Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences

C S A S
Canadian Science Advisory Secretariat

S C C S
Secrétariat canadien de consultation scientifique

Research Document 2012/098
Pacific Region

Document de recherche 2012/098
Région du Pacifique

Recovery Potential Assessment of Eulachon (*Thaleichthys pacificus*) in Canada

Évaluation du potentiel de rétablissement de l'eulakane (*Thaleichthys pacificus*) au Canada

Jake Schweigert[1], Chris Wood[1], Doug Hay[2], Murdoch McAllister[3], Jennifer Boldt[1], Bruce McCarter[1], Thomas W. Therriault[1], Heather Brekke[4]

[1]Fisheries and Oceans Canada, Science Branch, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, BC, V9T 6N7

[2]Nearshore Research, 2510 Holyrood Drive, Nanaimo B.C. V9S 4K9

[3]Fisheries Center, University of British Columbia, 2202 Main Mall, Vancouver, BC, V6T 1Z4

[4]Fisheries and Oceans Canada, Fisheries Management Branch, Regional Headquarters, 401 Burrard Street, Vancouver BC, V6C 3S4

ISSN 1499-3848 (Printed / Imprimé)
ISSN 1919-5044 (Online / En ligne)

Canada

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Correct citation for this publication:

Schweigert, J., Wood, C., Hay, D., M. McAllister, Boldt, J., McCarter,B., Therriault, T.W., and H. Brekke. 2012. Recovery Potential Assessment of Eulachon (*Thaleichthys pacificus*) in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/098. vii + 121 p.

ABSTRACT

In May 2011, COSEWIC assessed three designatable units (DU) of eulachon (*Thaleichthys pacificus*) in Canada: Fraser (endangered), Central Pacific (endangered), and Nass/Skeena (threatened; although this DU is being re-assessed by COSEWIC). In light of these designations, DFO undertook this recovery potential assessment to provide scientific advice in support of considering management scenarios and conducting socioeconomic analyses to inform SARA listing decisions and recovery planning. A lack of consistent long term indices of population abundance made it extremely difficult to determine the recovery potential for these DUs. Indices of in-river abundance were summarized for each DU and examined in relation to time series of putative threats in freshwater and marine environments, at both coastwide and localized scales. No single threat could be identified as most probable for the observed decline in abundances among DUs or in limiting recovery. However, mortality associated with coastwide changes in climate, fishing (direct and bycatch) and marine predation were considered to be greater threats at the DU level, than changes in habitat or predation within spawning rivers.

A Bayesian stock reduction model was developed for the Fraser DU. The analysis suggested that the decline in population abundance could be explained most parsimoniously by the sequential historical impacts of directed in-river catch (prior to 1970), bycatch in the shrimp trawl fishery (1990 to 2000), and several consecutive years of anomalously low productivity (2002-2007 brood years). The model indicates that, under conditions of average historical productivity and current levels of bycatch mortality from shrimp trawling effort but no directed exploitation, the Fraser River population should rebuild to 33-49 percent (range for the three cohorts) of the unfished abundance over a period of 16-18 years. A directed catch of 30 tonnes would reduce rebuilding to 1-30 percent of the unfished population. The analysis suggests that the species is relatively unproductive and can sustain a maximum sustainable fishing mortality rate of only 0.10. Data in the other DUs are sparse but not prohibitive for the development of similar models. One would expect these populations to share similar population dynamics and productivity, and also require a conservative approach to management and rebuilding. Continued monitoring of the Fraser DU is needed to determine whether productivity has returned to average levels and, therefore, permitting of any allowable harm should be considered with caution. A lack of adequate monitoring makes identification of recovery targets for the Fraser and Central Coast DUs difficult, but we recommend an initial goal of surpassing the COSEWIC criteria for special concern listing at a minimum is recommended, with a longer term goal of continued population increases towards historical levels.

RÉSUMÉ

En mai 2011, le COSEPAC a évalué trois unités désignables (UD) d'eulakane (*Thaleichthys pacificus*) au Canada : la population du fleuve Fraser (en voie de disparition), la population centrale de la côte du Pacifique (en voie de disparition) et la population des rivières Nass et Skeena (menacée; cette UD fait cependant l'objet d'une réévaluation par le COSEPAC). En raison de ces désignations, le MPO a entrepris la présente évaluation du potentiel de rétablissement dans le but de fournir un avis scientifique permettant d'examiner des scénarios de gestion et d'effectuer des analyses socio-économiques qui serviront de base aux décisions concernant l'inscription à la liste de la LEP et à la planification du rétablissement. Déterminer le potentiel de rétablissement de ces UD est extrêmement difficile étant donné le manque d'indices d'abondance à long terme fiables. On a répertorié les indices d'abondance en rivière pour chaque UD et on les a comparés à des séries chronologiques de menaces possibles dans les milieux marins et d'eau douce à l'échelle locale et sur l'ensemble de la côte. On n'a pu déterminer aucune menace qui expliquerait la diminution de l'abondance observée dans les UD ou qui limiterait le rétablissement de l'espèce. Toutefois, pour ce qui est de la mortalité, les changements du climat, des activités de pêche (dirigée et accessoire) et de la prédation marine sur l'ensemble de la côte constitueraient des menaces plus importantes à l'échelle de l'UD que les changements qui touchent l'habitat ou la prédation dans les rivières de frai.

On a élaboré un modèle bayésien de réduction des stocks pour l'UD du fleuve Fraser. D'après l'analyse, la diminution de l'abondance de la population s'expliquerait tout simplement par la séquence d'effets historiques de la pêche dirigée en rivière (avant 1970), les prises accessoires de la pêche de la crevette au chalut (de 1999 à 2000) et une productivité anormalement faible pendant plusieurs années de suite (années d'éclosion de 2002 à 2007). Le modèle indique que, si la productivité atteint la moyenne historique et que l'on maintient les niveaux actuels de prises accessoires de la pêche de la crevette au chalut (sans activité de pêche dirigée), la population du fleuve Fraser devrait se rétablir à 33-49 % (fourchette pour les trois cohortes) de l'abondance avant pêche d'ici 16 à 18 ans. Des prises dirigées de 30 tonnes se traduiraient par une diminution du rétablissement de 1-30 % de la population inexploitée. Cette analyse permet de penser qu'il s'agit d'une espèce relativement peu productive qui ne peut tolérer qu'un taux de mortalité par pêche maximum de 0,10. On dispose de peu de données pour les autres UD, mais suffisamment pour élaborer des modèles semblables. On pourrait s'attendre à ce que ces populations présentent des dynamiques de population et une productivité semblables et qu'elles requièrent une approche prudente en matière de gestion et de rétablissement. Il est indispensable de faire un suivi continu de l'UD du fleuve Fraser afin de déterminer si la productivité s'est rétablie et si l'on peut donc envisager, avec prudence, d'autoriser des dommages admissibles. Sans un suivi adéquat, il est difficile de déterminer les objectifs de rétablissement pour les UD du fleuve Fraser et de la côte centrale; on recommande comme objectif initial de dépasser, au minimum, les critères du COSEPAC pour les espèces désignées comme préoccupantes, et de viser une augmentation soutenue des populations de retour aux niveaux historiques comme objectif à long terme.

BACKGROUND

This document provides an assessment of the recovery potential (RPA) for eulachon (*Thaleichthys pacificus*) in Canada. The completion of an RPA is required to respond to the listing decision and recovery planning processes by the Department of Fisheries and Oceans (DFO) for species at risk under the *Species at Risk Act* (SARA). This document was also requested to provide scientific advice on a number of unresolved issues that are conceptually fundamental to recovery planning.

Eulachon is a semelparous species in the smelt family (Osmeridae). They occur only in a limited number of rivers of the eastern north Pacific from California to the Bering Sea. Eulachon spend most of their lives in the marine environment, are demersal and feed primarily on euphausiids. They have high lipid content and are an important prey item for a variety of fish, mammal, and avian predators. It is believed that most eulachon live for three years at which age they return to the freshwater rivers near their birthplace to spawn and die.

In this report, indices of abundance for individual populations are consolidated to portray a best estimate of the overall trend in mature (spawning) numbers in each designated unit (DU). Information on the stock composition of marine samples is used to estimate, for each DU, the magnitude and trend in exposure to trawl fishing effort, and to refine indices of immature (marine) abundance. Differences between marine and spawning (freshwater) indices are re-examined, but conflicting trends remain unresolved requiring further investigation. Potential causes of population declines are examined and assessed in terms of their ability to explain the timing of declines in spawning abundance, and to reconcile differences between the marine and freshwater indices.

Some existing threats (e.g., food, social and ceremonial (FSC) fisheries, marine mammal predation, and degradation of freshwater habitat) are unlikely to have been responsible for the recent widespread declines in abundance, but may now be preventing recovery from low abundance in some DUs. These threats are examined to provide advice on plausible recovery scenarios (i.e. targets), and corresponding levels of allowable harm.

DU STATUS AND TRENDS

Eulachon have been reported to spawn in at least 40 rivers in British Columbia (Figure 1, Table 1 from Levesque and Therriault 2011). Surveys of genetic variation indicate that eulachon probably exist as a dozen or more demographically isolated populations throughout this range (Beacham et al. 2005). In their assessment of May 2011, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) grouped eulachon populations within the BC coast into three 'Designatable Units' (DUs) based on their criteria for discreteness and evolutionary significance: The Fraser River DU, the Central Pacific Coast DU (including all rivers between the Fraser and Skeena rivers), and the Nass/Skeena DU (including the Nass, Skeena, and Bear Rivers) (see Figure 1). The Fraser and Central DUs were both assessed as *Endangered*. The Nass/Skeena DU was assessed as *Threatened* but is currently being reassessed by COSEWIC.

The current document builds on the background material summarized by Levesque and Therriault (2011), written prior to the COSEWIC listing recommendations. COSEWIC did not define the offshore extent of the three DUs. For the purpose of this document, we have used the COSEWIC DU designations for the inshore areas and throughout the paper refer to the Nass/Skeena Rivers DU as the Nass/Skeena DU, the Central Pacific Coast DU as the Central DU and the Fraser River DU as the Fraser DU (Figure 2). These three groupings are not functionally linked to the three regions we have delineated for the offshore area to deal with marine samples and groundfish and shrimp trawl fishing effort. These offshore regions are referred to as North Coast, Central Coast and West Coast Vancouver Island (Table 2, Figure 2).

Eulachon stock composition estimates are available from each of these three offshore regions allowing for the partitioning of samples and fishing effort to each DU.

Trends in freshwater biomass

A difficulty in determining the status and trends for each DU is the lack of any consistent monitoring over an extended period of time within the various river systems. Catch data are available for many systems, but these may or may not include First Nations harvest data, are frequently intermittent, and may not be representative of abundance. Consistent monitoring through egg and larval surveys has occurred on the Fraser River from 1995 to present and in the Kitimat River from 1994-2006, Bella Coola River from 2001 to present and intermittently in other systems (Gustafson et al. 2010).

Moody (2008) used fuzzy logic analysis to describe the in-river trends in eulachon biomass throughout the Canadian range. Moody's work provides the only available qualitative or quantitative indicators of trends in spawning abundance for eulachon within 9 river systems in British Columbia and a 7-year smoothed index scaled to the range of historical values for each of these rivers (Figures 3-7). It is important to recognize that these scaled indices are used only to reveal trends over time, and to look for differences in trends among DUs that might help to identify factors causing the trends. It would be meaningless to compare the absolute values of the scaled indices among DUs.

Fraser DU

Three indices are available for the Fraser DU – the smoothed index of biomass from Moody (2008) for the entire period 1881 to 2006, CPUE in the gillnet test fishery from 1995 to 2005 (Hay et al. 2003), and the estimate of spawning stock biomass (SSB) from egg and larval surveys from 1995 to 2011 (McCarter, unpublished data). Moody's (2008) analysis for the Fraser River (Figure 3) indicates that spawning biomass had been relatively stable prior to 1945, but declined steadily thereafter, with a steep decline from 2000 to 2006. Indices from the recent gillnet test fishery and egg-larval survey are highly positively correlated (r=0.94, n=10) and indicate that spawning biomass has declined dramatically over the past decade (see Figures 10 and 11).

Central DU

Moody's (2008) analysis of the trends in biomass for six rivers in the Central Coast indicates considerable annual variability among rivers, but all rivers show an overall decline to very low levels by 2006,. The Kitimat and Kemano systems (Figure 4) both show a decline beginning in the mid-1980s while the Bella Coola River (Figure 5) shows a gradual decline from the mid-1940s through the mid-1990s followed by a dramatic drop to the recent low level of abundance. The Klinaklini and Kingcome Rivers (Figure 6) show an extended but more gradual long term decline in biomass. For the purposes of this RPA, we obtained an overall smoothed trend for the Central DU by averaging the smoothed trends from the 6 rivers (Kitimat, Kemano, Bella Coola, Wannock, Kingcome, Klinaklini, and Kingcome) for which figures are available in Moody (2008). This overall trend for the Central DU reveals a gradual decline in biomass beginning in 1970, with a steep decline from 1995 to 2006 (Figure 32).

