY) from about mid-April to mid-June during the period of the surveys. Data collected by the Water Survey of Canada at the Hope gauging station.

DOY	1995	1996	1997	1998	1999	2000	2001	2002
116	2160	4060	4260	2390	4540	3110	2090	3190
117	2320	4020	4490	2830	4740	3280	2370	3070
118	2510	4410	4810	3170	5110	3190	2750	2890
119	2590	4720	5240	3320	5450	3070	2920	2760
120	2650	4520	5840	3440	5460	2940	3140	2790
121	2760	4200	6130	3710	5270	3110	3400	3120
122	2880	3920	6130	4100	4990	3520	3390	3650
123	2900	3730	6020	4490	4750	3790	3170	4090
124	2850	3630	5860	4830	4650	3800	2970	4680
125	2850	3480	5710	5180	4630	3830	2880	4650
126	2980	3340	5690	5590	4650	3970	2780	4560
127	3120	3260	5710	5900	4600	3990	2930	4230
128	3190	3200	5730	6000	4490	3910	3100	3960
129	3320	3140	5780	6000	4360	3810	3050	3740
130	3560	3120	5930	5970	4330	3680	2900	3500
131	3700	3050	6090	5960	4330	3560	2880	3510
132	3810	2950	6320	5960	4290	3450	2900	3460
133	4040	2850	6660	5950	4160	3390	2880	3640
134	4530	2790	7040	5930	4030	3350	2840	3850
135	4990	2860	7540	5910	3990	3390	2910	4130
136	5430	2930	8290	5930	4060	3470	2940	4580
137	5740	3080	9310	6020	4210	3560	3070	5160
138	6020	3380	9620	6100	4330	3690	3230	5200
139	6120	3850	9920	6120	4420	3750	3400	5080
140	6050	4190	10000	6070	4550	3990	3420	5320
141	5780	4360	9690	5960	4740	4330	3390	5550
142	5430	4510	9170	5880	4970	4670	3480	5890
143	5100	4710	8510	5830	5220	5120	3760	6620
144	4870	4910	7960	5790	5590	5270	4150	7390
145	4780	4990	7550	5780	6200	5490	4180	7640
146	4760	5100	7350	5800	6710	5820	4380	7390
147	4850	5320	7290	5880	7140	5830	4790	7370
148	5060	5560	7390	6030	7740	5640	5180	7400
149	5270	5780	7790	6150	8220	5410	5340	7800
150	5460	6040	8050	6340	8240	5010	5600	7860
151	5720	6160	9770	6590	7910	4880	6080	7680
152	6040	6010	9990	6710	7580	4910	6540	8056
153	6440	5790	10300	6670	7340	5000	6500	8311
154	6680	5720	10700	6520	7290	5080	5940	8247
155	6660	5890	11200	6370	7440	5110	5960	7966
156	6570	6340	11300	6200	7630	5260	6610	7765
157	6460	6680	11000	5980	7760	5540	6820	7809
158	6450	7000	10600	5720	7740	5760	6430	7801
159	6650	7510	10400	5490	7980	5950	6180	8201
160	6840	8050	10200	5270	8470	6440	6220	8594
161	6780	8100	9980	5100	8620	7120	6200	8519
162	6620	7900	9760	4980	8360	7530	6130	8075
163	6460	7830	9470	4880	8040	7560	6150	7741
164	6290	7720	9240	4840	7880	7540	6100	7878
165	6160	7520	9290	4820	7880	7540	5830	8291
166	5990	7340	9610	4810	8080	7560	5500	8659
167	5800	7150	9800	4780	8800	7450	5370	8940
168	5590	6840	9880	4690	9360	7180	5280	9190

Table 2. Summary of Fraser River adult eulachon sampling data showing, for each sex and both sexes combined, the sample size (number), percent by number, sum of sample weight and percent by weight. No samples were collected in 1999.

Year	Data category	Male	Female	Both sexes
1995	Number	311	352	663
	Percent by number	46.91	53.09	100.00
	Sum of wt (g)	13300	15600	28900
	Percent by wt	46.02	53.98	100.00
1996	Number	241	218	459
	Percent by number	52.51	47.49	100.00
	Sum of wt (g)	9802	9321	19100
	Percent by wt	51.32	48.68	100.00
1997	Number	254	259	513
	Percent by number	49.51	50.49	100.00
	Sum of wt (g)	9669	9835	19500
	Percent by wt	49.58	50.42	100.00
1998	Number	260	156	416
	Percent by number	62.50	37.50	100.00
	Sum of wt (g)	9536	5780	15300
	Percent by wt	62.33	37.68	100.00
2000	Number	108	93	201
	Percent by number	53.73	46.27	100.00
	Sum of wt (g)	4670	4294	8964
	Percent by wt	52.10	47.90	100.00
2001	Number	50	50	100
	Percent by number	50.00	50.00	100.00
	Sum of wt (g)	1836	1869	3705
	Percent by wt	49.55	50.45	100.00
All	Number	1224	1128	2352
	Percent by number	52.04	47.96	100.00
	Sum of wt (g)	48813	46697	95510
	Percent by wt	51.12	48.89	100.00

Table 3. Summary of Fraser River adult eulachon sampling data showing the sample size, mean length (mm) and weight (g), with standard deviations (in brackets) for each year and sex from 1995 to 2001. No samples were collected in 1999.

	Males	**Females**	**All**
1995	311	352	663
length	158.06 (11.02)	158.22 (10.45)	158.14 (10.71)
weight	42.81 (10.93)	44.29 (9.61)	43.59 (10.27)
1996	241	218	459
length	155.78 (10.42)	154.84 (10.67)	155.33(10.54)
weight	40.84 (9.51)	42.76 (9.93)	41.75 (9.75)
1997	254	259	513
length	161.45 (11.98)	158.41 (10.42)	159.91(11.31)
weight	38.06 (9.09)	37.97 (7.06)	38.02 (8.12)
1998	260	156	416
length	158.13 (12.65)	157.48 (15.57)	157.89(13.80)
weight	36.68 (8.65)	37.049 (9.89)	9.125(36.82)
2000	108	93	201
length	161.63 (10.42)	162.54 (9.32)	162.05 (9.91)
weight	43.24 (9.05)	46.17 (8.41)	44.60 (8.86)
2001	50	50	100
length	159.54 (6.36)	156.36 (5.32)	157.95 (6.05)
weight	36.72 (4.95)	37.37 (3.53)	37.05 (4.29)
All years	1224	1128	2352
length	158.70 (11.44)	157.78 (11.24)	158.26(11.35)
weight	39.92 (9.79)	41.39 (9.48)	40.63 (9.67)

Table 4. Summary of total and relative fecundity of Fraser River eulachon. (a) Estimates for all samples (n = 521) and (b) estimates for a sub-sample (n = 492) selected from fish with estimated GSI greater than 15 but less than 30. Sub-sample (b) excluded fish with excessive loss of eggs or somatic tissue (see text for explanation). Each summary shows the sample size by year, the mean, median and standard deviation (st. dev.) for the total fecundity and the relative fecundity (Rel. fec).

Year	Sample Count	Total fec. mean	Rel. fec. mean	Total fec. median	Rel. fec. median	Total. fec. st. dev.	Rel. fec. st. dev.
(a) all samples							
1995	169	31213	682.86	30050	694.39	8249	121.62
1996	100	31647	713.76	29785	723.64	9184	106.43
1997	100	34111	898.35	34474	899.28	6733	143.42
1998	152	31541	861.93	32667	863.58	9127	146.24
All	521	31948	782.39	31656	776.40	8485	160.07
(b) sub-sample (15>GSI>30)							
1995	152	31996	697.68	31278	700.86	7762	101.35
1996	77	32227	739.31	29811	740.55	8422	79.75
1997	67	34368	906.78	34748	917.23	6651	97.11
1998	125	32094	871.83	32867	867.84	9087	140.61
All	421	32445	790.28	31799	776.4	8157	141.02

Table 5. Statistical summary of Fraser River eulachon relative fecundity (RF) based on a sub-sample of fish with estimated GSI greater than 15 but less than 30 (See Table 4). For each year the descriptive statistics include sample size, mean (relative fecundity or eggs/g), mean, standard deviation and standard error (SE) of the mean. The results of a Kolmogorov-Smirnov normality test, are shown as D with a probability P(D) that the data are not normality distributed. The results of linear regression analysis shows the intercept, slope, r^2, and probability P(R) that the regression is significantly different than 0 (from a regression of relative fecundity by length (RF = b + aL), where RF is 'relative fecundity', b is the slope, a in the intercept, L is standard length in mm)

YEAR	1995	1996	1997	1998
N	152	77	67	125
Mean	697.7	713.8	906.8	871.8
Median	700.9	723.6	917.2	867.8
St deviation	101.4	106.4	97.1	140.6
SE mean	8.22	10.6	11.9	12.6
Kolmogorov-Smirnov normality test				
D	0.64	0.85	0.56	0.73
P(D)	0.124	>0.15	p>0.15	0.101
Linear regression				
b - intercept	828.303	793.900	1096.59	1166.34
a - lope	0.82371	0.51751	1.20565	1.87491
r^2	0.8 %	0.3 %	1.6 %	4.4 %
F	1.18338	0.293361	1.05408	5.60660
P(R)	0.278	0.589	0.308	0.019

Table 6. Dead and live eulachon eggs collected in Fraser River plankton nets. A summary showing the number of larvae (L) and eggs (E) from randomly chosen samples for months of April, May and June in 1998 and 1999. The samples were collected from throughout the river. The egg categories are differentiated into alive or 'viable' (V) and 'dead' (D) eggs, and the percentage live eggs (relative to all eggs) is shown as 100V/E+L, and the percentage of viable offspring (larvae plus live eggs, relative to all larvae and eggs) is shown as 100(L+V)/E+L.

month		1998	1999	All
April	larvae (L)	316	16	332
	all eggs (E)	375	246	621
	eggs and larvae (E+L)	691	262	953
	percent eggs (100E/E+L)	54.27	93.89	65.16
	viable eggs - (V)	224	188	412
	dead eggs - (D)	151	58	209
	percent viable eggs (100V/V+D)	53.97	76.42	73.718
	percent viable all (100(L+V)/E+L)	78.14	77.86	78.06
May	larvae (L)	6097	21249	27346
	all eggs (E)	6788	3402	10190
	eggs and larvae (E+L)	12885	24651	37536
	percent eggs (100E/E+L)	52.68	13.80	27.14
	viable eggs - (V)	3308	2171	5479
	dead eggs - (D)	3480	1231	4711
	percent viable eggs (100V/V+D)	48.73	63.82	53.77
	percent viable all (100(L+V)/E+L)	72.99	95.01	87.45
June	larvae (L)	45	1949	1994
	all eggs (E)	121	805	926
	eggs and larvae (E+L)	166	2754	2920
	percent eggs (100E/E+L)	72.89	29.33	31.71
	viable eggs - (V)	12	495	507
	dead eggs - (D)	109	310	419
	percent viable eggs (100V/V+D)	9.92	61.49	54.75
	percent viable all (100(L+V)/E+L)	34.33	88.74	85.65
All months	larvae (L)	6458	23214	29672
	all eggs (E)	7284	4453	11737
	eggs and larvae (E+L)	13742	27667	41409
	percent eggs (100E/E+L)	53.00	16.09	28.34
	viable eggs - (V)	3544	2854	6398
	dead eggs - (D)	3740	1599	5339
	percent viable eggs (100V/V+D)	48.65	64.09	54.51
	percent viable all (100(L+V)/E+L)	72.78	94.22	87.11

Table 7. Summary of the mean density of eggs and larvae according to the sampling time of day and the position (station) in the river. The samples were collected at the New Westminster sampling area from May 23-24, 1996.

Sample time		North	Middle	South	All
2200	(dark)	0.8650	1.8871	0.2670	1.0063
0400	(dark)	2.6524	0.9840	0.2153	1.2839
1000	(light)	1.7725	1.0815	0.1953	1.0165
1600	(light)	1.8921	0.5827	0.2726	0.9158
All		1.7955	1.1338	0.2376	1.0556

Table 8. Results of bootstrap method #1 (weekly estimate) showing the mean and 95% confidence limits of eulachon spawning biomass estimates (tonnes) for different areas on the Fraser River, organized by year.

Year/Area	Biomass Estimate (t)	Lower 95% CI	Upper 95% CI
Barnston Island			
1995	200.01	91.88	331.61
1996	24.17	11.02	41.28
1997	18.38	14.11	23.95
1998	51.16	15.57	104.88
1999	43.09	10.97	110.09
2000	16.50	6.28	32.77
2001	1123.28	732.50	1507.39
New Westminster			
1995	135.74	83.75	200.36
1996	92.08	70.07	117.69
1997	44.18	32.87	56.41
1998	106.32	67.97	155.00
1999	123.30	77.36	172.60
2000	93.62	49.51	149.27
2001	803.60	400.34	954.32
2002	785.47	408.56	1114.98
Tilbury Island			
1997	86.235	58.197	116.228
1998	99.279	61.793	157.039
1999	506.30	210.48	1128.50
2000	117.654	63.527	180.890
2001	450.21	332.99	571.84
2002	na	na	na
Deas Island			
1997	45.40	35.04	56.75
1998	103.31	72.93	137.62
1999	391.20	286.92	513.45
2000	49.35	34.52	65.77
2001	402.97	341.51	467.72
2002	414.18	352.59	481.22
SARM: all 'South Arm' samples			
1995	257.46	184.04	335.01
1996	1587.80	1406.72	1775.45
1997	56.93	45.22	69.38
1998	105.90	83.18	131.03
1999	395.12	289.59	525.86
2000	71.64	54.48	91.17
2001	421.81	366.48	478.86
2002	na	na	na
NARM: all 'North Arm' samples			
1995	44.500	7.621	74.532
1996	327.69	38.43	441.66
1997	17.050	2.6277	26.322
1998	27.509	2.753	35.491
1999	25.252	3.456	37.059
2000	54.820	6.729	79.136
2001	186.61	12.02	218.66
2002	na	na	na

Table 9. Results of bootstrap method #2 (single annual estimate) showing the mean and 95 percent confidence limits of spawning eulachon biomass estimates for each year from 1995-2001 at two sampling areas: (a) the South Arm, representing pooled sample data from Tilbury and Deas Island sampling stations and (b) the New Westminster sampling station. These estimates are approximately similar to those shown in Table 8, but have tighter confidence limits.

(a) South Arm: Deas and Tilbury Island sampling stations pooled

	Biomass Estimate (t)	Lower 95% CI	Upper 95% CI
1995	301.2	207.5	389.4
1996	1492.4	1433.5	1723.5
1997	69.7	54.6	84.9
1998	102.7	72.7	128.1
1999	436.6	333.9	563.6
2000	79.1	58.7	97.9
2001	589.1	506.4	691.0

(b) New Westminster:

	Biomass Estimate (t)	Lower 95% CI	Upper 95% CI
1995	140.4	89.1	192.2
1996	111.6	86.4	141.7
1997	44.1	30.8	57.3
1998	158.6	96.7	238.1
1999	133.9	79.8	199.7
2000	99.0	67.2	133.1
2001	873.6	723.0	1062.6

Table 10. The mean and 95% confidence limits of spawning eulachon biomass estimates (tonnes) for different areas on the Fraser River (BI=Barnston Island, NW=New Westminster, TI=Tilbury Island, DI=Deas Island, SA=South Arm, NA=North Arm), organized by sampling year. The presentation of biomass estimates for each year is followed by a commentary explaining the probable distribution of spawning, based on the numbers, and a suggestion about the approximate spawning biomass.

Area/Year	**Mean**	**Lower 95% CI**	**Upper 95% CI**
BI-1995	200.01	91.88	331.61
NW-1995	135.74	83.75	200.36
DI-1995	na	na	na
SA-1995	257.46	184.04	335.01
NA-1995	44.500	7.621	74.532

Comment: In 1995 much of the spawning occurred above BI. Probably there was little spawning between BI and NW, indicating no spawning in the Pitt River. The estimate for NA (about 20% of the SA estimate) is consistent with the relative flow rates (25% NA, 75% SA). There may have been some additional spawning in the South Arm. Probably the total spawning biomass was between 200 to 300 tonnes.

Area/Year	**Mean**	**Lower 95% CI**	**Upper 95% CI**
BI-1996	24.17	11.02	41.28
NW-1996	92.08	70.07	117.69
DI-1996	na	na	na
SA-1996	1587.80	1406.72	1775.45
NA-1996	327.69	38.43	441.66

There was little spawning above BI, but perhaps about 70 tonnes spawning between NW and BI, and perhaps in the Pitt River. There was a an extraordinary pulse of spawners, in both the lower reaches of the South and North Arm, for a total spawning biomass of almost 1900 tonnes. Although there was clearly a substantial spawning biomass, and it was clearly confined to the lower reaches, the biomass estimate should be regarded as approximate, because the total sample size was small (high number of eggs and larve/m^3) and may have had an inflating effect. The estimate of the NA is about 20% of that of the SA. Probably the spawning biomass was not less than 1500 tonnes.

Area/Year	**Mean**	**Lower 95% CI**	**Upper 95% CI**
BI-1997	18.38	14.11	23.95
NW-1997	44.18	32.87	56.41
TI-1997	*86.23*	*58.20*	*116.23*
DI-1997	45.40	35.04	56.75
SA-1997	56.93	45.22	69.38
NA-1997	17.05	2.628	26.32

The year 1997 was a very poor year for eulachon spawning, with less than 20 tonnes above Barnston Island, and perhaps an additional 20 tonnes between NW and BI. The estimates for DI and SA are approximately the same (expected) but TI seems high and anomalous, although total numbers are low. The NA estimate is about 33% of the SA. Probably total spawning biomass was less than 100 tonnes.

Area/Year	Mean	Lower 95% CI	Upper 95% CI
BI-1998	51.16	15.57	104.88
NW-1998	106.32	67.97	155.00
TI-1998	*99.279*	*61.793*	*157.039*
DI-1998	103.31	72.93	137.62
SA-1998	105.90	83.18	131.03
NA-1998	27.509	2.753	35.491

Surveys in 1998 involved more samples than previous years, and the estimates appear to be more consistent over space. There was about 50 tonnes spawning above BI and perhaps an additional 50 tonnes spawning between BI and NW. The estimates of NW, TI, DI and SA are very similar. This indicates that there was no substantial spawning anywhere in the SA, and all the production seen there originated above NW. The NA estimate was about 25% of the total. Probably the total spawning biomass was less than 150 tonnes.