Nass/Skeena DU

Moody's (2008) analysis for the Nass River system (Figure 7) indicates a gradual long-term decline in abundance over the past century, with indications of an increase during the past decade. Data from the Skeena River (Figure 7) are very limited, so it could be misleading to average them with more reliable data from the Nass River. Therefore, Skeena River data were not included in the index for the Nass/Skeena DU.

Trends in marine biomass

Marine distribution

Information on the offshore distribution of eulachon is available from undirected catches in the DFO groundfish research trawl survey (Figure 8) and the DFO multispecies small mesh survey (Figure 9). The multispecies small mesh surveys have been conducted consistently with DFO research vessels, using a small mesh otter trawl net towed along the bottom and a target duration of 30 min at a depth range of 50-200m. The surveys are conducted during April to May within the west coast of Vancouver Island (WCVI) region and Central Coast region, and in September in the North Coast region (restricted to Chatham Sound). The surveys include multiple tows throughout the trawlable area and are intended to sample all species in the area. The surveys capture eulachon of all age groups although very few young-of-the-year are captured during the spring survey. Usually, two distinct size modes are present and the largest mode represents eulachon that are likely to spawn in the rivers the following spring (February-May). These surveys began in 1973 in the WCVI region, but did not begin until 1998 and 1999 in the North Coast and Central Coast regions, respectively.

Genetic analysis to determine stock composition of these incidental catches has been conducted by DFO in each region since 2002, but not in every year. The most complete coverage has been on the west coast of Vancouver Island (Table 3). Samples from the North coast region originate mainly from the Nass/Skeena DU (average 48%) and Central DU (45%), with smaller contributions from more southerly populations (averaging 6% from the Fraser River and 1% from the Columbia River, ranges and confidence intervals are shown in Table 3). Samples from the Central Coast region include roughly equal proportions from the Nass/Skeena DU (average 27%), Central DU (26%), and Fraser DU (28%), with a lesser component from the Columbia River (18%). Samples from the WCVI were dominated by eulachon from the Columbia River (average 56 %) and the Fraser DU (average 39%), with only small contributions from the Central DU (3%) and Nass/Skeena DU (2%). This consistent latitudinal gradient suggests that the marine distribution of eulachon is relatively restricted to offshore areas adjacent and immediately north of the natal river system. No genetic sampling was conducted off the coast of Washington so we cannot yet rule out the possibility that some Fraser eulachon migrate southward as suggested by a recent US study (Al-Humaidhi et al. 2012).

Indices of marine biomass

An annual index of marine biomass for each DU was determined by summing annual catch per unit effort (CPUE in kg/h) in each survey region weighted by the average percentage contribution from that DU to the survey catch. This procedure is similar to that used to compute exposure to fishing effort by DU (see groundfish trawling below). Because this weighting calculation requires a biomass index from each survey region, the marine indices of biomass by DU are available only for the period 1999 to 2011 (longest time series available from DFO multispecies small mesh survey). Over this period, the marine indices of eulachon biomass have been stable or increasing for all DUs, in contrast to the decline for the in-river indices of biomass for the Central and Fraser DUs (Figure 10).

Reconciling marine and freshwater abundance

Because the marine biomass indices are dominated by age 2+ fish that would have matured in the following spring, it is appropriate to lag these marine indices by one year before comparison to the in-river indices. As a result, the marine indices can be compared to the smoothed freshwater indices for only 7 years (2000 to 2006). Over this short period, the marine and in-river biomass indices are not significantly correlated for any of the DUs. The correlations are positive for the Nass/Skeena DU (r= 0.375, n=7, P=0.42), but negative for the Central DU (r= -0.50, n=7, P=0.26) and for the Fraser DU (r= -0.22, n=7, P=0.63 for the smoothed index) or weakly positive for the Fraser SSB index (r=0.08, n=12, P=0.80). Similarly, longer term comparisons of the CPUE index in the WCVI survey with in-river indices for the Fraser DU are both negative (r= -0.37, n=28, P=0.05 for the smoothed in-river index; r= -0.15, n=17, p=0.56 for the SSB index) (Figure 11).

Evaluating the threats to eulachon, causes for their decline, and factors affecting their potential recovery requires reconciliation of these two apparently disparate indicators of biomass. Both indices are variable and influenced by assumptions about eulachon behaviour and distribution. It is worth noting that the offshore indices are substantially larger than the in-river indices, but this comparison could be misleading in that each index provides only relative rather than absolute biomass estimates. Even so, the indices also reveal conflicting trends in two DUs (Central and Fraser) that must be explained. The following explanations have been considered:

(1) The marine trends are misleading: A cross-correlation analysis of the times series of age-specific components of the marine index (i.e. biomass of age 1+ and age 2+ cohorts) indicates that the WCVI marine biomass index may only weakly reflect actual eulachon abundance in the offshore areas. In years when age composition data are available (1999-2010), the indices of age 1+ and age 2+ cohort biomass are more strongly correlated within the same year than in consecutive years indicating that factors associated with year-to-year variations in availability to the survey gear have a larger influence on the index than cohort abundance. This result held when the index was recomputed to include only the Fraser DU based on genetic estimates of composition available for 2002 and 2006 to 2010; note that the mean Fraser proportion of 39% was assumed in the other years. Similarly, it is apparent that the spawning biomass was exceptionally high in the Fraser River in 1996, but the WCVI survey index remained near historic low values during this period (Figure 11).

(2) The in-river trends are misleading. The observation that independent in-river indices (egg and larval survey and the gillnet test fishery) for the Fraser DU are significantly positively correlated (ρ = 0.84) strongly suggests that both in-river indices correctly reflect a real decline in spawning biomass in the known spawning areas. However, if some eulachon spawning occurred in unmonitored areas then spawning biomass could be under-estimated. Some evidence for this hypothesis comes from past egg and larval surveys that found eulachon yolk-sac larvae in small rivers and streams that were previously undocumented as eulachon spawning sites (Hay and McCarter 2000, McCarter and Hay 1999). However, it is not known whether these or other undocumented spawning sites still exist, and there is no evidence to indicate that unmonitored sites are being utilized increasingly in a way that could account for the opposite trends evident in the marine and in-river indices for the Central and Fraser DUs.

(3) Eulachon recruitment may have been adequate to maintain a stable immature biomass offshore, despite increasingly intense mortality that occurs after the marine surveys (spring and summer) and before in-river monitoring. Such mortality could occur though natural predation or fishing impacts, such as trawling that could entrain and kill eulachon, predominately associated with the migration from offshore feeding grounds to river spawning grounds. However, this explanation requires that small (and decreasing) spawning populations can produce sufficient progeny to maintain a stable (or increasing) abundance offshore.

Further investigation is warranted to examine the relative plausibility of these alternative explanations. **For the purposes of this RPA, and consistent with the assessment by COSEWIC, we have assumed that explanation 1 is correct, and have disregarded the marine indices as an abundance index in the remainder of this report.**

THREATS DIRECTLY RELATED TO HUMAN ACTIVITIES

The term ‘threat’ is used in the context of SARA as defined in the Environment Canada 2007 *Draft Guidelines on Identifying and Mitigating Threats to Species at Risk* (DFO 2010a)

> “as any activity or process (both natural and anthropogenic) that has caused, is causing, or may cause harm, death, or behavioural changes to a species at risk or the destruction, degradation, and/or impairment of its habitat to the extent that population-level effects occur.”

The cause(s) of the apparent coastwide decline of most eulachon populations is unclear. A number of potential sources of mortality were identified previously (Hay and McCarter 2000, Pickard and Marmorek 2007, Moody 2008, Clarke and Therriault 2009, Gustafson et al. 2010, Levesque and Therriault 2011) and those for which new data became available are revisited here.

FISHERIES

Eulachon can be captured at sea, usually as bycatch in bottom trawl fisheries targeting shrimp or groundfish species, or in mid-water trawls directed at pelagic species such as hake. The fisheries occur both in offshore regions and occasionally in coastal areas in fjords or inlets that form migratory corridors for eulachon or in the estuaries off the mouths of spawning rivers. Eulachon also can be captured in rivers, usually by gillnets, seines or dipnets. Most rivers with consistent eulachon runs have supported fisheries by First Nations, but long-term commercial and recreational fisheries have occurred on the Fraser River, and infrequently on other rivers.

In-river fishery

The in-river eulachon fisheries have been conducted largely by First Nations for food, social, and ceremonial usage (FSC). The only regular commercial harvesting was in the Fraser River, although historically a short-term commercial fishery occurred in the Nass nearly a century ago and small, brief commercial harvests were taken from the Skeena and some Central DU systems (Moody 2008). Currently, commercial harvesting of eulachon is prohibited within British Columbia due to conservation concerns. Gustafson et al. (2010) provide an extensive review of commercial harvests of eulachon throughout its range south of the Nass River.

Fraser Du

The historical in-river commercial eulachon harvest from the Fraser DU peaked at about 300 metric tonnes (mt) in the early 1950s (Figure 12) when there was a ready market for the product. Subsequently, markets changed and catches gradually declined until the closure in 2002 (Moody 2008). First Nations FSC harvest occurred throughout the period but was poorly documented. A very small ceremonial fishery continues today (DFO, unpubl. data).

A recreational fishery has occurred in the Fraser River. The inception of the fishery is uncertain but may have started in the late 1800s. Mainly eulachon were captured with dip nets. The cumulative catch sizes are uncertain, as there was virtually no monitoring of the fishery. It is presumed that the recreational fishery in recent decades has been relatively small.

Central DU

The harvest of eulachon within the Central Coast is primarily conducted by First Nations, although small amounts of commercial harvest occurred within the Knight and Kingcome Inlets for a short period during the 1940s (Moody 2008). The First Nation harvest of eulachon was not well documented, so it is difficult to estimate total eulachon catch on an annual basis, but it appears to have averaged about 150 tonnes since the 1950s (Figures 13-15). Modest FSC harvest continues on some of the Central DU systems (Kingcome, Klinaklini, Kemano) today when runs are abundant.

Nass/Skeena DU

The combined commercial and First Nations harvests within the Nass River system peaked at about 400 tonnes in the 1940s (Figure 16, Moody 2008). Subsequent catches are slightly lower. Small commercial harvest also occurred for a short time on the Skeena River but that run has declined to very low levels and is no longer fished commercially (Moody 2008). A significant eulachon harvest by First Nations continues today in the Nass River and is managed by the Nisga'a First Nation.

Marine fisheries - Groundfish trawling

The domestic commercial groundfish trawl fishery operates in many areas of the British Columbia coast and frequently catches eulachon in low numbers. The fisheries are diverse, operating with differing gear at various times and locations throughout the year. The groundfish fishery has had 100% monitoring with onboard observers since 1996. In general, the nets used in the trawl fishery have mesh sizes that would normally not retain eulachon, but small numbers are observed at various times. We cannot yet estimate how many eulachon are entrained by groundfish trawl nets, or what proportion of them are injured and die after escaping though the large meshes of these nets.

To estimate the potential impact of the groundfish trawl fisheries on eulachon, we analysed the available data from the groundfish research surveys that have been conducted by DFO in each of the three offshore regions for many years. We have restricted our analysis to the period since 2002, because the net used for the surveys since that time most closely approximates the gear used by the commercial fleet (Workman, pers. comm., Table 4). The groundfish research surveys also employ a liner in the codend of the net increasing the probability that eulachon will be retained in the net (relative to commercial nets). However, it is likely many eulachon escape through the wings and some of the body of the net and so these data do not provide an absolute abundance index. The research surveys have had a consistent small catch of eulachon except for an unusually large tow in one year on the west coast of Vancouver Island (Figure 9). Eulachon retention during these surveys in all three offshore regions has generally been about 1 kg/hr or less with a few exceptions. The average across all survey areas and years was 2.24 kg/hr (Figure 17).