Area/Year	Mean	Lower 95% CI	Upper 95% CI
BI1999	43.09	10.97	110.09
NW1999	123.30	77.36	172.60
TI-1999	*506.30*	*210.48*	*1128.50*
DI1999	391.20	286.92	513.45
SA1999	395.12	289.59	525.86
NA1999	25.252	3.456	37.059

There was limited spawning above BI, and perhaps an additional 80 tonnes spawning between BI and NW, and perhaps in the Pitt River. The three independent estimates of spawning in the South Arm all are relatively high and roughly similar, and it appears that there was a substantial spawning between TI and NW. This explanation is consistent with the observation that the NA spawning was about 20% of the NW estimate. This indicates that the densities of larvae in the NA and NW were similar. Probably total spawning biomass was about 400 tonnes.

Area/Year	Mean	Lower 95% CI	Upper 95% CI
BI2000	16.50	6.28	32.77
NW2000	93.62	49.51	149.27
TI-2000	*117.654*	*63.527*	*180.890*
DI2000	49.35	34.52	65.77
SA2000	71.64	54.48	91.17
NA2000	54.820	6.729	79.136

There was little spawning above BI, but about 70 tonnes spawning between BI and NW. The estimate for NW is roughly similar to that of TI and SA which indicates relatively little spawning in the south Arm in 2000. The differences between DI and TI are surprising and unexplained, although total numbers are low. The NA estimate is over 1/2 of the NW estimate. This indicates that some spawning occurred in the North Arm. Probably total spawning biomass was less than 150 tonnes.

Area/Year	Mean	Lower 95% CI	Upper 95% CI
BI2001	1123.28	732.50	1507.39
NW2001	803.60	400.34	954.32
TI-2001	*450.21*	*332.99*	*571.84*
DI2001	402.97	341.51	467.72
SA2001	421.81	366.48	478.86
NA2001	186.61	12.02	218.66

Year 2001 saw a substantial spawning in the portions of the river upstream of BI, although it is not clear if the BI estimate (1100 tonnes) is accurate, although it is roughly similar to the NW estimate (800 tonnes). The three South Arm estimates are very similar, and all are lower than NW. This indicates that little or no spawning occurred in the SA. The NA estimate is about 20-25% of the NW estimate. This is consistent with the North vs South Arm discharge divergence. This distribution of biomass is consistent with the hypothesis that all of the spawning in 2001 occurred in upstream areas, probably about 800 tonnes. The sum of the NA (187 t) plus the SA (421 t) is about 600 tonnes, which is about 75% of the NW estimate. Therefore the 2001 spawning biomass probably was at least 600 tonnes and maybe was as high as 1000 tonnes.

Area/Year	Mean	Lower 95% CI	Upper 95% CI
NW2002	785.47	408.56	1114.98
TI-2002	*na*	*na*	*na*
DI2002	414.18	352.59	481.22
SA2002	na	na	na
NA2002	na	na	na

Only samples from NW and DI have been completely analyzed in 2002. Biomass estimates indicate that most, or all spawning occurred above NW, with little or no spawning in the South Arm.

Table 11. Summary of mean egg and larval density estimates (n/m3) compared between the north, middle and south sides of the river, for all years between 1995 and 2002, for sampling stations at (a) Deas Island, (b) New Westminster and (c) Barnston Island. Note: in years 1995 and 1996 samples were collected only from 'middle' positions in the river at Barnston and Deas Island.

(a) Deas Island

Year		Middle	North	South	All
1995	n	21	0	0	21
	mean	5.044	--	--	5.044
	minimum	0.000	--	--	0.000
	maximum	34.520	--	--	34.520
1996	n	25	0	0	25
	mean	21.618	--	--	21.618
	minimum	0.000	--	--	0.000
	maximum	93.553	--	--	93.553
1997	n	20	26	26	72
	mean	0.676	1.349	0.307	0.786
	minimum	0.052	0.000	0.000	0.000
	maximum	1.799	4.484	1.062	4.484
1998	n	50	30	32	112
	mean	1.070	3.424	0.913	1.656
	minimum	0.000	0.033	0.000	0.000
	maximum	5.212	18.046	10.677	18.046
1999	n	52	52	48	152
	mean	2.973	10.645	1.153	5.023
	minimum	0.000	0.000	0.000	0.000
	maximum	19.397	81.568	14.124	81.568
2000	n	54	52	54	160
	mean	1.343	1.307	0.295	0.978
	minimum	0.000	0.000	0.000	0.000
	maximum	12.762	12.170	4.794	12.762
2001	n	56	55	57	168
	mean	8.703	11.205	3.750	7.842
	minimum	0.037	0.000	0.037	0.000
	maximum	62.425	60.600	25.847	62.425
2002	n	56	56	58	170
	mean	5.815	7.221	3.956	5.644
	minimum	0.000	0.000	0.000	0.000
	maximum	30.368	40.478	36.311	40.478
All	n	288	271	275	880
	mean	3.844	6.568	2.006	4.642
	minimum	0.000	0.000	0.000	0.000
	maximum	62.425	81.568	36.311	93.553

Table 11**(b) New Westminster**

Year		Middle	North	South	All
1995	n	10	13	5	83
	mean	0.376	1.130	0.160	3.244
	minimum	0.000	0.000	0.000	0.000
	maximum	1.313	7.824	0.600	64.274
1996	n	38	28	28	120
	mean	1.667	2.662	0.513	1.696
	minimum	0.000	0.000	0.000	0.000
	maximum	16.433	18.008	2.643	18.008
1997	n	48	45	49	142
	mean	0.523	1.133	0.154	0.589
	minimum	0.000	0.000	0.000	0.000
	maximum	8.848	4.729	1.746	8.848
1998	n	46	16	13	75
	mean	0.972	4.291	0.121	1.532
	minimum	0.000	0.000	0.000	0.000
	maximum	4.286	21.825	0.473	21.825
1999	n	49	23	24	96
	mean	1.188	3.103	0.179	1.395
	minimum	0.000	0.000	0.000	0.000
	maximum	12.293	15.588	1.748	15.588
2000	n	52	27	26	105
	mean	1.291	4.765	0.251	1.927
	minimum	0.000	0.000	0.000	0.000
	maximum	5.309	16.648	0.976	16.648
2001	n	48	24	24	96
	mean	18.714	19.060	5.880	15.592
	minimum	0.000	0.084	0.000	0.000
	maximum	109.356	68.728	55.610	109.356
2002	n	49	26	26	101
	mean	11.839	17.786	1.944	10.823
	minimum	0.000	0.045	0.000	0.000
	maximum	72.448	118.998	10.094	118.998
All	n	340	202	195	818
	mean	5.120	6.578	1.163	4.398
	minimum	0.000	0.000	0.000	0.000
	maximum	109.356	118.998	55.610	118.998

Table 11(c) Barnston Island

Year		Middle	North	South	All
1995	n	33	0	0	33
	mean	3.719	--	--	3.719
	minimum	0.000	--	--	0.000
	maximum	35.083	--	--	35.083
1996	n	28	0	0	28
	mean	0.603	--	--	0.603
	minimum	0.000	--	--	0.000
	maximum	3.994	--	--	3.994
1997	n	12	12	11	35
	mean	0.182	0.435	0.029	0.221
	minimum	0.000	0.000	0.000	0.000
	maximum	0.574	1.026	0.140	1.026
1998	n	25	13	13	51
	mean	0.383	3.074	0.099	0.996
	minimum	0.000	0.000	0.000	0.000
	maximum	1.723	11.449	0.674	11.449
1999	n	47	24	24	95
	mean	0.095	1.679	0.026	0.478
	minimum	0.000	0.000	0.000	0.000
	maximum	0.469	11.913	0.265	11.913
2000	n	47	24	25	96
	mean	0.112	1.230	0.075	0.382
	minimum	0.000	0.000	0.000	0.000
	maximum	0.680	8.065	0.280	8.065
2001	n	40	20	19	79
	mean	29.047	33.827	7.783	25.143
	minimum	0.078	0.382	0.000	0.000
	maximum	140.985	124.980	79.784	140.985
2002	n	4	2	2	8
	mean	0.093	0.022	0.000	0.052
	minimum	0.048	0.000	0.000	0.000
	maximum	0.229	0.044	0.000	0.229
All	n	175	95	94	425
	mean	6.764	8.332	1.617	5.334
	minimum	0.000	0.000	0.000	0.000
	maximum	140.985	124.980	79.784	140.985

Fig. 1. The lower Fraser River showing the original sampling sites examined in 1995 and 1996. HS=Hatzic Slough, MI=Mission, SI=Silverdale, WH=Whonnock, HA=Haney, BI=Barnston Island, PR=Pitt River, PM=Port Mann, NW=New Westminster (at North/South Arm divergence), TI=Tilbury Island (South Arm), DI=Deas Island (South Arm), RB=Roberts Bank, SH=Sand Heads, SB=Sturgeon Bank, PG=Point Grey, IO=Iona Island (North Arm), OAK=Oak St. Bridge (North Arm) and PL= Pipeline (Norm Arm).