The impact of the groundfish commercial trawl fishery was evaluated by estimating the total hours of trawl effort conducted in each offshore region at depths less than 500m. This is likely an overestimate of total effort because survey data indicate that eulachon are encountered generally at depths of 100-250m. The effort data for each DU were further adjusted according to the origins of eulachon based on the genetic composition data presented in Table 3. The total effort per DU was determined as follows:

$$EFF_{NS} = E_{NS} \bullet P_{NS}^{NS} + E_{CC} \bullet P_{CC}^{NS} + E_{FR} \bullet P_{FR}^{NS}$$
$$EFF_{CC} = E_{NS} \bullet P_{NS}^{CC} + E_{CC} \bullet P_{CC}^{CC} + E_{FR} \bullet P_{FR}^{CC}$$
$$EFF_{FR} = E_{NS} \bullet P_{NS}^{FR} + E_{CC} \bullet P_{CC}^{FR} + E_{FR} \bullet P_{FR}^{FR}$$

where,

EFF = total effort attributed to the Nass/Skeena, Central, or Fraser DU

E_{NS} = total effort in the North coast region

P_{NS}^{NS} = proportion of Nass/Skeena DU eulachon in the North coast region

E_{CC} = total effort in the Central region

P_{CC}^{NS} = proportion of Nass/Skeena DU eulachon in the Central region

E_{FR} = total effort in the west coast of Vancouver Island region

P_{FR}^{NS} = proportion of Nass/Skeena DU eulachon in the west coast of Vancouver Island region

P_{NS}^{CC} = proportion of Central DU eulachon in the North coast region

P_{CC}^{CC} = proportion of Central DU eulachon in the Central coast region

P_{FR}^{CC} = proportion of Central DU eulachon in the west coast of Vancouver Island region

P_{NS}^{FR} = proportion of Fraser DU eulachon in the North coast region

P_{CC}^{FR} = proportion of Fraser DU eulachon in the Central coast region

P_{FR}^{FR} = proportion of Fraser DU eulachon in the west coast of Vancouver Island region

The result of applying these adjustments to the groundfish trawl effort data is presented in Figure 18 and indicates a stable but increasing trend through the early 1990s, when effort rose rapidly and peaked for a few years, subsequently declining to long term average levels.

The potential threat of ground fisheries trawling to eulachon cannot be clearly established but all reasonable measures should be taken to avoid interception of eulachon in groundfish nets. Further research that examined the potential effect of entrainment but not capture of eulachon would be useful.

Marine fisheries - Shrimp trawling

It is evident from small mesh multispecies research surveys and fisheries catch data that eulachon are often closely associated with shrimp and are a common bycatch in the shrimp trawl fishery (Pickard and Marmorek 2007, Gustafson et al. 2010, Levesque and Therriault 2011). In fact, some believe that the shrimp trawl fishery has been responsible for much of the recent decline in eulachon abundance. An objective evaluation of the impact of this fishery, however, is complex (e.g. Hay et al. 1999a, 1999b, Olsen et al. 2000). The observer data on the British Columbia shrimp trawl fishery is very limited in time and space and has only been collected since 1997. The shrimp fishery prior to 1975 was conducted primarily with beam trawls but subsequently otter trawls have supplemented catches, particularly during the 1980s and 1990s. It is generally accepted that otter trawls have a higher incidence of eulachon bycatch than beam trawls. Beam trawling currently dominates in all three eulachon offshore regions amounting to about 70-80 percent of the total effort. Fishing effort has been variable and driven largely by market demand and the availability of shrimp licenses.

We considered two approaches to estimate the bycatch of eulachon in the shrimp trawl fishery. One was a similar approach to the analysis of groundfish research surveys to determine catch rates of eulachon during the small mesh multispecies survey. However, the advice from DFO experts on the shrimp fishery was that the gear used during the survey and the areas covered were not representative of the fishery so this approach was not pursued further. A second approach, similar to that used in the past by Hay et al. (1999a,b), was to calculate the ratio of eulachon weight to shrimp weight in the catches. Unfortunately, there were few observations for any offshore area except for the west coast Vancouver Island region and we were uncertain about how representative recent data would be of the historic landings. As a result, we did not attempt to estimate bycatch in the shrimp fishery directly.

As an alternative to the two approaches above we elected instead to estimate the total trawl effort (hours fished) applied on each eulachon DU by using the genetic data as described above for groundfish. The available data are similar to the groundfish pattern with effort increasing slightly over time but dramatically in the early 1990s for several years then declining rapidly towards the long-term average level (Figure 19).

It is clear that eulachon can be captured and killed in shrimp nets as bycatch, but it is not clear if the bycatch is responsible for the coastwide eulachon decline. Even if bycatch were not the cause of the decline, the mortality related to bycatch may impede potential recovery and is suggested by the analysis in Appendix 3. This analysis indicates that eulachon populations are not able to sustain high fishing mortality rates, either from directed fisheries or from bycatch. Further, in the mid-1990s there may have been some years when mortality from bycatch negatively impacted recruitment in the Fraser River eulachon population. It follows that reduction and elimination of bycatch in shrimp fisheries is a worthwhile objective.

Levesque and Therriault (2011) also noted that the multispecies small mesh trawl survey directed at shrimp may have an impact on eulachon but given their duration this would be expected to be minor, and because it provides the only available offshore index to monitor eulachon abundance it must be permitted to continue.

HABITAT IMPACTS

Habitat impacts in freshwater

Impacts on the available spawning and rearing habitat for eulachon in freshwater have been described previously by Levesque and Therriault (2011), Gustafson et al. (2010) and Pickard and Marmorek (2007).

The impacts include:

- (i) log booming;
- (ii) dredging;
- (iii) discharge alteration of flow rates;
- (iv) industrial pollution and agricultural chemical runoff;
- (v) disposal of organic wastes;
- (vi) in-river disturbances during spawning.

Gustafson et al. (2010) note that because of the high lipid content of eulachon that they are particularly susceptible to incorporation of a variety of contaminants and toxins. This is consistent with the findings of Rogers et al. (1990) who examined contaminants in Fraser River eulachon. They found that contaminants in eulachon tissues increased with the upstream distance from the river mouth. In general, however, Fraser River water quality appears to be improving with time (Pickard and Marmorek 2007) but no studies of the subsequent effects on eulachon have been conducted.

While impacts (i to iv above) and other effects might be important, they vary in significance and magnitude among rivers in the three DUs and have occurred over different time periods. The fact that abundance trends have been somewhat synchronous across river systems indicates that freshwater habitat impacts are not the major factor responsible for the decline or lack of recovery of eulachon at the DU scale.

<u>Habitat impacts in the marine environment</u>

Impacts in the marine environment, particularly the estuarine rearing areas, vary in scope among river systems (Levesque and Therriault; 2011, Pickard and Marmorek 2007). Little is known about the offshore marine habitat for eulachon other than the general depth distribution which was described by Sinclair et al. (2007), Figures 20 and 21 and modelled in the study by Finney (unpublished data). The main threats would include marine traffic of various types in the offshore and foreshore development, including aquaculture facility siting in the coastal zone and the shallowing of the anaeorbic zone which is discussed further under climate change below.

THREATS NOT DIRECTLY RELATED TO HUMAN ACTIVITIES

IN-RIVER PREDATION

Levesque and Therriault (2011) and Gustafson et al. (2010) describe predators that feed on eulachon during their spawning runs. They note the importance of bird and fish species as well as marine mammals, particularly sea lions and seals. Predation impact in estuarine staging areas and in fresh water has a limited duration and may target spawning as well as post-spawning individuals. Such predation may be significant at certain times and places but is not likely sufficient to generate the large scale dramatic declines observed in the 1990's throughout much of the Pacific coast.

MARINE PREDATION AND COMPETITION

Many species have been observed to feed on eulachon but identifying those that could be considered a serious threat to the recovery of eulachon is difficult. For a species to be considered a threat it must be sufficiently abundant to consume a substantial quantity of eulachon to the extent that the cumulative effect exerts a marked natural mortality rate on the species. Gustafson et al. (2010) provide a detailed review and we consider the available evidence for British Columbia below.

<u>Marine mammals</u>

In some cases predators can exert top-down control on prey resources in marine ecosystems (Baum and Worm 2009). Marine mammals in British Columbia that are known to consume or have the potential to consume eulachon include part-time residents and migratory species, such as humpback whales (*Megaptera novaeangliae*), northern fur seals (*Callorhinus ursinus*), and California sea lions (*Zalophus californianus*), as well as resident species, such as harbour seals (*Phoca vitulina*) and Steller sea lions (*Eumetopias jubatus*). Total consumption of eulachon by marine mammals depends on a number of factors including mammal abundance, residence time, diet composition, daily ration, weight, age, sex, and temporal and spatial overlap with eulachon. Information on most of these factors is scarce for marine mammal species in BC. Information that is available is summarized in Appendix 4 and at a minimum, estimated marine mammal population trends can be qualitatively compared to indices of eulachon abundance. In general, eulachon has not been a significant component of the diet of any marine mammals, but determining their overall consumption is complex.

Migratory marine mammals are highly mobile and can travel great distances; therefore, they likely consume prey in more than one eulachon DU. Population abundance trends of migratory marine mammals were therefore examined on a BC-wide basis. The assumption is that trends are common across all areas in BC waters and have similar effects on prey in the different eulachon DUs.

Marine fish

Eulachon in the offshore marine environment susceptible to predation are primarily juveniles and adults larger than about 50 mm. Pearsall and Fargo (2007) summarize one of the few comprehensive studies of stomach content data attempting to understand predator prey relationships in British Columbia from groundfish research surveys. The study focuses on Hecate Strait but the interactions are likely indicative of similar linkages in the other two eulachon DUs. Additionally, Sinclair et al. (2007) summarized the available abundance and distribution data from groundfish research surveys for 67 fish species commonly found in this area. Of the species identified in the Pearsall and Fargo (2007) study, which feed extensively on forage fish or unidentified fish and were also noted by Sinclair et al. (2007) to have increased in abundance over the period from 1984-2003, a limited number were found to occur in the same depth strata as eulachon (Figures 20, 21). These species included sablefish, walleye pollock, and arrowtooth flounder (Figures 22, 23). However, the arrowtooth flounder was by far the most piscivorous of these species, with its diet consisting primarily of herring and other forage species including eulachon.

Comparable data for arrowtooth flounder are available from the west coast of Vancouver Island region in the multispecies small mesh trawl survey. The data are shown in Figure 24, and although their presence was intermittent for the period of the 1980s, the data suggest that there has been an increasing trend in abundance through to about 2005, followed by a collapse and recovery.

Pacific hake is another species that has been identified as an important predator on eulachon in the west coast of Vancouver Island and Central coast regions (Pickard and Marmorek 2007, Gustafson et al. 2010, Levesque and Therriault 2011). Pacific hake abundance increased through the 1970s and 1980s and subsequently declined (Figure 25). Hake constitutes one of the largest single species fish biomasses on the west coast of North America and, although primarily a planktivore, the larger adults also consume fish such as eulachon. Pacific hake spawn off California and migrate into British Columbia waters each summer to feed, the extent of their movement is dependent on ocean conditions such as temperature.

Another species that may have had coastwide impacts on eulachon in recent decades is the Pacific sardine (Figure 26). Although sardine are unlikely to prey on eulachon (except perhaps the larvae) and are largely a surface oriented species, whereas eulachon are primarily demersal, both species feed extensively on euphausiids (Gustafson et al. 2010, McFarlane et al. 2005). Pacific sardine, like hake, spawn off southern California migrating to the rich feeding grounds off British Columbia during the summer and potentially compete for food with eulachon and other forage species. Sardines are known for dramatic fluctuations in abundance increasing from complete absence to great abundance over a period of only a decade. Sardine abundance was believed to be less than 10,000 mt in the early 1980s, subsequently expanding to upwards of 1.5 million mt in two decades. It is conceivable that competitive pressure for food may have impacted eulachon in the offshore environment. It should, however, be noted that sardine were abundant in the 1920s through the early 1950s, while eulachon were also apparently abundant in-river.

Marine birds

Many bird species consume eulachon, taking advantage of this lipid-rich food source (Gustafson et al. 2010). Birds aggregate in intertidal areas and lower reaches of rivers during eulachon spawning runs (Collison 1916, Marston et al. 2002), and predation on eulachon may be particularly high during this period. Bird species observed to consume eulachon include: bald eagles (*Haliaeetus leucocephalus*), gulls, terns (Laridae), ducks (Anatidae), shorebirds (Scolopacidae), Kingfisher (Alcedinidae), raptors (Falconidae) and passerines (Corvidae, Motacillidae, Emberizidae), grebes (*Podiceps* spp.), scoters (*Melanitta* spp.), mergansers (*Mergus* spp.) and marbled murrelets (*Brachyrhamphus marmoratus*) (Marston et al. 2002, Ormseth et al. 2008). In the Gulf of Alaska, Ormseth et al. (2008) provided model estimates (based on model and diet data) of forage fish in seabird diets. Eulachon represented 7% to 50%, by weight, of seabird diets: murres (7.4%), albatross and jaegers (8.3%), kittiwakes (10.1%), shearwaters (11.7%), puffins (14.2%), gulls (19.2%), cormorants (49.9%; Ormseth et al. 2008).

CLIMATE CHANGE

Climate change impacts were examined in detail by Gustafson et al. (2010) and may be expected to impact both marine and freshwater habitats. The temporal pattern of climate impacts probably cannot be predicted with precision, but sudden changes in ocean temperature over broad geographic areas, such as those associated with extreme El Nino events, could explain synchronous impacts on different eulachon populations and could explain the synchronous decline in eulachon in the Columbia and Fraser systems in the mid-1990s (Hay et al. 1997).

CLIMATE CHANGE IMPACTS ON FRESHWATER HABITATS

Changes in freshwater habitats that could affect eulachon would likely be factors that affect the timing and volume of discharge in different rivers or tributaries of large rivers. Such changes may have the potential to impact several stages of eulachon including direct impacts on success of spawning and survival of eggs through the incubation stage, and indirect impacts on larval survival through timing related changes in feeding opportunities in estuaries. Gustafson et al. (2010) note that increasing global temperatures are expected to result in reduced snowpack with the resultant impact on the timing and magnitude of river discharge. Such changes would potentially impact eulachon because spawning rivers appear to be those subject to spring runoff – or spring ‘freshets’, in contrast to ‘fall-freshet’ rivers that have peak discharge periods in the fall months. Fall-freshet rivers are characteristic of coastal islands where eulachon spawning runs are virtually unknown. Hay and McCarter (2000) described the apparent association of eulachon spawning with snow-pack or glacier-fed rivers. However, Eaton and Moore (2010) explain that within a calendar year the temporal sequence of river discharge changes from precipitation as rain, followed by melting snow with the latest, usually in the summer months, by glacier ice melts. Based on the descriptions by Eaton and Moore (2010), it seems that if there is a connection between eulachon spawning and the source of water in their spawning rivers, it is from ‘snow-melting’ (or rivers known to have ‘snow-melt regimes’) and not necessarily glaciers. If such an association between eulachon spawning and snow melt regimes exists, there are implications for impacts from future climate change. In general, scenarios of climate change for the BC coast anticipate warmer summers and wetter (higher precipitation) winters, but this varies regionally within the province. Depending on the severity and rapidity of warming, snow melt input into coastal rivers could vary, with some rivers receiving less snow and others more. In general, northern areas in BC may see increased snowpacks and an expansion in glacier growth as a consequence of increased winter precipitation but the opposite effect could occur in southern areas (Taylor and Taylor 1997, Figure 29). Over the next century such possible effects could be beneficial for freshwater eulachon spawning habitat in the north and deleterious in the south.

The other consideration with the expected increase in global temperature is the possibility of increased in-river temperatures to the extent that some might no longer be inhabitable for eulachon, with the resulting contraction of the range northward over time. There are many complexities associated with attempting to predict the future impact of climate change on rivers. Pike et al. (2010) point out that the capacity to anticipate change depends mainly on the types of questions asked, as well as the available resources (i.e. data) to respond to the question.

CLIMATE CHANGE IMPACTS ON MARINE HABITATS

The most depressed eulachon populations are mainly at the southern edge of their range, especially between California and southern BC (Hay and McCarter 2000, Gustafson et al. 2010), so it seems probable that these populations exist closer to their physiological and ecological limits imposed by climate. It also seems probable that climate-induced changes in the sea are the most likely to impact a number of different eulachon populations simultaneously, or within the same season. This is because eulachon spend most of their lives at sea (>95 percent) and the short durations of their fresh-water residence varies temporally among different rivers.

Gustafson et al. (2010) noted that regime shifts associated with warm and cold phases of the Pacific Decadal Oscillation (PDO) may be expected to impact the productivity of the marine environment. In particular, the warm phase since 1977 would result in less productive ocean conditions (Figure 27). Climate warming may also be resulting in changes in the timing and intensity of upwelling with associated negative impacts on primary and secondary productivity (Gustafson et al. 2010). Mackas (2011, in Crawford and Irvine 2011) has summarized the available information on zooplankton abundance trends along the British Columbia coast (Figure 28). These data are variable but suggest a period of lower than average abundance of copepods and euphausiids in the late 1980s and early 1990s.

Ocean habitats in the Northeast Pacific are experiencing a decrease in dissolved oxygen (DO) and an increase in hypoxia in shallower depths. It is conceivable that this change will impact eulachon. When examined over extended time periods or geographical range, increases in hypoxia will appear gradual but local variation is subject to climate variation. It seems probable that such local changes may already have impacted eulachon in the Columbia River estuary and perhaps other areas. This assertion is based on the evidence presented by Roegner et al. (2011) that describes how wind-induced upwelling of low-DO water onto shelf waters, and eventually into estuarine waters can have deleterious impacts on benthic organisms, including fish species like eulachon. Similar events may occur in some estuaries of the British Columbia coast, as there is strong evidence of effects in Saanich Inlet and Howe Sound (F. Whitney, Institute of Ocean Sciences, pers. comm.).

Ocean acidification is occurring globally and regionally so impacts on fish such as eulachon are possible but the effect uncertain (Doney et al. 2009). Increased acidification has been linked to blooms in jellyfish (potential predators and competitors of eulachon) and possible changes in water turbidity so effects of acidification could be ecological as well as physiological. Regardless, the impacts of acidification probably occur gradually, over decadal scales or longer, and would not account for the relatively sudden, and almost synchronous decreases in eulachon abundance observed since the mid-1990s in different parts of the north-east Pacific and adjacent watersheds.

The effects of these changes in the marine environment are likely to influence eulachon growth, maturation, survival, and migration. They are also likely to affect the distribution and abundance of eulachon predators and competitors, particularly Pacific hake and sardine.

PRIORITIZATION OF THREATS

Prioritizing threats to eulachon survival and recovery requires a ranking of the various explanations and hypotheses about the reason for their decline. Such a ranking is difficult because of the scarcity of quantitative data for each of the potential threats through the period preceding the collapse to the present. To help rank the relative impact of historical threats, time series of data on the within DU abundance estimates of eulachon (the trends that require explanation) and the magnitude of various threats described above have been plotted together on comparable historical scales. Threats that could not be quantified at the spatial resolution for individual DUs (e.g. marine mammal and fish predators, PDO index) are presented for the entire Pacific coast of Canada in Figure 30. Threats that could be quantified for the individual DUs (in-river catch, fishing effort in groundfish and shellfish trawl fisheries, and euphausiid abundance) are presented in Figures 31 to 33.

As a first step, the ability of each threat hypothesis to account for historical patterns of decline in eulachon biomass was ranked by applying three criteria:

(1) spatial pattern: can the putative threat explain differences in eulachon trends among DUs?

(2) temporal pattern: is causation plausible in the sense that the putative threat precedes or coincides with eulachon decline?

(3) consistency over time series: is the putative threat correlated with eulachon biomass or does it appear to have a consistent effect on eulachon biomass throughout the time series?

No single threat hypothesis met all three criteria, but some threats could be ranked as less likely than others. For example, human activities affecting freshwater habitat cannot by themselves account for the recent widespread declining trends in virtually all eulachon populations in the Fraser and Central DUs, and the increasing trend in the Nass River.

In contrast, it seems likely that recent changes in climate could have affected marine or freshwater habitats over a wide geographic area, and that eulachon productivity could have been reduced most severely near the southern limit of the species' range. Despite the spatial plausibility of the climate change hypothesis, no direct evidence has been presented to support the hypothesis. Trends in the indices of PDO and plankton biomass do not match trends in eulachon biomass, and reported changes in dissolved oxygen concentration and acidification have likely been too recent and gradual to account for the recent dramatic collapse of eulachon populations in the Fraser and Central DUs.

Human fishing effort (both directed and incidental due to trawling) has also been widespread, and generally greater in the southern and central regions, but the temporal patterns of fishing activity are not consistently related, in any obvious way, with historical trends in eulachon biomass. Even so, because the timing of large in-river catches and peak effort in shrimp and groundfish fisheries often precedes or coincides with periods of eulachon decline, fishing likely contributed to the historical decline of eulachon populations, and remains a strong candidate hypothesis.

The potential for predation by marine mammals has also been widespread, but not consistently related to trends in eulachon biomass. This analysis is weakened by the fact that only coastwide data are available, which precludes the opportunity to examine correlations at the DU scale. However, some evidence suggests that the distribution of some marine mammals (especially Steller sea lions and humpback whales), and by inference predation has shifted northward in recent decades, yet eulachon biomass is increasing in the Nass River. Even if marine mammals have played only a minor role in the historical decline of eulachon populations, the current abundances of Steller sea lions, humpback whales, and harbour seals may pose a threat to the recovery of any eulachon populations now reduced to low abundance.

No single threat hypothesis appears adequate to meet all three criteria suggesting that threatening factors may have interacted in ways too complicated to assess by simple visual inspection of trends. Indeed, preliminary results from a Bayesian, age-structured, stock reduction model demonstrate that the sequential effects of directed in-river catch, shrimp trawl by-catch (estimated from effort data), and several consecutive years of anomalously low productivity in the past decade, were together sufficient to account for the declining trends in spawning biomass of Fraser River eulachon (see Appendix 3). This model was formulated to estimate deviations in productivity, but not to identify their cause; thus, the recent anomalies in productivity may have resulted from poor freshwater habitat conditions for spawning, unfavourable marine conditions during early life, predation, or other factors. Near significant negative and positive correlations were found between annual recruitment deviates and Pacific hake abundance and *T. spinifera* abundance, respectively (Appendix 3). Further modelling with additional consideration of marine indices and marine mammal abundance might help to narrow the set of plausible hypotheses for the cause of the reduced productivity.

RECOVERY TARGETS

The recovery target for eulachon coast-wide, at a minimum, should be to promote the populations' recovery such that it can qualify as special concern within the COSEWIC assessment criteria. Achieving such a recovery will require addressing the knowledge gaps for eulachon as well as eliminating, reducing or mitigating potential threats to eulachon as listed above. An interim goal is to observe positive growth in eulachon spawning in river systems throughout the DU ranges. A long term goal is to have eulachon populations reaching historic levels. Further detail is described for each DU below.

FRASER RIVER DU

The endangered designation for this population assigned by COSEWIC is based on an observed population decline of greater than 50% over three generations (approximately 10 years for eulachon) as identified by Moody's (2008) index. Thus, recovery of the population should be reflected in an increase in this index to historical levels. However, given considerable uncertainty as to the initial cause of the population decline and factors preventing recovery, the first goal towards recovery would be a population increase that would exceed COSEWIC's criteria for endangered status, and bring the assessment down to a species of special concern. Additional rebuilding would be required to bring the Fraser River DU to a point where it was not at risk based on COSEWIC criteria. Additionally, distribution targets for the population would include an expansion of sustained spawning ranging to the historical extent.

CENTRAL PACIFIC COAST DU

The endangered designation for this population assigned by COSEWIC is based on a population decline of greater than 50% over three generations as identified by Moody's (2008) population index. Thus, recovery of the population should be reflected in an increase in this index to historical levels. However, given considerable uncertainty as to the initial cause of the population decline and factors preventing recovery, the first goal towards recovery would be a population increase that would exceed COSEWIC's criteria for endangered status, and bring the assessment down to a species of special concern. Additional rebuilding would be required to bring the Central Pacific coast DU to a point where it was not at risk based on COSEWIC criteria. In addition, the spatial configuration of eulachon populations within the Central DU suggests distribution targets should include resumption in confirmed and sustained spawning runs within all river systems that historically supported a First Nations harvest.

SKEENA / NASS RIVERS DU

Current run sizes in the Nass/Skeena area are estimated to be less than 10% of what they were in the 1800s, when annual First Nation harvests were in the range of 2000t. However, indications for the Nass/Skeena DU are that this population continues to be stable or even slightly increasing. As the Nass/Skeena DU is currently being reassessed by COSEWIC, a recovery target for this DU would be dependent on the outcome of this reassessment, but would likely be similar to the recovery target provided for the Fraser River and Central Pacific coast DUs above.

MITIGATION AND ALTERNATIVES TO ACTIVITIES

Without accurate estimates of the offshore or inshore eulachon abundance for each DU, it is difficult to suggest mitigation measures or alternatives to existing activities, as there is no basis for evaluation of their efficacy. The activities that are under human control could be modified under the presumption that they would reduce mortality on eulachon and thereby foster their recovery. These potential mitigations fall broadly under the areas of in-river impacts and offshore fishery impacts and are detailed below.

IN-RIVER MITIGATION

Foreshore development, logging debris, and point source pollution are all activities that may have small but significant cumulative deleterious impacts on the availability of suitable spawning and rearing habitat within each river system. Management regulations could be developed or refined to ensure that these effects are minimized within known eulachon spawning habitats.

Log booming

Log booming can occur in rivers and estuaries at the time of eulachon spawning. Mitigation would require suspension of booming or re-location or re-scheduling of the activity so that potential impacts are eliminated. Monitoring the temperature, pH and dissolved oxygen of bottom sediments of booming areas, used prior to- and after spawning, would help assess whether impacts are sustained after booming operations are adjusted.