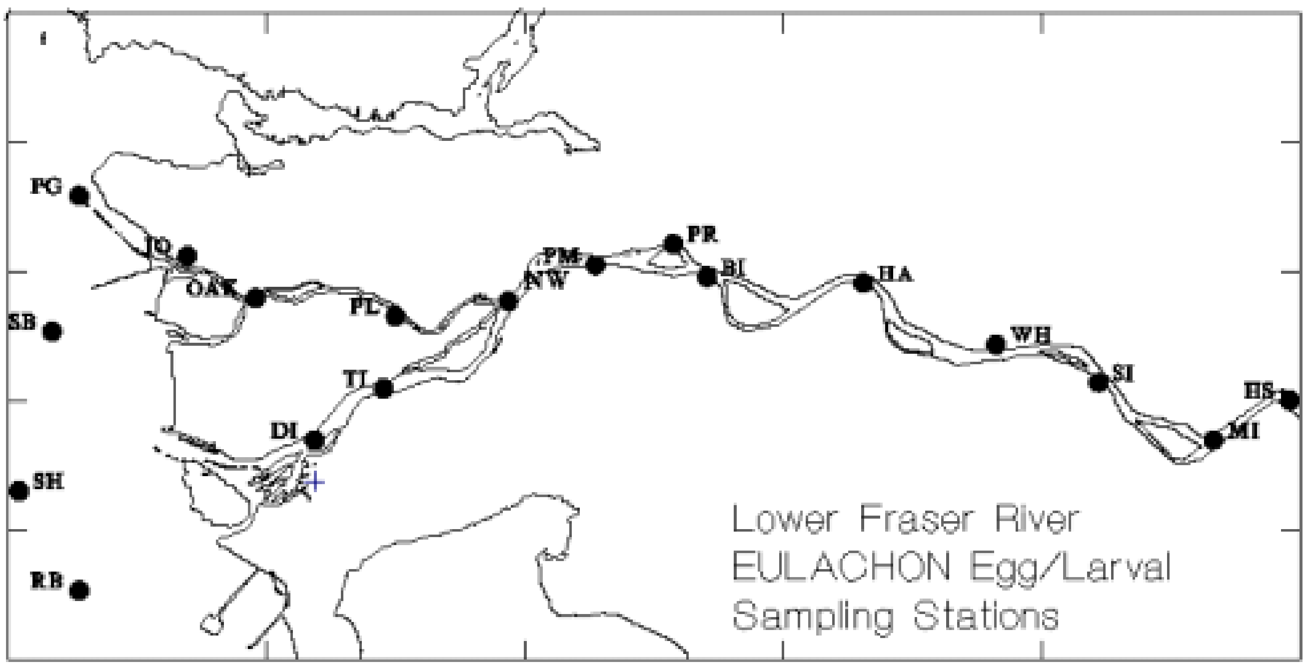


Fig. 2. The key sampling locations examined throughout all years (1995-2002). BI=Barnston Island (upriver of the Pitt River confluence), NW=New Westminster (near the North/South Arm divergence), TI=Tilbury Island (South Arm) and DI= Deas Island (South Arm).

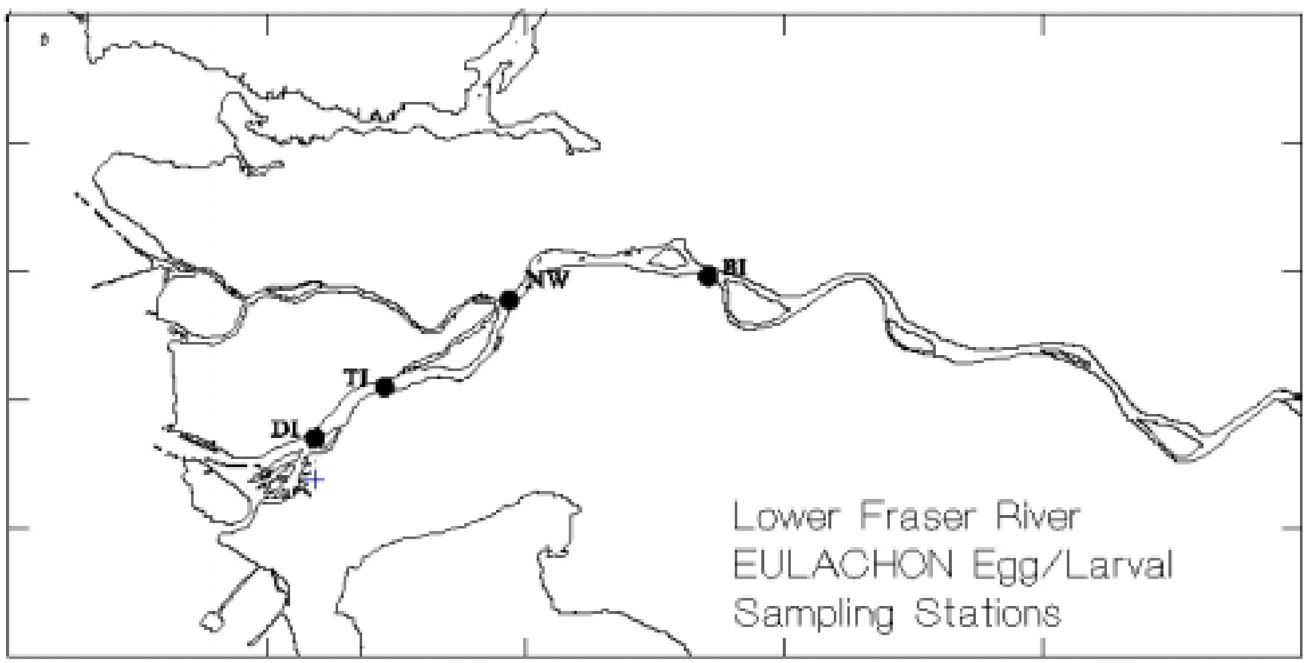


Fig. 3. The relationship between eulachon weight and length, based on measurements of approximately 2500 eulachon collected between 1995 and 2001.

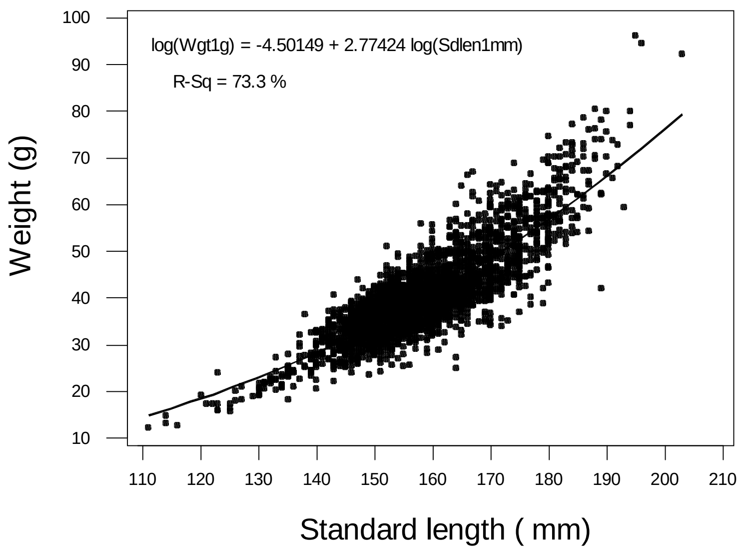


Fig. 4. Differences in inter-annual, eulachon weight-length relationships, from data shown in Table 3. Each line is calculated from the Minitab© LOWESS (Locally-Weighted Scatter plot Smoother) a smoothing function that selects 50% of all points closest in x-value, on either side of the point. The value for each point is then weighted according to the distance between that point and the point to be smoothed (Minitab©, 1997).

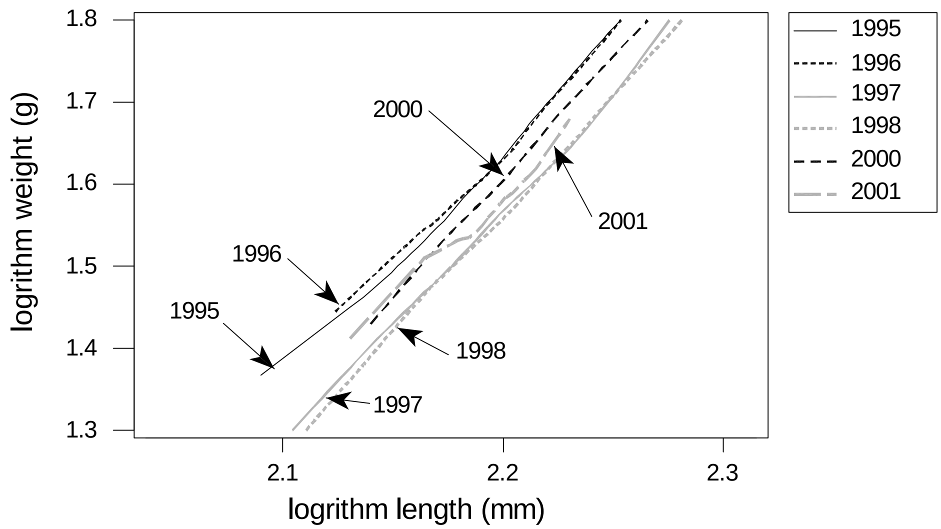


Fig. 5. Frequency distribution of Fraser River eulachon relative fecundities (rel_fec) based on 521 fish, collected between 1995 and 1998.