Dredging

A more direct impact on eulachon spawning habitat is the in-season or inter-annual dredging within areas of known eulachon spawning, particularly within the Fraser River. Mitigation could include an extension of the dredging temporal closure (currently March 15-May 15) to reflect any changes in eulachon run timing or blanket closure to cover known eulachon spawning times within each system. Re-examining spawning time(s) in rivers would ensure that spawning time is not changing and that the dredging temporal closure is appropriate to the spawning period.

Discharge alteration of flow rates

Stream flow alteration can occur from activities such as banking for road building. Avoidance of any changes that alter stream flow characteristics without first determining if such changes could be deleterious to eulachon is recommended. Such mitigation might be achieved by imposing a requirement that, on any eulachon-bearing river identified in this report, any proposed changes would require approval by a qualified hydrologist deemed cognizant of issues facing eulachon. (Note: background material prepared for the Kemano completion hearings may provide useful guidelines).

Stream flow alteration may also occur by water withdrawal, so avoidance of water removal during eulachon spawning periods could be an effective mitigation measure. Such an activity may not be occurring at the present time but potential future industrial developments (or agriculture) may be interested in using freshwater for cooling or other purposes.

Stream flow alteration and sedimentation may occur following logging in watersheds. Logging operations that could affect the quality or quantity of stream-flow in any eulachon-bearing river could be suspended at the time of eulachon spawning. Exemption from this restriction could be provided by a review by qualified habitat biologists, hydrologists and foresters. Mitigation could include changing the timing of logging activity.

Industrial pollution and agricultural chemical runoff in rivers

Mitigation could consider attempts to withhold chemical disposal in rivers, especially during the periods of eulachon spawning runs to avoid interfering with eulachon migration, egg incubation, and deleterious impacts on egg development and survival. The alternative is to develop different disposal methods and sites and change the practice, materials and timing for agricultural fertilizing. Similarly, the disposal of human sewage in the river during spawning times could be avoided or mitigated through the use of treatment or waste handling facilities and would be river specific.

Disposal of organic wastes

Discharge of any organic waste into fish-bearing streams and rivers has long been known to be deleterious to fish, especially species that are vulnerable to hypoxia. Enhanced enforcement of existing regulations could be adequate mitigation for most rivers.

Like salmonids, eulachon can change swimming habits and may exit rivers where odors of mammals (marine or terrestrial) exist. L-serine is an ingredient in mammalian skin that has been shown to interfere with salmonid migrations (Idler et al. 1956, 1961). Eulachons and salmon are related phylogenetically and First Nations observation indicates that eulachon respond to mammalian presence similar to salmonids. The mitigation of this concern is to prohibit disposal of any waste or material of mammalian origin (marine mammals, wild game or agriculture carcasses) in eulachon-bearing rivers before or during eulachon spawning times.

Directed fishing mortality by commercial fishing in rivers and estuaries

Mitigation applied during much of the last decade has been the suspension of commercial fishing on migrating or spawning eulachon in rivers, but this is implemented year-by-year. An alternative could be a license buy back for commercial fishers in the Fraser River. Mitigation for the First Nations FSC fishery could be the acquisition of eulachon from other jurisdictions (eg. Alaska) as interim dispensation.

Recreational fisheries for eulachon

All recreational fisheries for eulachon, for consumption or for bait, in the Fraser DU and elsewhere and other rivers could be suspended. As of 2012, Areas 6-10 and 28-29 tidal waters are closed to recreational fishing for eulachon due to conservation concerns. The remaining tidal areas (1-5 and 11-27) as well as freshwater recreational fishing could be added to the list of closures.

In-river disturbances during spawning.

Noise effects from pile driving and other activities (eg. Jet boats, heli-logging) that could impact the spawning runs of eulachon should be evaluated prior to initiation. Activities deemed to disturb spawning could be curtailed or prohibited prior to and during the eulachon spawning run in affected river systems.

MARINE OR OFFSHORE MITIGATION

Reduce potential mortality in nearshore waters from trawl fisheries

Trawl fisheries in the vicinity of the mouths of known or suspected eulachon spawning rivers could be suspended during the spawning period.

Reduce and eliminate bycatch in groundfish trawl fisheries

Eulachon can be entrained in commercial mid-water and bottom trawl gear, although the quantities are usually small. The level of observer coverage in these fisheries is effectively 100%. Therefore, it seems reasonable to expect that these fisheries could be conducted in a way that could minimize eulachon interception and capture. Observers could be required to respond to pre-determined standards of bycatch that were deemed to be acceptable (very low rates of interception) or unacceptable. If fishing activity in particular areas or times had unacceptable eulachon interception rates, then the vessel could be required to move or suspend operations.

Reduce and eliminate bycatch in shrimp trawl fisheries.

Eulachon seem to be especially vulnerable to capture in shrimp trawl gear. Virtually all eulachon brought aboard vessels from trawl gear are dead or moribund. Some fish may swim through the nets, but it is not clear if eulachon that pass through nets are injured or killed (a form of 'collateral mortality'), but evidence from studies in the Baltic on herring (Suuronen et al. 1996) and elsewhere on small pelagic fishes, indicates that collateral mortality may be high, perhaps exceeding 60-70 percent of the fish that enter a net. Estimates are size-dependent and likely vary with species and types of gear, but there is no reason to expect that collateral mortality of eulachon would be lower than that of other species.

Complete mitigation could be achieved by suspending all trawl fisheries that intercept eulachon so there would be no eulachon bycatch, but there may be a range of much less drastic, incremental alternatives that could be considered and perhaps implemented. A potential list follows. The list was developed from approaches under investigation and implemented in Norway, and have since spread to other Scandinavian countries. These are described in a general way on Norwegian Government websites:

http://www.regjeringen.no/en/dep/fkd/dok/veiledninger_og_brosjyrer/2009/discard.html?id=570990

http://www.regjeringen.no/en/dep/fkd/Press-Centre/Press-releases/2011/historic-agreement-to-ban-discards.html?id=663935

Some of the suggestions may be impractical and could be refined. All would require the cooperation of the fishing industry to be effective.

1) Alter fishing gear:

Of the two main types of shrimp fishing gear (otter and beam trawls) the latter have substantially lower eulachon bycatch (Olsen et al. 2000). Therefore, a simple form of mitigation could be to encourage the industry to adopt beam trawl gear, or use gear that mimics the catch characteristic of beam trawls. It could involve towing nets at slower speeds and perhaps configuring the gear so that the vertical opening of the mouth of the net was reduced.

Comparisons of eulachon catch rates from slightly different configurations of beam-trawls (low-rise versus high rise) indicate that low-rise nets, with smaller vertical openings than high rise beam trawls, appear to catch fewer eulachon (Dan Clark, pers. comm.).

2) Bycatch rate monitoring – pre-fishery testing:

As a possible condition for initiation of fishing, test fishing vessels could be employed to determine bycatch rates in various locations. In instances where bycatch was determined to be too high (a rate that would need to be established), fishing activity could be delayed, suspended, or re-located. Similar pre-fishing activities occur in the herring roe fishery, where a few select vessels assess roe quality of herring prior to fishery openings.

3) Eulachon-free zone: temporal/spatial options for fishery openings

Although it is known that eulachon bycatch varies among years it is not clear if there are possible –'within-year' or seasonal patterns of eulachon bycatch. For example, it could be possible to define areas that have low or negligible quantities of eulachon designated as 'eulachon free zones' – EFZ), where fishing could occur without putting eulachon at risk. As such, EFZ's could be defined annually, or as required, by test fishing or other methods.

4) Standardization of fishing practices

Some commercial shrimp vessels make tows of exceptionally long duration (>4 hours). Such long tows do not provide operators any opportunity to examine catch composition – so that operators can avoid fishing in locations where eulachon bycatch is high. A simple mitigation could be to limit tow duration to some shorter time that would allow operators to better monitor bycatch.

5) Electronic monitoring – an alternative to observers

A variety of video monitoring techniques are being used in other fisheries and could be adapted for the shrimp and or groundfish fisheries to assess the levels of bycatch in the fisheries and assist managers in decisions regarding fishing times and areas.

6) Land all bycatch – an alternative to observers.

The degree of observer coverage for shrimp fishing is low, largely because the cost of hiring observers to be aboard vessels is expensive. Also, it can be difficult or inconvenient for operators of small vessels to provide accommodation for an extra person. Mitigation could be to require 100% observer coverage on all trips. A potential alternative could be to require 100% retention of all bycatch. It could be stored separately, in labeled bags, and validated at the point of landing with shrimp catches. The species composition of the catches could then be determined with accuracy and precision by subsequent laboratory analysis.

Marine shellfish or finfish aquaculture mitigation

It is not established whether any aquaculture facilities have deleterious impacts on eulachon, although the potential threat from this activity exists and further investigation is warranted. Recent research indicates that crowding of organisms in net pens leads to higher levels of disease that can be transmitted to other species in the adjacent ecosystem (Marty et al. 2003). Restricting the location and timing of active farms, to avoid eulachon spawning times could mitigate disease concerns.

1) Salmon (and other finfish) netpens:

Marine aquaculture of finfish floating netpens may use bright lights to promote growth and may also attract marine mammals to the vicinity of netpens. It is uncertain whether these conditions could interfere with eulachon migrations, or any other aspect of eulachon biology. Nevertheless, mitigation could include avoiding locating net pen operations (i) in the vicinity of eulachon-bearing rivers (a distance of several km away from the river mouth could be appropriate but need to be confirmed); (ii) in cases where net pen operations are located in fjords with major eulachon rivers, develop a set of regulatory protocols to guide activity during eulachon spawning periods.

2) Shellfish aquaculture:

Although shellfish aquaculture (except for oysters) is still in the early stages of development, the suspension of intense shellfish rearing lines and other equipment could interfere with fish passage in some situations. Therefore, it would be preferable if such potential shellfish sites could avoid being established in estuarine areas known to be eulachon migration corridors.

3) Herring roe-on-kelp:

Roe-on-kelp operations usually occur in March and April, approximately similar to eulachon spawning times. Roe-on-kelp operations are now known to be potential sources of disease for some marine species (Hershberger et al. 2001). Therefore, these operations could be restricted to avoid fjords or other inshore areas, that support eulachon bearing rivers.

ALLOWABLE HARM CONSIDERATIONS

The Species at Risk Act (SARA) has general prohibitions that make it an offence to kill, harm, harass, capture, or take one or more individuals of a wildlife species listed as endangered, or threatened or to destroy their residences. However, SARA permits for activities that may have such effects can be obtained under certain conditions. A key condition to be addressed in the RPA is whether or not a given activity can jeopardize the survival or recovery of the species as a whole. As such, there may be some activities that have virtually negligible deleterious impacts. Such activities could be so localized in space and time that they would affect only a small proportion of the overall population and would not have a significant impact at the population level.

FRASER RIVER DU

A population dynamics model for the Fraser DU indicates that even a small removal or increased mortality rate (5t of the weakest cycle line) would substantially slow the recovery rate of the population. However, an increasing population trend is expected if productivity returns to the longer term average (i.e. prior to brood year 2002), but it is not possible to predict when, or if, this will happen. Given the large uncertainty regarding magnitude of threats to the eulachon, minimal allowable harm should be permitted at this time, and be reduced below current levels to the extent possible. This level of harm may allow for some activities to be undertaken while working towards population recovery.

CENTRAL COAST DU

Similar analyses are not available for the Central Coast DU at this time, but a stock depletion analysis could be conducted if additional information on Central DU rivers becomes available. Given the large uncertainty regarding magnitude of threats to the eulachon, minimal allowable harm should be permitted at this time, and be reduced below current levels to the extent possible. This level of harm may allow for some activities to be undertaken while working towards population recovery.

NASS/SKEENA DU

The status of the Nass/Skeena DU is unclear due to conflicting data sources. An analysis of the population dynamics for this system needs to be completed to determine sustainable levels of removal. As the Nass/Skeena DU is currently being reassessed by COSEWIC, allowable harm for this DU was not considered in this RPA.

DATA AND KNOWLEDGE GAPS

Assessing the recovery potential for any species requires a good understanding of its biology and the factors that determine its survival including factors responsible for growth and reproduction, and those that are inducing mortality. There are substantial knowledge gaps of eulachon biology and ecology including: life history parameters, population size, population structure and genetics, habitat use and requirements, particularly outside of the Fraser DU. Additional ATK may exist within the First Nations communities and should be accessed to the extent possible.

There currently is no validated ageing technique for eulachon. The available evidence, from a variety of sources indicates that most eulachon in BC spawn at age three, although this has yet to be confirmed.