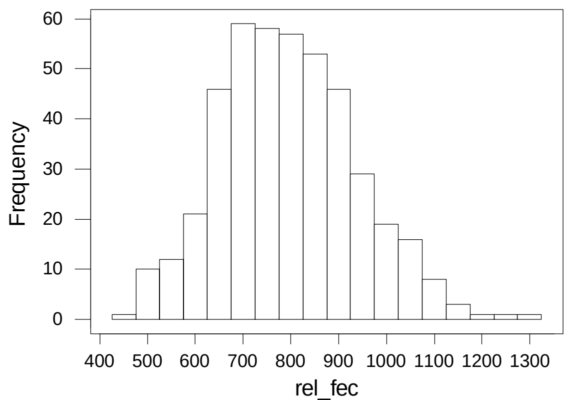


Fig. 6. Linear regression of Fraser River eulachon relative fecundity by standard length. The regression line for this plot, which shows data for all years, is significant ($P < 0.01$) but similar regression analyses estimated independently for each year, are not different (See Table 5 and text for explanation).

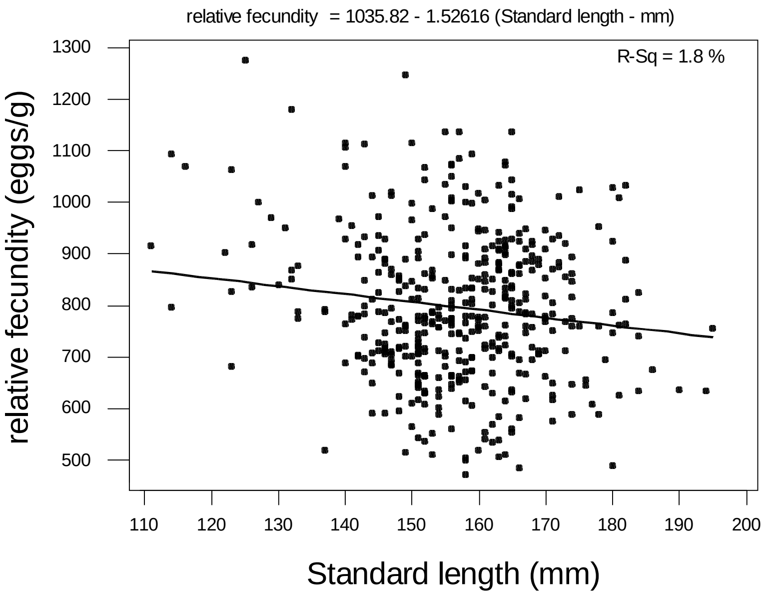


Fig. 7. Fraser River eulachon biomass and confidence limits estimated from bootstrap method #1, for major sampling areas. Within each panel, the earliest samples are shown at the left and the latest at the right. The open bars show the mean and the 95% confidence limits for each week of the sampling period and the dark bars show the mean and 95% confidence limits for the cumulative biomass.

(a) Spawning biomass estimates for Barnston Island, 1995-2001.

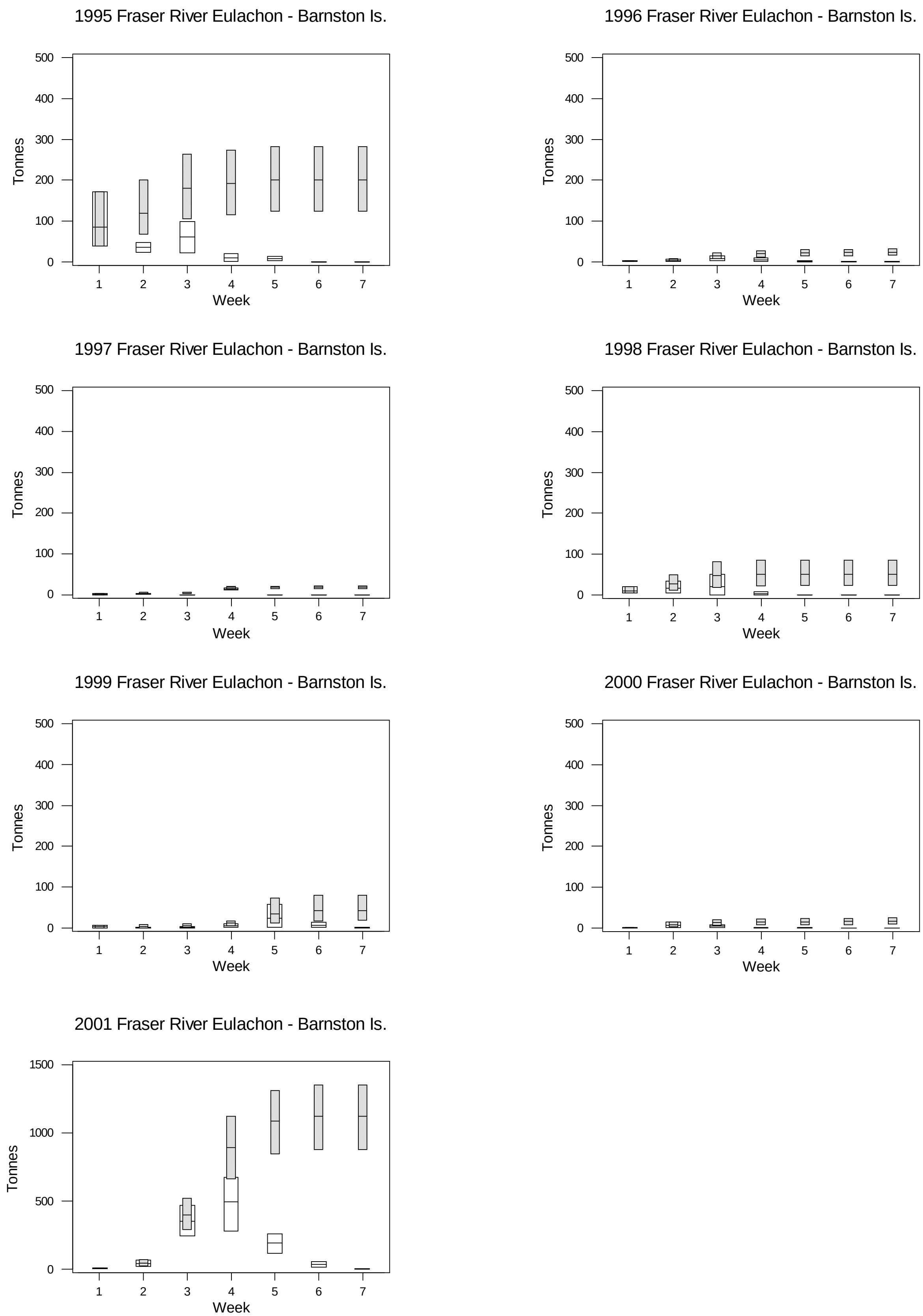


Fig. 7b. Spawning biomass estimates for New Westminster, 1995-2002.