We were unable to derive estimates of natural mortality associated with most of the threats identified for the three DUs and were only able to estimate recruitment, carrying capacity, and sustainable harvest for the Fraser DU (with considerable uncertainty). Similar data are required for the other two DUs to assess their recovery potential and rate.

Genetic samples of eulachon have been collected for some but not all known spawning rivers. Additional samples should be collected from any unsampled systems to broaden the baseline and more accurately characterize river origin for mixed stock samples from the offshore areas. Also, additional samples should be taken from rivers that have been previously sampled to examine any potential temporal changes.

Eulachon catch rates in otter trawls with BRDs (bycatch reduction devices) are lower than those without BRD's (Olsen et al. 2000). Although theoretically effective, it is not clear if the eulachon that escape through BRD's survive (i.e. 'collateral mortality'). If they do not survive, then BRD's serve no useful purpose related to mitigation of eulachon bycatch mortality. Understanding the impacts of BRDs on eulachon mortality remains a significant knowledge gap.

Aquaculture facilities may exist along eulachon migration corridors or in estuaries at the mouths of eulachon spawning rivers and may be a source of disease that could impact their survival. It remains unclear whether this is an additional source of mortality for eulachon and further research to address the issue is warranted.

First Nations experience indicates that any significant sources of noise in eulachon bearing rivers or estuaries leading into the rivers affect eulachon spawning behavior. The extent of the impact of noise pollution on the spawning success needs to be better understood.

More detailed analysis of the commercial and research catches of offshore eulachon and of the potential effects of oceanographic factors on seasonal catches would provide a better understanding of eulachon habitat requirements in the marine environment and thereby provide a more scientific basis for developing management strategies to minimize fishery impacts on the species.

A more thorough cataloguing of the range and type of habitat impacts that have occurred within the freshwater spawning rivers and marine offshore would help to understand and better manage these impacts to foster recovery.

A long-term monitoring program of marine fish, avain and marine mammal predator diets would assist in better understanding the potential impact of predation on eulachon survival and mortality.

Implementation of small scientifically-based test fisheries and sampling programs on key index rivers in each DU would provide the basis for assessing current population abundance as well as measuring progress towards recovery. Also, an index of egg and larval production similar to those conducted on the Fraser and Bella Coola Rivers should be considered for each DU to better support management of the species.

REFERENCES

Al-Humaidhi, A.W., Bellman, M.A., Jannot, J. and Majewski, J. 2012. Observed and estimated total bycatch of green sturgeon and Pacific eulachon in 2002-2010 U.S. west coast fisheries. West Coast Groundfish Observer Program. National Marine Fisheries Service, NWFSC. Online at: http://www.nwfsc.noaa.gov/research/divisions/fram/observer/datareport/docs/GreenSturgeonEulachon_0210Rpt_final.pdf

Barlow, J. 1988. Harbor porpoise, *Phocoena phocoena*, abundance estimation for California, Oregon, and Washington: I. Ship Surveys. Fishery Bulletin 86:417-432.

Baum, J.K., and Worm, B. 2009. Cascading top-down effects of changing oceanic predator abundances. J. Animal Ecol. Volume 78 (4): 699–714.

Beacham, T.D., Hay, D.E., and Khai, D.Le. 2005. Population structure and stock identification of eulachon (*Thaleichthyus pacificus*), an anadromous smelt, in the Pacific Northwest. Marine Biotechnology 7: 363-372.

Bigg, M. A. 1985. Status of the Steller sea lion (*Eumetopias jubatus*) and California sea lion (*Zalophus californianu*s) in British Columbia. Canadian Special Publication of Fisheries and Aquatic Sciences, 77: 1–20.

Calambokidis, J., Osmek, S., and Laake, J. L. 1997. Aerial surveys for marine mammals in Washington and British Columbia inside waters. Cascadia Research, Olympia, WA.

Clarke, A.D., Lewis, A., Telmer, K.H. and Shrimpton, J.M. 2007. Life history and age at maturity of an anadromous smelt, the eulachon *Thaleichthys pacificus* (Richardson). Journal of Fish Biology 71, 1479-1493.

Clemens, W.A., Hart, J.L. and Wilby, G.V. 1936. Analysis of stomach contents of fur seals taken off the west coast of Vancouver Island in April and May, 1935.

Clemens, W.A. and Wilby, G.V. 1946. Fishes of the Pacific coast of Canada. Fish. Res. Board Can. Bull. 68: 368 p.

Collison, W. H. 1916. In the wake of the war canoe: a stirring record of forty years' successful labour, peril, and adventure amongst the savage Indian tribes of the Pacific Coast, and the piratical head-hunting Haidas of the Queen Charlotte Islands, B.C. The Museum Book Company, Toronto, Ontario.

Crawford, W.R. and Irvine, J.R. 2011. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/054. x + 163 p.

DFO 2005. A framework for developing science advice on recovery targets for aquatic species in the context of the species at risk act. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2005/054. 16 p.

DFO. 2007a. Recovery Potential Assessment for Northern Fur Seals (*Callorhinus ursinus*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/052.

DFO, 2007b. Documenting Habitat Use of Species at Risk and Quantifying Habitat Quality. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/038.

DFO. 2008. Population Assessment: Steller Sea Lion (*Eumetopias jubatus*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2008/047.

DFO. 2009. Management Plan for the Pacific Harbour Porpoise (*Phocoena phocoena*) in Canada [Proposed]. Species at Risk Act Management Plan Series. Fisheries and Oceans Canada, Ottawa. vi+ 53 pp.

DFO. 2010a. Management Plan for the Steller Sea Lion (*Eumetopias jubatus*) in Canada [Final]. Species at Risk Act Management Plan Series. Fisheries and Oceans Canada, Ottawa. vi + 69 pp.

DFO. 2010b. Population Assessment Pacific Harbour Seal (*Phoca vitulina richardsi*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/011.

Dohl T.P., Guess, R.C., Duman, M.L. and Helm, R.C. 1983. Cetaceans of central and northern California, 1980-1983: Status, abundance, and distribution. Los Angeles: Pacific OCS Region Minerals Management Service. Report nr OCS Study MMS 84- 0045. 284 p.

Doney, S.C., Fabry, V.J., Feely, R.A. and Kleypas, J.A. 2009. Ocean acidification: the other CO_2 Problem. Annu. Rev. Mar. Sci.1: 169–192.

Eaton, B.C. and R.D. Moore. (2010) *Chapter 4 - Regional hydrology* In: R.G. Pike, T.E. Redding, R.D. Moore, R.D. Winkler and K.D. Bladon (editors). 2010. Compendium of forest hydrology and geomorphology in British Columbia. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. 66. pp. pp. 85-110., B.C. Ministry of Forests and Range Research Branch, Victoria, B.C. and FORREX Forest Research Extension Partnership, Kamloops.

Ford, J.K.B, and Olesiuk, P.F. 2010. Session A: Hypothesis: Predation by marine mammals is an important contributor to the Fraser sockeye situation. In: Peterman R.M., D. Marmorek, B. Beckman, M. Bradford, N. Mantua, B. Riddell, M. Scheuerell, M. Staley, K. Wieckowski, J. Winton, C. Wood. 2010. Synthesis of evidence from a workshop on the decline of Fraser River Sockeye. June 15-17, 2010. Vancouver Island Conference Centre, Nanaimo B.C., 123 pp. + 35 pp. appendices.).

Ford, J. K. B., Rambeau, A. L., Abernethy, R. M., Boogaards, M. D., Nichol, L. M., and Spaven, L. D. 2009. An assessment of the potential for recovery of humpback whales off the Pacific coast of Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/015. iv + 33 pp.

Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. Can. J. Fish. Aquat. Sci. 49, 922-930.

Gaskin, D.E. 1984. The harbour porpoise, *Phocoena phocoena* (L.): regional populations, status and information on direct and indirect catches. Rep. Int. Whal. Commn. 34: 569-586.

Gustafson, R.G., M.J. Ford, D. Teel, and J.S. Drake. 2010. Status review of eulachon (*Thaleichthys pacificus*) in Washington, Oregon, and California. U.S. Dept. Comm., NOAA Tech. Memo. NMFS-NWFSC-105, 360 p.

Hall, A.M. 2004. Seasonal abundance, distribution and prey species of harbour porpoise (*Phoceona phocoena*) in southern Vancouver Island waters. M.Sc, Thesis, University of British Columbia, Vancouver, 100 p.

Hancock, D. 1970. California sea lion as a regular winter visitant off the British Columbia coast. Journal of Mammalogy, 51: 614.

Hay, D. E., and McCarter, P. B. 2000. Status of the eulachon *Thaleichthys pacificus* in Canada. CSAS Res. Doc. 2000/145. 92p.

Hay, D.E., West, K.C. and Anderson, A.D. 2003. Indicators and 'response' points for management of Fraser River eulachon: a comparison and discussion with recommendations. DFO Can. Sci. Advis. Sec. Res. Doc. 2003/51. 47p.

Hay, D.E., Boutillier, J., Joyce, M. and Langford, G. 1997. The eulachon (*Thaleichthys pacificus*) as an indicator species in the North Pacific. Proceedings. Forage Fishes in Marine Ecosystems. Wakefield Fisheries Symposium. Alaska Sea Grant College Program AK-SG-97-01, p 509-530.

Hay, D.E., Harbo, R., Southey, K., Clarke, J.R. Parker, G. and McCarter, B.P. 1999a. Catch composition of British Columbia shrimp trawls and preliminary estimation of bycatch – with emphasis on Eulachons. CSAS Res. Doc. 1999/26. 45p.

Hay, D.E., Harbo, R., Boutillier, J., Wylie, E., Convey, L. and McCarter, P.B. 1999b. Assessment of bycatch in the 1997 and 1998 shrimp trawl fisheries in British Columbia, with emphasis on eulachons. CSAS Res. Doc. 1999/179. 44p.

Heise, K. 1997. Diet and feeding behaviour of Pacific white-sided dolphins (*Lagenorhynchus obliquidens*) as revealed through the collection of prey fragments and stomach content analyses. Rep. Int. Whal. Commn. 47:807-815.

Heise, K., Ford, J. and Olesiuk, P. 2007. Appendix J: Marine mammals and turtles. *In* Ecosystem overview: Pacific North Coast Integrated Management Area (PNCIMA). Edited by Lucas, B.G., Verrin, S., and Brown, R. Can. Tech. Rep. Fish. Aquat. Sci. 2667: iv + 35 p.

Hershberger, P.K., Kocan, R.M., Elder, N.E., Marty, G.D., and Johnson, J. 2001. Management of Pacific Herring spawn-on-kelp fisheries to optimize fish health and product quality. N.A. Journal of Fisheries Management, 21:976-981.

Hilborn, R. and Walters, C.J. 1992. Quantitative fisheries stock assessment: choice, dynamics, and uncertainty. Chapman and Hall, New York.

Hill, K.T., Lo, N.C.H., Macewicz, B. J., Crone, P. R. and Felix-Uraga, R. 2010. Assessment of the Pacific sardine resource in 2010 for U.S. management in 2011. Pacific Fishery Management Council, Nov 2010 Briefing Book, Agenda Item I.2.b. Attachment 2. 128 p.

Idler, D.R., Fagerlund, U.H.M. and Mayoh, H. 1956. Olfactory perception in migrating salmon. I. L-serine, a salmon repellent in mammalian skin. J. Gen. Physiol. 39:889-892

Idler, D.R., McBride, J.R., Jonas, R.E.E., and Tomlinson, N. 1961. Olfactory perception in migrating salmon. Studies on a laboratory bio-assay for homestream water and mammalian repellent. Can. J. Biochem. Physiol. 39: 1575-1584.

Jensen, A.L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Can. J. Fish. Aquat. Sci. 53: 820-822.

Kass, R.E. and Raftery, A.E. 1995. Bayes factors. J. Am. Stat. Assoc. 90: 773–795.

Kimura, D.K., and Tagart, J.V.1982. Stock Reduction Analysis, another solution to the catch equations. Can. J. Fish. Aquat. Sci. 39: 1467 - 1472.

Lance, M.M., and Jeffries, S.J. 2007. Temporal and spatial variability of harbor seal diet in the San Juan Island archipelago. Contract Report to SeaDoc Society Research Agreement No. K004431-25. Washington Department of Fish and Wildlife, Olympia WA. 21 pp.

Levesque, C.A. and Therriault, T.W. 2011. Information in support of a recovery potential assessment of eulachon (Thaleichthys pacificus). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/101, viii + 71p.

Marston, B, Willson, M.F., and Gende, S.M. 2002. Predator aggregations during eulachon *Thaleichthys pacificus* spawning runs. Mar. Ecol. Prog. Ser. 231: 229-236.