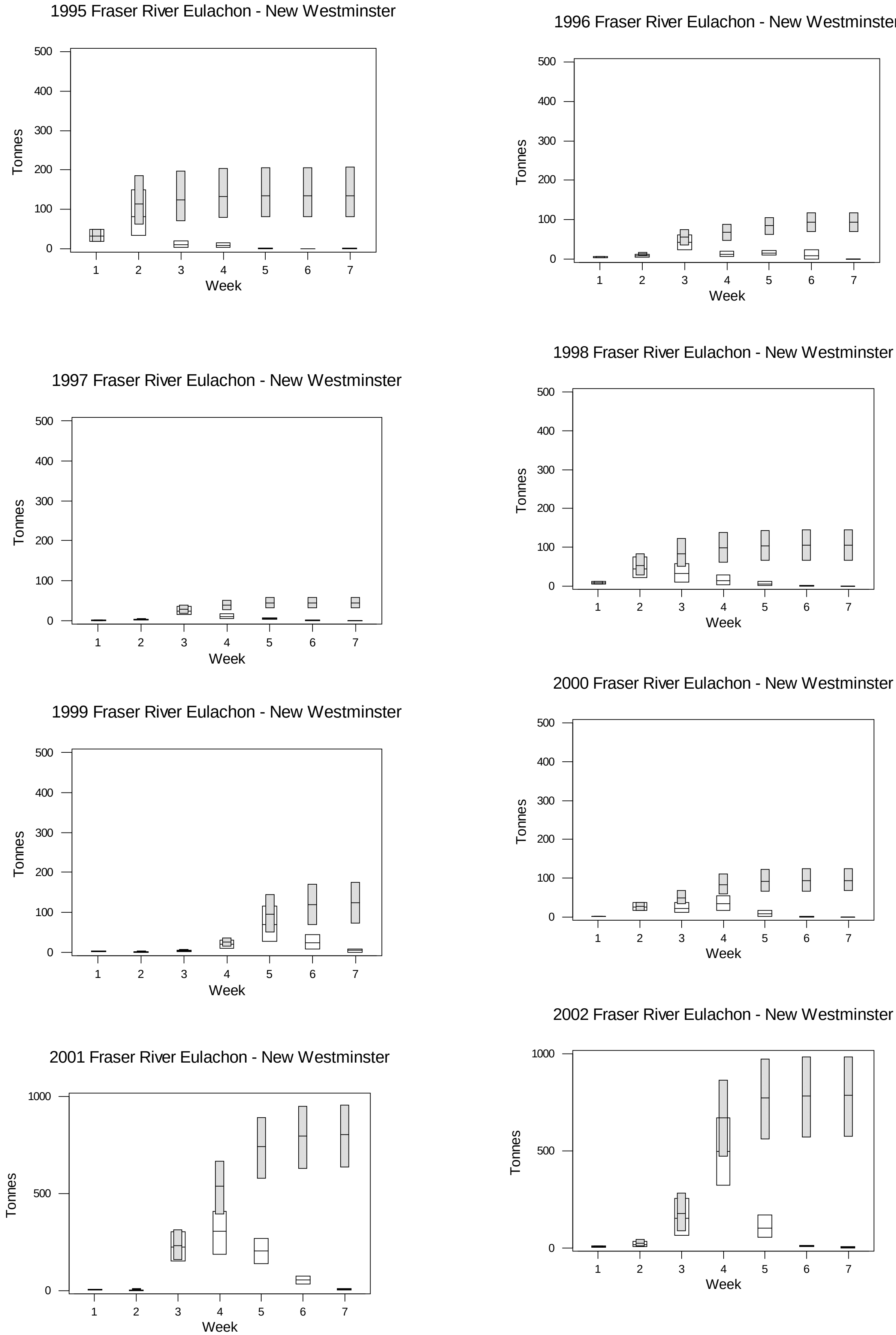


Fig 7c. Spawning biomass estimates for Tilbury Island, 1997-2001.

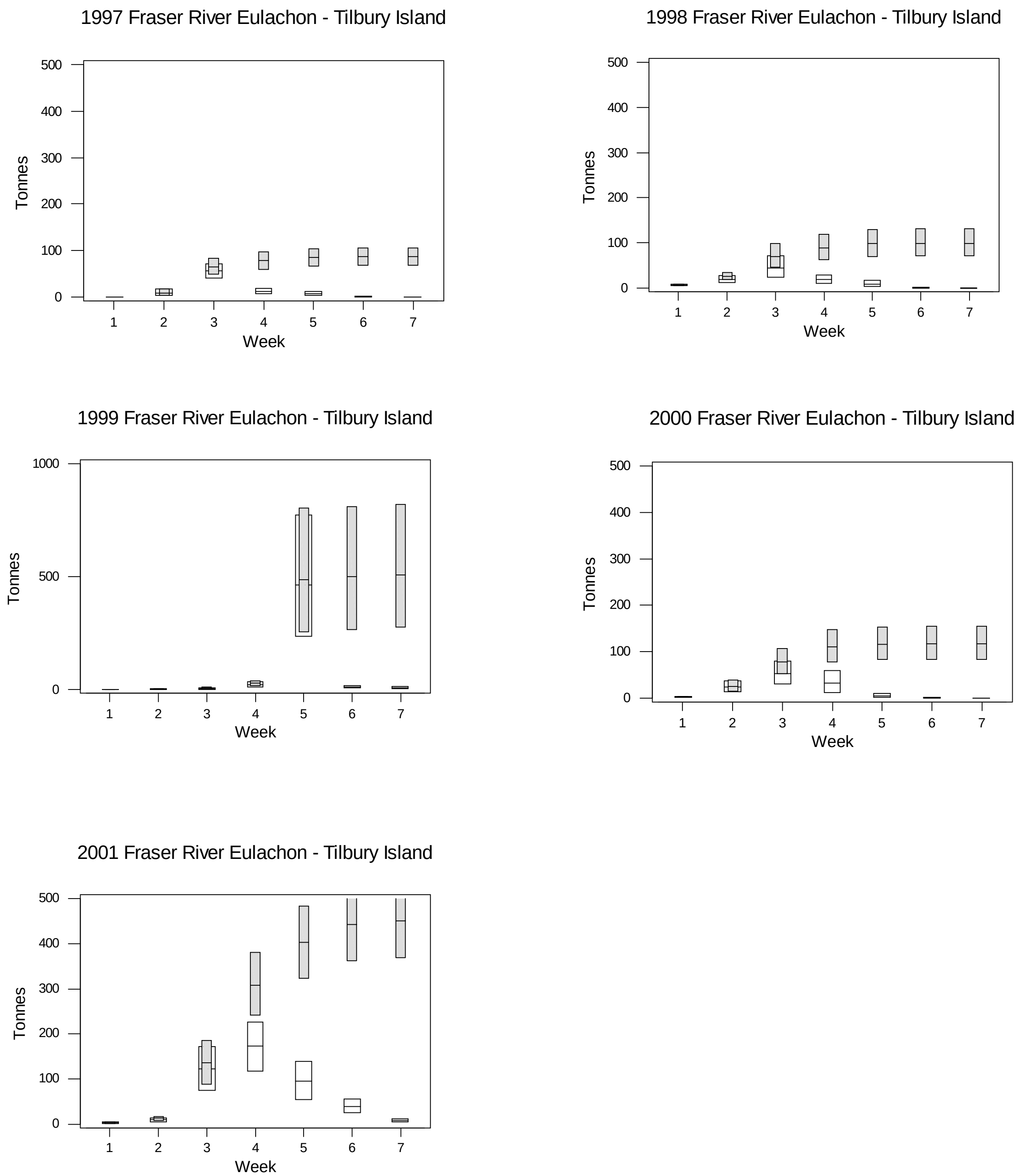


Fig. 7d. Spawning biomass estimates for Deas Island, 1997-2002.

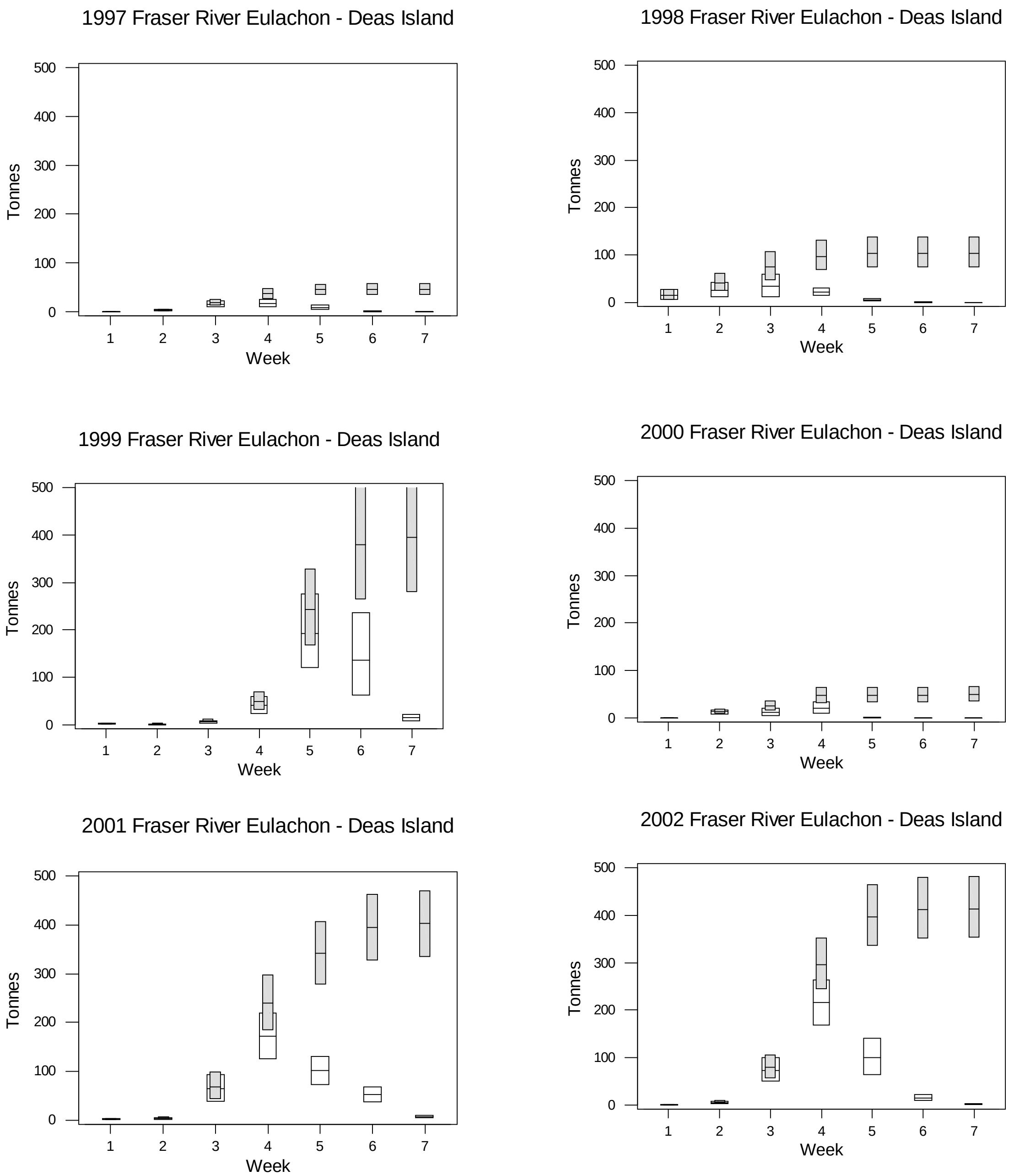


Fig. 7e. Spawning biomass estimates for Fraser River North Arm (combined stations), 1995-2001.

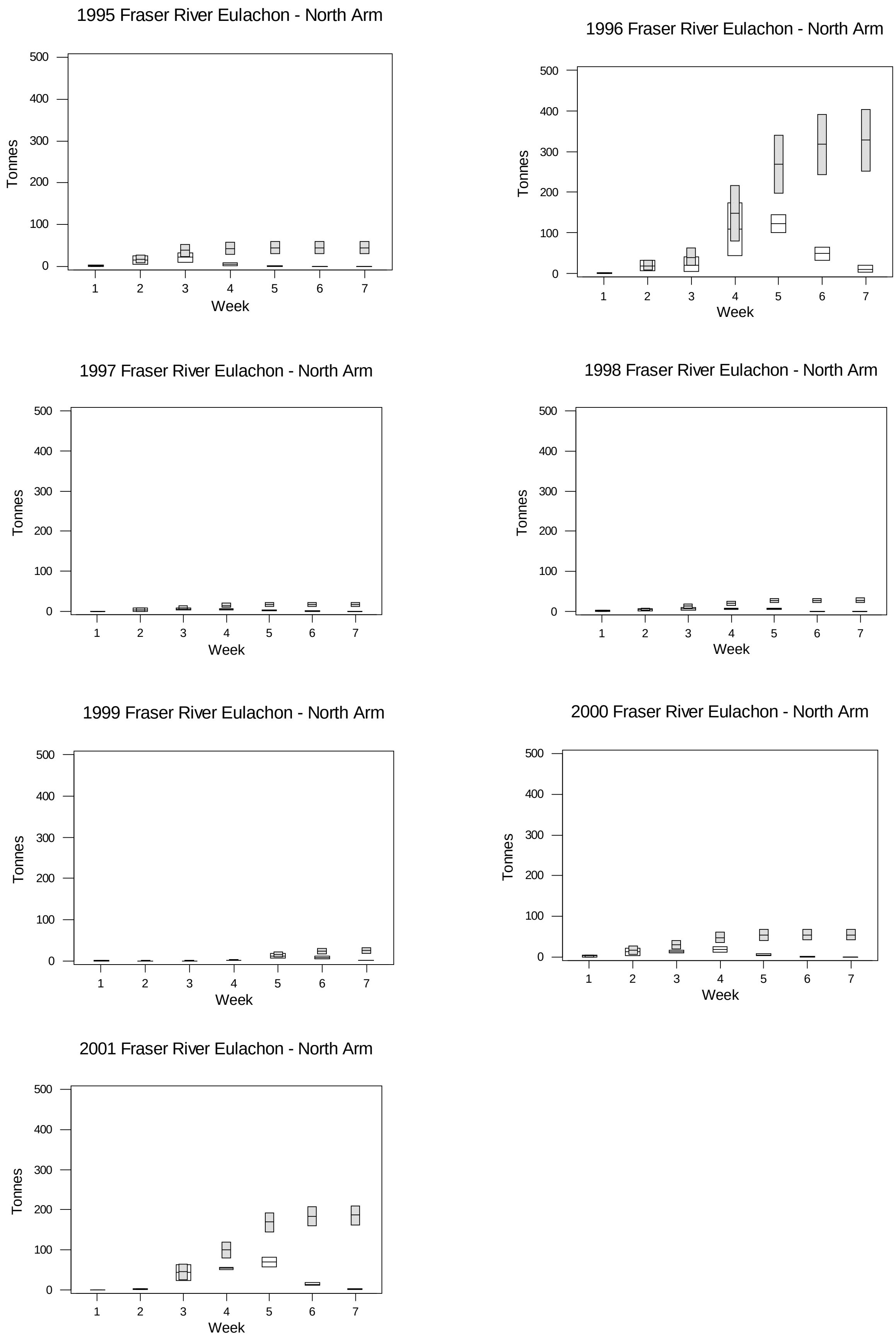


Fig. 7f. Spawning biomass estimates for Fraser River South Arm (combined stations), 1995-2001.

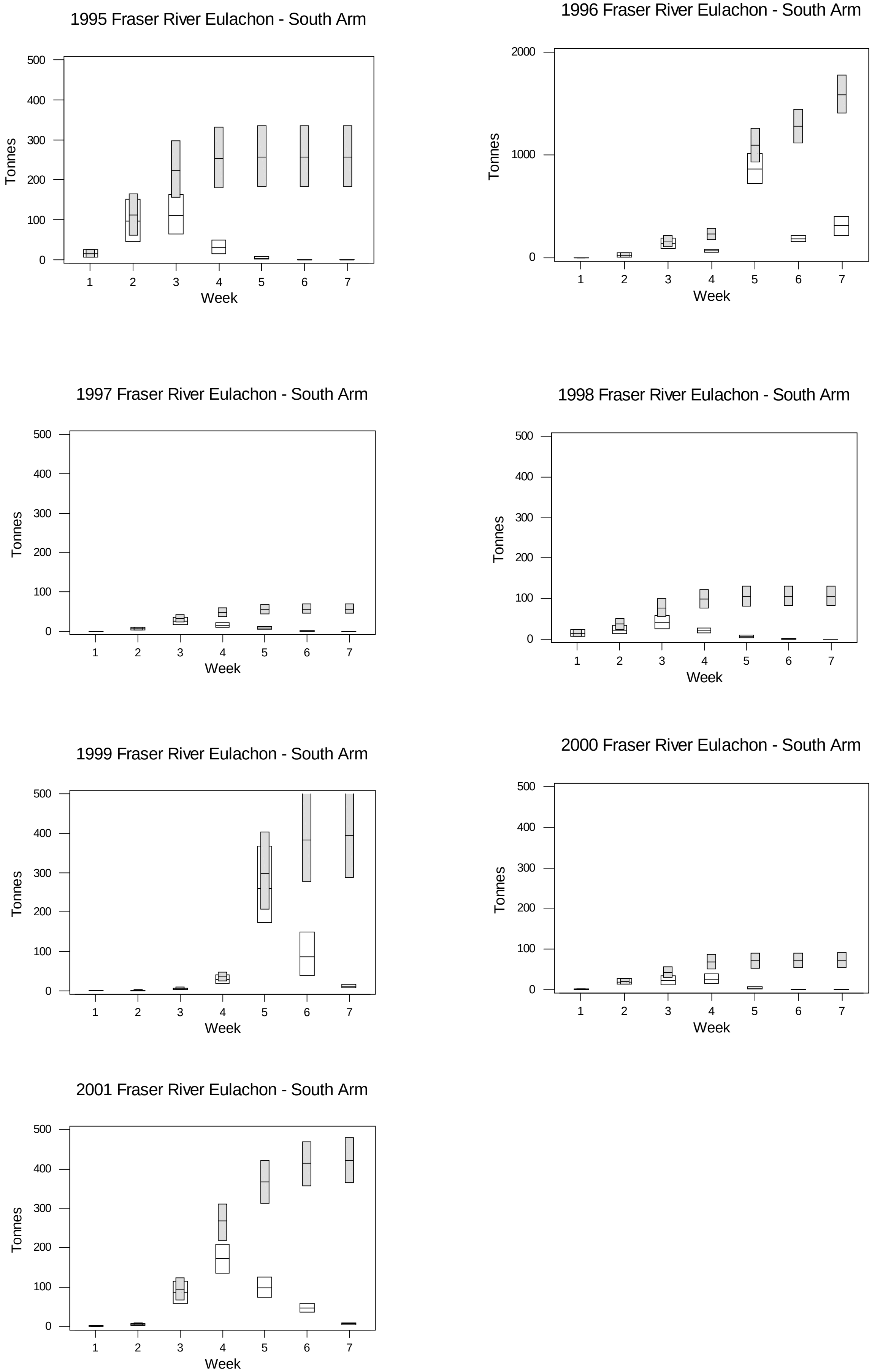
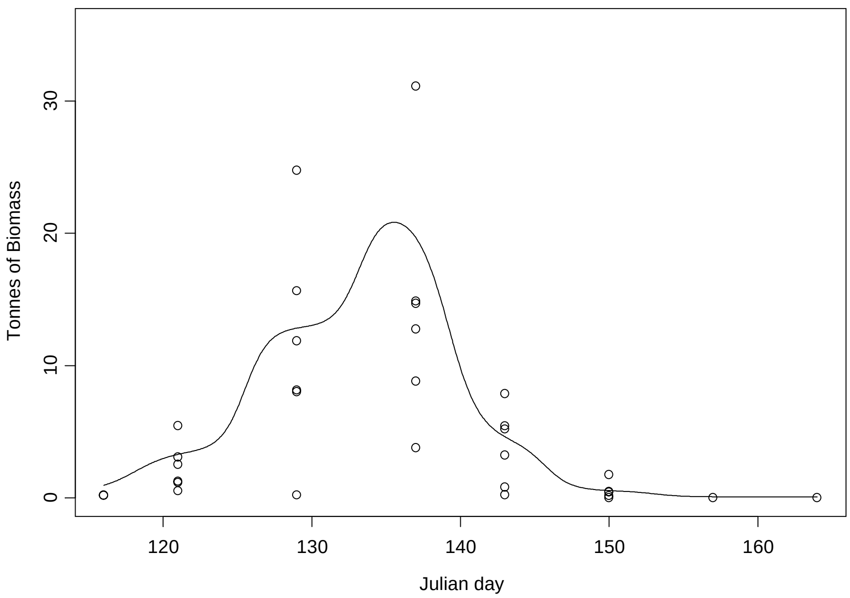


Fig. 8. The smoothed line and data sampling points at Tilbury Island, 1995, with (a) untransformed and (b) log-transformed data. The line shows the tonnes of spawning biomass.