Marty, G. D., Quinn, T. J., Carpenter, G.,Meyers, T. R., and Willits, N. H. 2003. Role of disease in abundance of a Pacific herring (Clupea pallasi) population. Canadian Journal of Fisheries and Aquatic Sciences, 60: 1258–1265.

McAllister, M.K. and Kirchner, C.H. 2002. Accounting for structural uncertainty to facilitate precautionary fishery management: illustration with Namibian orange roughy In: Targets, Thresholds, and the Burden of Proof in Fisheries Management. (ed. M. Mangel). Bull. of Mar. Sci., 70(2): 499-540.

McAllister, M.K., Pikitch, E.K., Punt, A.E., and Hilborn, R. 1994. A Bayesian approach to stock assessment and harvest decisions using the Sampling/ Importance Resampling Algorithm. Can. J. Fish. Aquat. Sci. 51: 2673-2687.

McCarter, P.B. and Hay, D.E. 1999. Distribution of spawning eulachon stocks in the central coast of British Columbia as indicated by larval surveys. CSAS Res. Doc. 1999/177. 67p.

McFarlane, G. A. and Beamish, R.J. 2001. The re-occurrence of sardines off British Columbia characterizes the dynamic nature of regimes. Progress in Oceanography, 49: 151–165.

McFarlane, G. A., Schweigert, J., MacDougall, L. and Hrabok, C. 2005. Distribution and biology of Pacific sardine (Sardinops sagax) off British Columbia, Canada. California Co-operative Fishery Investigations Reports, 46: 144–160.

Moody, M.F. 2008. Eulachon past and present. M.Sc. thesis, Resource Management and Environmental Studies, The University of British Columbia, Vancouver, BC.

Morton, A. 2000. Occurrence, photo-identification and prey of Pacific white-sided dolphins (*Lagenorhyncus obliquidens*) in the Broughton Archipelago, Canada 1984-1998. Marine Mammal Science, 16(1): 80-93.

National Marine Fisheries Service (NMFS). 2006. Harbor Porpoise (*Phocoena phocoena*): Washington Inland Waters Stock. Stock Status Report Revised 12/15/2006:7.

Olesiuk, P. F. 1993. Annual prey consumption by harbor seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. Fish. Bull. 91:491–515.

Olesiuk, P. F. 2008. Abundance of Steller sea lions (*Eumatopias jubatas*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/063. 33p.

Olesiuk, P.F. 2009. Preliminary assessment of the recovery potential of northern fur seals (*Callorhinus ursinus*) in British Columbia. DFO Can. Sci. Advis. Sec. Res. Doc. 2007/076. 71p. Updated: February 2009. http://www.dfo-mpo.gc.ca/csas/Csas/DocREC/2007/RES2007_076_e.pdf

Olesiuk, P.F., and Bigg, M.A. 1988. Seals and sea lions on the British Columbia coast. DFO/4104, Cat. No. Fs 23-130/1988E.

Olesiuk, P. F., Bigg, M. A., Ellis, G. M., Crockford, S. J., and Wigen, R. J. 1990. An assessment of the feeding habits of harbour seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia, based on scat analysis. Can. Tech. Rep. Fish. Aquat. Sci., 1730. 135 pp.

Olsen, N., Boutillier, J. and Convey, L. 2000. Estimated bycatch in the British Columbia shrimp trawl fishery. CSAS Res. Doc. 2000/168. 14 p.

Ormseth, O.A., Conners, L., Guttormsen, M. and Vollenweider, J. 2008. Appendix 2: Forage fishes in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 657–702. North Pacific Fishery Management Council, Anchorage. Online at http://www.afsc.noaa.gov/refm/docs/2008/GOAforage.pdf [accessed 9 November 2011].

Pearsall, I.A., and Fargo, J.J. 2007. Diet composition and habitat fidelity for groundfish assemblages in Hecate Strait, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2692: vi + 141 p.

Pedersen, R.V.K., Orr, U.N. and Hay, D.E. 1995. Distribution and preliminary stock assessment (1993) of the eulachon, Thaleichthys pacificus, in the lower Kitimat River, British Columbia. Can. Man. Rep. Fish. Aquatic. Sci. 2330: 20p.

Perez, M. A., and M. A. Bigg. 1986. Diet of northern fur seals. *Callorhinus ursinus*, off western North America. Fishery Bulletin, U.S. 84: 957-97 1.

Pickard, D. and D. R. Marmorek. 2007. A workshop to determine research priorities for Eulachon, workshop report. Prepared by ESSA Technologies Ltd., Vancouver British Columbia for Fisheries and Oceans Canada, Nanaimo, British Columbia. 58 p.

Pike, R.G., Redding, T.E., Wilford, D.J., Moore, R.D., Ice, G., Reiter, M.L. and Toews, D.A.A. 2010. Detecting and Predicting Changes in Watersheds. Chapter 16. *in* Pike, R.G., T.E. Redding, R.D. Moore, R.D. Winker and K.D. Bladon (*editors*). 2010. Compendium of forest hydrology and geomorphology in British Columbia. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. 66. 807 pp. *www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm*

Ricker, W.E., Manzer, D.F. and Neave, E.A. 1954. The Fraser River Eulachon fishery, 1941-1953. Fisheries Research Board of Canada, manuscript report no. 583. 35 p.

Robinson, C.L.K. 1994. The influence of ocean climate on coastal plankton and fish production. Fish. Oceanogr. 3:159–171.

Roegner, G.C., Needoba, J.A. and Baptista, A.M. 2011. Coastal upwelling supplies oxygen-depleted water to the Columbia River estuary. PLoS ONE, 6(4)(e18672.). doi:doi:10.1371/journal.pone.0018672. *http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0018672 (accessed November 2, 2011)*

Rogers, I.H., Birtwell, I.K. and Kruzynski, G.M. 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.

Scheffer, V.B. and Slipp, J.W. 1948. The whales and dolphins of Washington State with a key to the cetaceans of the west coast of North America. American Midland Naturalist 39:257-337.

Sinclair, A., Krishka, B.A. and Fargo, J. 2007. Species trends in relative biomass, occupied area and depth distribution for Hecate Strait Assemblage Surveys from 1984-2003. Can. Tech. Rep. Fish. Aquat. Sci. 2749: 141 p.

Suuronen, P., Perez-Comas, J. A., Lehtonen, E. and Tschernij, V. 1996. Size-related mortality of herring (Clupea harengus L.) escaping through a rigid sorting grid and trawl codend meshes. – ICES Journal of Marine Science, 53: 691–700.

Tanasichuk, R.W., Ware, D.M., Shaw, W. and McFarlane, G.A. 1991. Variations in diet, daily ration, and feeding periodicity of Pacific hake (*Merluccius productus*) and spiny dogfish (*Squalus acanthias*) off the lower west coast of Vancouver Island. Can. J. Fish. Aquat. Sci. 48: 2118–2128.

Taylor E. and B. Taylor (eds.). 1997. Responding to Global Climate Change in British Columbia and theYukon, Volume I of the Canada Country Study: Climate Impacts and Adaptation. Vancouver, BC.

Walker, W.A., Hanson, M.B., Baird, R.W. and Guenther, T.J. 1998. Food habits of the harbour porpoise, *Phocoena phocoena*, and Dall's porpoise, *Phoecoenoides dalli*, in the inland waters of British Columbia and Washington. AFSC Processed Report 98-10, 14 pp.

Walters, C. J., and Ludwig, D. 1994. Calculation of Bayes posterior probability distributions for key population parameters: a simplified approach. Canadian Journal of Fisheries and Aquatic Sciences, 51: 713–722.

Walters, C.J., Martell, S.J.D. and Korman, J. 2006. A stochastic approach to stock reduction analysis. Can. J. Fish. Aquat. Sci. 63: 212-223.

Ware, D. M., and McFarlane, G. A. 1995. Climate-induced changes in Pacific hake (*Merluccius productus*) abundance and pelagic community interactions in the Vancouver Island upwelling system. *In* Climate change and northern fish populations, pp. 509–521. Ed. by R. J. Beamish. Canadian Special Publication Fisheries and Aquatic Sciences, 121.

Williams R. and Thomas, L. 2007. Distribution and abundance of marine mammals in the coastal waters of British Columbia, Canada. J. Cetacean Res. Manag., 9:15-28.

Witteveen, B.H., Foy, R.J., and Wynne, K.M. 2006. The effect of predation (current and historical) by humpback whales (*Megaptera novaeangliae*) on fish abundance near Kodiak Island, Alaska. Fishery Bulletin, 104: 10–20.

ACKNOWLEDGEMENTS

We thank the following for their assistance on this project through critical discussion, provision of data summaries or analytical support: Leslie Barton, Dan Clark, Janelle Curtis, Bridget Ennevor, Ken Fong, Sean MacConnachie, Megan Moody, Peter Olesiuk, Dennis Rutherford, Kate Rutherford, Greg Workman. We appreciate the engagement with the First Nations Fisheries Council on this project. We also thank M. Nicolsen, R. Bocking, D. Ralston, J. Hawryshyn, and H. Gartner for comments on an earlier draft.

TABLES

Table 1 List of confirmed and probable eulachon spawning rivers in British Columbia. Rivers are ordered geographically, from northern to southern BC. Table modified from Levesque and Therriault (2011).

#	Spawning river or adjacent area to a potential unknown river	Estuary/Marine Area	Status[a]	Fishery[b]	References
1	Bear River	Portland Canal			
2	Nass River	Portland Inlet	C	FN, Co	Hay and McCarter (2000), Moody (2008)
3	Skeena River	Chatham Sound	C	FN, Co	Hay and McCarter (2000), Moody (2008)
4	Kitimat	Douglas Channel – Kitimat Arm	C	FN	Hay and McCarter (2000), Moody (2008)
5	Kildala River	Douglas Channel – Kitimat Arm	C	FN	Hay and McCarter (2000), Moody (2008)
6	Gilttoyees Inlet	Douglas Channel	P		Hay and McCarter (2000), McCarter and Hay (1999)
7	Foch Lagoon	Douglas Channel	P		Hay and McCarter (2000), McCarter and Hay (1999)
8	Kemano/Wahoo Rivers	Gardner Channel	C	FN	Hay and McCarter (2000)
9	Kowesas River	Gardner Channel	C	FN	Hay and McCarter (2000)
10	Kitilope River	Gardner Channel	C	FN	Hay and McCarter (2000)
11	Khutze River	Princess Royal Channel	P		Hay and McCarter (2000), McCarter and Hay (1999)
12	Aaltanhash River	Princess Royal Channel	P		Hay and McCarter (2000), McCarter and Hay (1999)
13	Mussel River	Mussel Inlet, North of Mathieson Channel	C	FN	Hay and McCarter (1999), Megan Moody (Nuxalk Fisheries, pers. comm. 2011)
14	Kainet or Lard Creek	Kynoch Inlet, Mathieson Channel	P		Hay and McCarter (2000), McCarter and Hay (1999)
15	Kimsquit River	Dean Channel	C	FN	Hay and McCarter (2000), Moody (2008)
16	Dean River	Dean Channel	C	FN	Hay and McCarter (2000),

					Moody (2008)
17	Skowquiltz River	Dean Channel – west side	P		McCarter and Hay (1999), Hay and McCarter (2000)
18	Cascade Inlet	Dean Channel	P		McCarter and Hay (1999), Hay and McCarter (2000)
19	Bella Coola River	Dean Channel - North Bentick Arm	C	FN	Hay and McCarter (2000), Moody (2008)
20	Necleetsconay River	Dean Channel. North - Bentick Arm	C		Moody (2008)
21	Paisla Creek	Dean Channel - North Bentick Arm	C	FN	Moody (2008)
22	Noeick River	Dean Channel - South Bentick Arm	C	FN	Hay and McCarter (2000), Moody (2008)
23	Taleomy River	Dean Channel - South Bentick Arm	C	FN	Hay and McCarter (2000), Moody (2008)
24	Asseek River	Dean Channel - South Bentick Arm	C	FN	Moody (2008)
25	Kwatna River	Burke Channel - Kwatna Inlet	C	FN	Hay and McCarter (2000), Moody (2008)
26	Quatlena River	Burke Channel - Kwatna Inlet	C		Moody (2008)
27	Clyak River, Moses Inlet	Rivers Inlet - Moses Inlet	C		Hay and McCarter (2000), Winbourne (2002) as cited in Moody (2008)
28	Wannock River	Rivers Inlet – Queen Charlotte Strait	C	FN	Hay and McCarter (2000), Moody (2008)
29	Chuckwalla/Kilbella Rivers	Rivers Inlet – Queen Charlotte Strait	C	FN	Hay and McCarter (2000), Moody (2008)
30	Hardy Inlet (uncertain source)	Rivers Inlet	P		McCarter and Hay (1999), Hay and McCarter (2000)
31	Nekite River	Queen Charlotte Strait - Smith Inlet	P		McCarter and Hay (1999), Hay and McCarter (2000), Winbourne and Dow (2002) as cited in Moody (2008)
32	Kingcome River	Kingcome Inlet	C	FN	Hay and McCarter (2000),

					Moody (2008)
33	Kakweiken River	Johnstone Strait - Thompson Sound	P		Hay and McCarter (2000) McCarter and Hay (1999)
34	Klinaklini River	Knight Inlet	C	FN	Hay and McCarter (2000), Moody (2008)
35	Franklin River	Knight Inlet	C	FN	Hay and McCarter (2000), Moody (2008)
36	Port Neville	Johnstone Strait	P		Hay and McCarter (2000). Potential from larval survey, although not directly mentioned in McCarter and Hay (1999) but deduced from this data
37	Stafford and/or Apple Rivers	Johnstone Strait -Loughborough Inlet	P		Hay and McCarter (2000), McCarter and Hay (1999), Moody (2008)
38	Homathko River	Johnstone Strait - Bute Inlet	P		McCarter and Hay (1999), Hay and McCarter (2000)
39	Squamish River	Strait of Georgia - Howe Sound	Suspect ed		Hay and McCarter (2000), Moody (2008)
40	Fraser River	Strait of Georgia	C	FN, Co	Hay and McCarter (2000), Moody (2008)

.[a] Probable rivers/areas are based on anecdotal information and/or the density and lengths of larvae found in adjacent inlets/estuaries during ichthyoplankton surveys in coastal mainland inlets (McCarter and Hay 1999) and are indicated as 'Confirmed (C) or Probable (P)'. Confirmed (C) rivers are where adult, egg and/or larval eulachon have been observed within the river.