(a) South Arm, 1995 - untransformed data



(b) South Arm, 1995 - transformed data

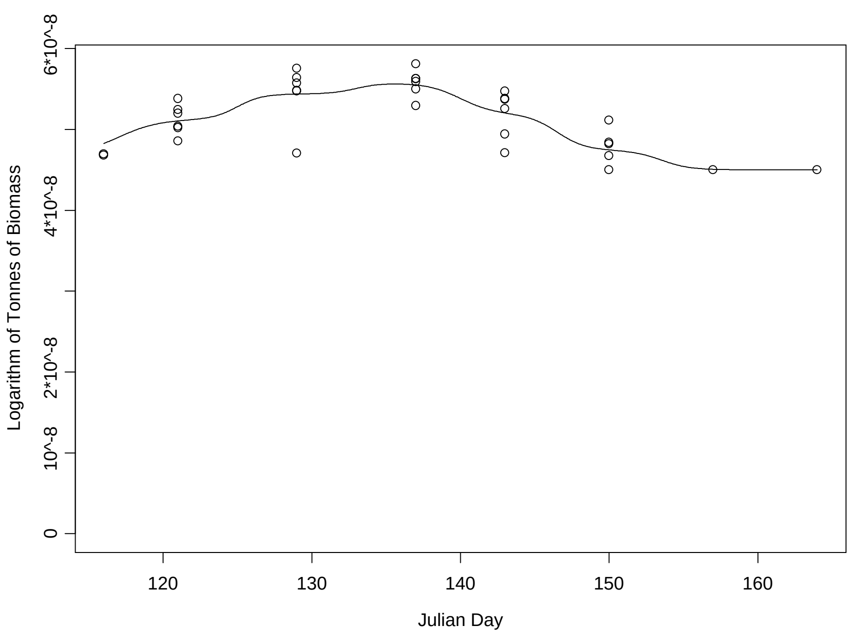
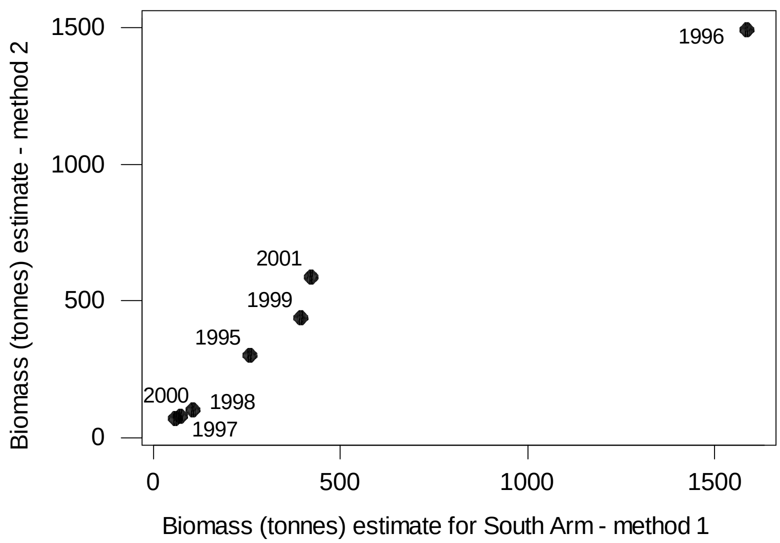


Fig. 9. Comparison of the eulachon spawning biomass estimates from 1995-2001 from the two methods, shown for (a) the South Arm and (b) New Westminster. The correlation coefficients are 99 and 98% respectively.



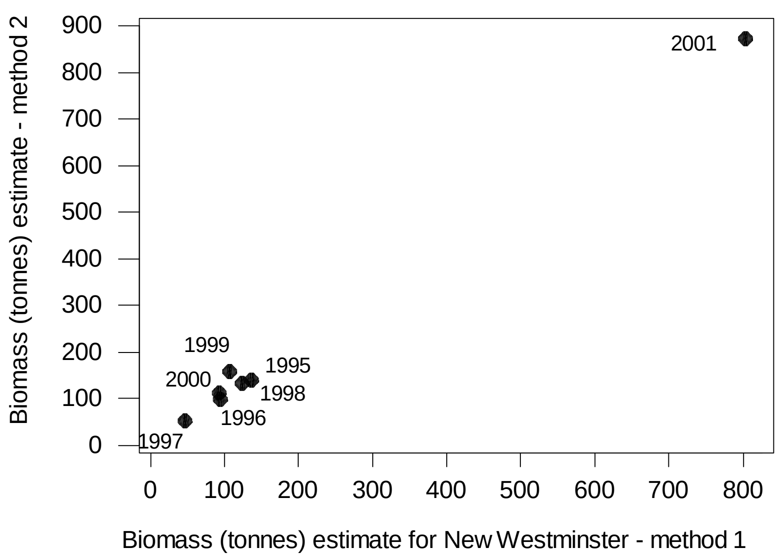
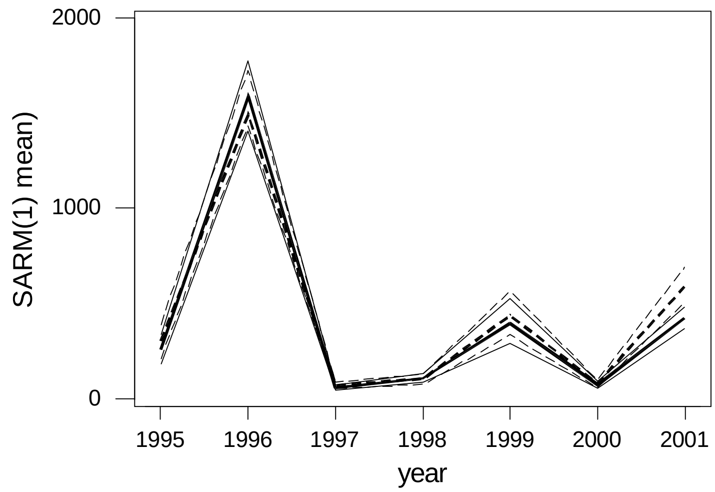


Fig. 10. Comparison of the eulachon spawning biomass estimates from 1995-2001 from the two bootstrap methods, shown for (a) the South Arm and (b) New Westminster. The three solid lines represent the mean, upper and lower 95% CL of bootstrap estimates from method #1 and the three dashed lined represent the mean, upper- and lower 95% CL of bootstrap method #2. Although the means are similar, the confidence limits of method #2 are tighter.

(a) The South Arm



b) New Westminster

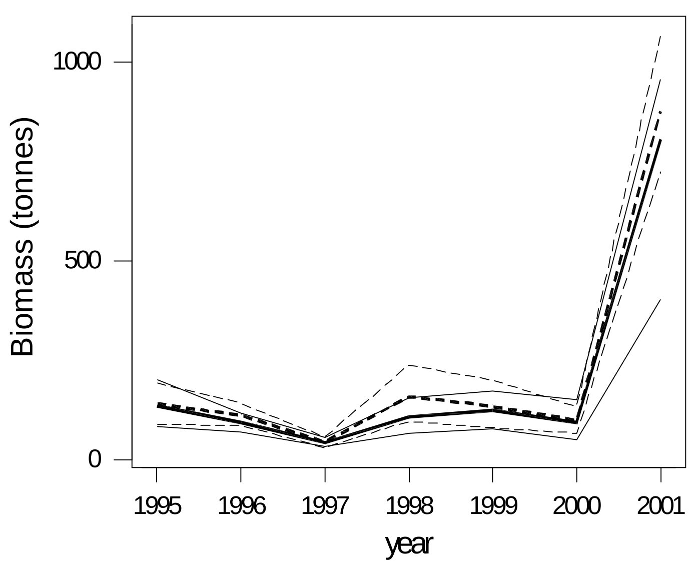


Fig. 11. An illustration and example of positional variation in egg and larval density between the north, middle and south sampling positions in the Fraser River. The x-axis shows the sampling positions (north, middle and south) and the y-axis shows the sample depth, from the surface to 10 meters. Each circle represents the results of a single tow with the radius of each circle proportional to the egg and larval density (n/m^3). While there is no apparent differences in abundance by depth, it is clear that the north and middle positions in the river had many instances of higher density than the south positions.