.[b] The 'Fishery' column indicates whether First Nations (FN) and/or Commercial (Co) fisheries existed..

Table 2 Pacific Fishery Management areas included in each of the three designated offshore regions.

Offshore Regions	Pacific Fishery Management Areas
North Coast	1,2,3,4,5,101,102,103,104,105,142
Central Coast	6,7,8,9,10,11,12,27,106,107,108,109, 110,111,127,130
West Coast Vancouver Island	20,21,22,23,24,25,26,123,124,125,126.

Table 3 Estimated average contributions and standard deviation (SD) of eulachon from each DU and the Columbia River in samples from offshore areas between 2002 and 2010 based on genetic sampling (DFO unpubl data).

Region	Year		Estimated percentage by DU							
		N	Nass-Skeena	SD	Central	SD	Fraser	SD	Columbia	SD
North Coast	2002	50	35.0	21.2	60.4	22.4	3.0	5.5	1.6	4.1
		149	65.7	9.8	32.6	9.9	1.1	2.5	0.6	1.5
	2003	49	44.1	18.8	40.8	18.1	14.1	10.0	1.1	2.9
	average		**48.3**		**44.6**		**6.1**		**1.1**	
Central Coast	2006	50	39.5	18.5	41.6	22.0	11.0	13.0	8.0	8.6
	2007	184	41.5	10.7	36.4	10.4	21.0	6.2	1.2	2.3
	2008	431	28.7	5.7	21.2	5.7	21.4	5.0	28.7	5.1
	2009	434	9.7	4.9	15.6	5.3	45.3	6.0	29.4	6.0
	2010	195	14.7	7.0	17.3	7.5	43.6	7.7	24.4	7.3
	average		**26.8**		**26.4**		**28.4**		**18.3**	
West Coast	2002	218	0.7	1.4	1.2	1.7	41.5	6.9	56.6	7.0
	2006	50	7.5	8.7	9.0	9.0	33.6	20.3	49.9	18.6
	2007	254	2.6	3.1	1.3	1.9	33.4	7.0	62.8	7.0
	2008	657	1.3	1.5	0.8	1.1	42.7	4.3	55.2	4.4
	2009	575	0.5	1.0	1.2	1.4	28.8	5.1	69.5	5.1
	2010	180	1.3	2.2	3.5	3.5	54.7	7.9	40.5	8.0
	average		**2.3**		**2.8**		**39.1**		**55.7**	

Table 4 Estimates of mean catch of eulachon (kg/hour) from DFO Groundfish research surveys in the three offshore regions from 2002-2010.

	North Coast (Hecate Strait Pacific Cod Monitoring)	North Coast (Hecate Strait Synoptic Survey)	Central Coast (Queen Charlotte Sound)	West Coast Vancouver Island
Area	1122 km2	13259 km2	24908 km2	11556 km2
2002	0.150			
2003	0.136		0.613	
2004	0.286		2.344	19.987
2005		1.373	0.492	
2006				0.863
2007		0.508	0.243	
2008				0.988
2009		3.054	1.476	
2010				1.070

FIGURES

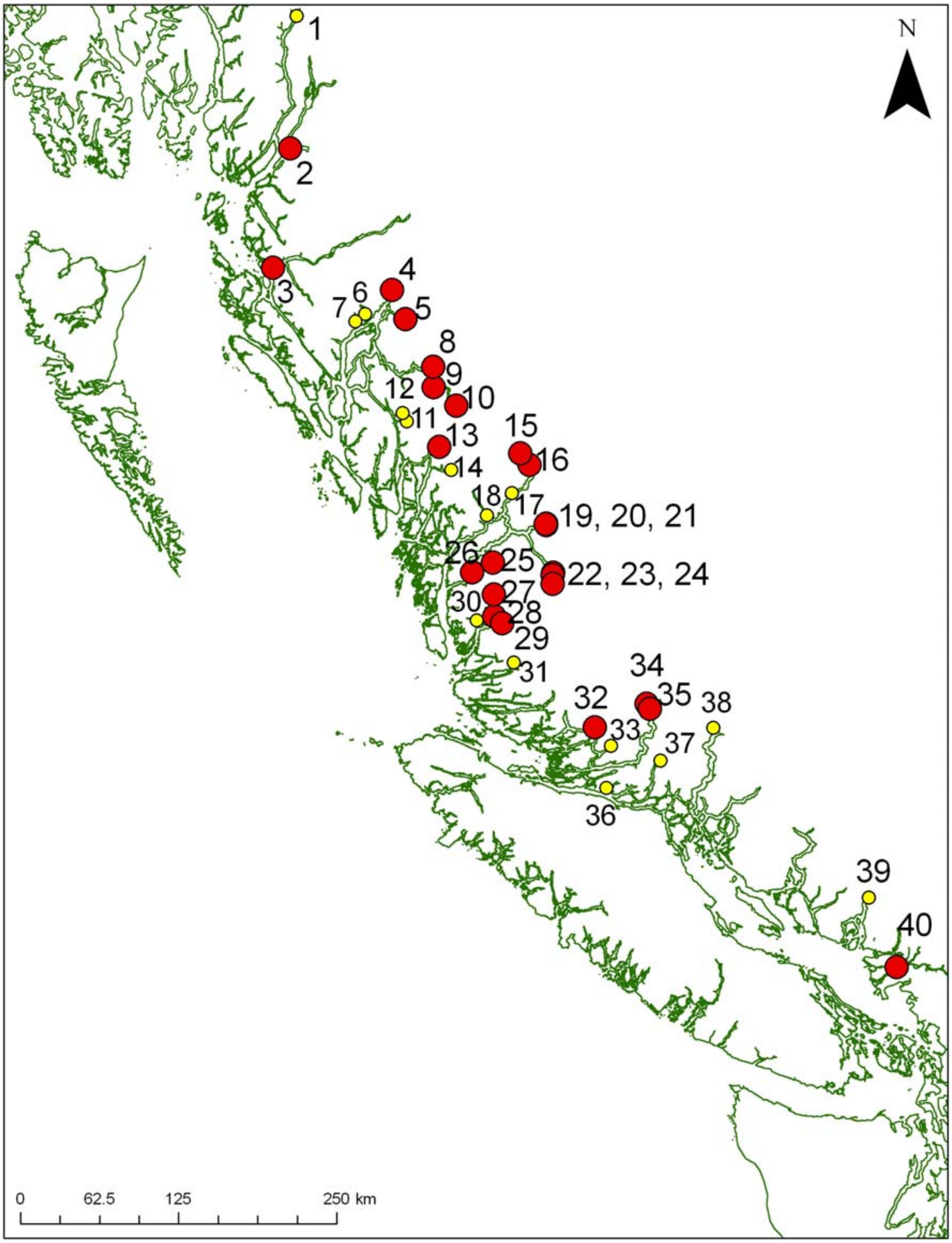


Figure 1: Eulachon spawning rivers in British Columbia. Red circles are confirmed rivers by the presence of adult eulachon and/or eggs or larvae (Hay and McCarter 2000, Moody 2008). Smaller yellow circles are probable rivers deduced from larval distribution and length frequency in the adjacent waters (McCarter and Hay 1999), from Levesque and Therriault 2011.

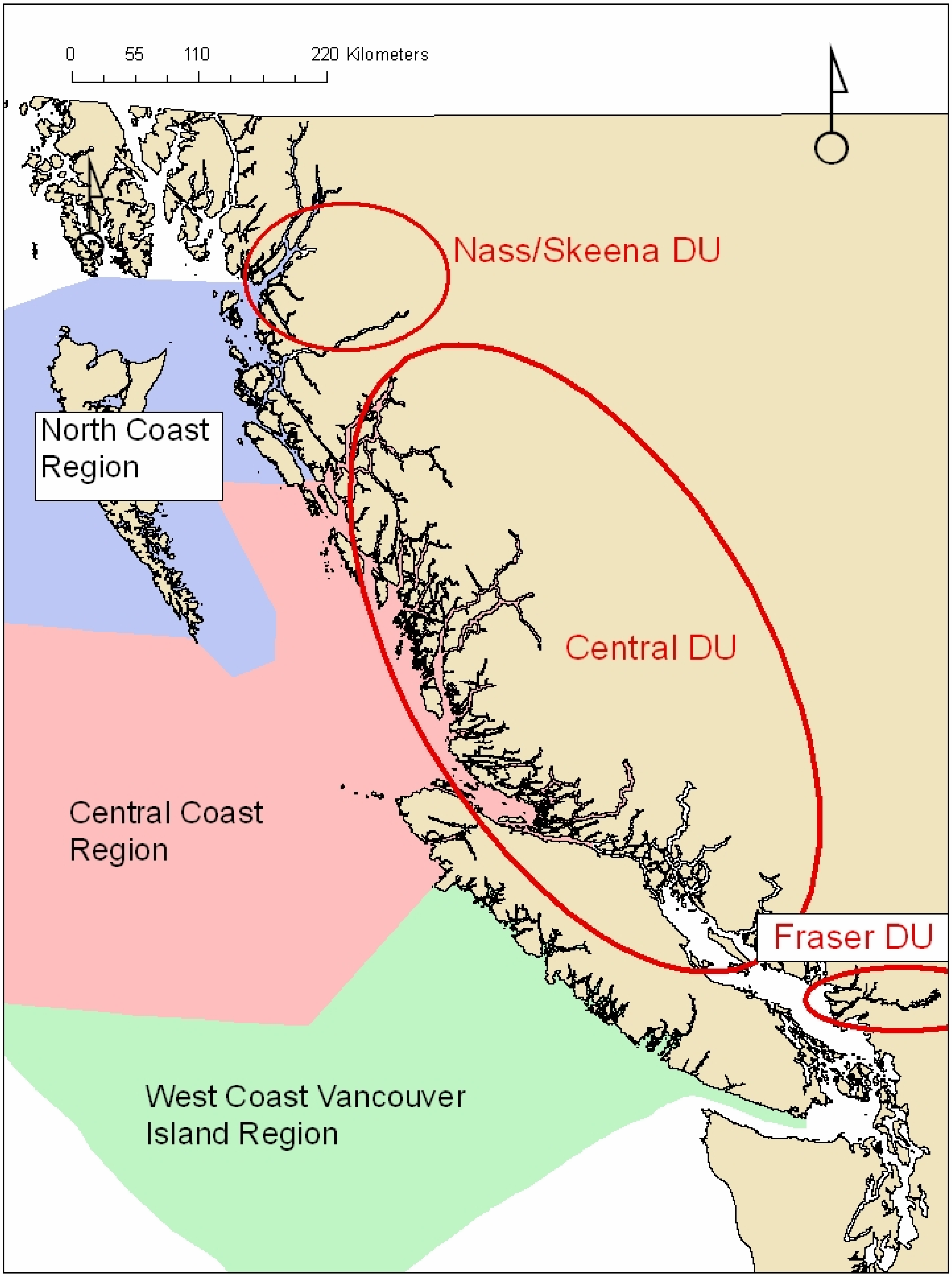


Figure 2 Delineation of the offshore area into regions relative to the eulachon DUs. The Strait of Georgia was not included in any calculations.

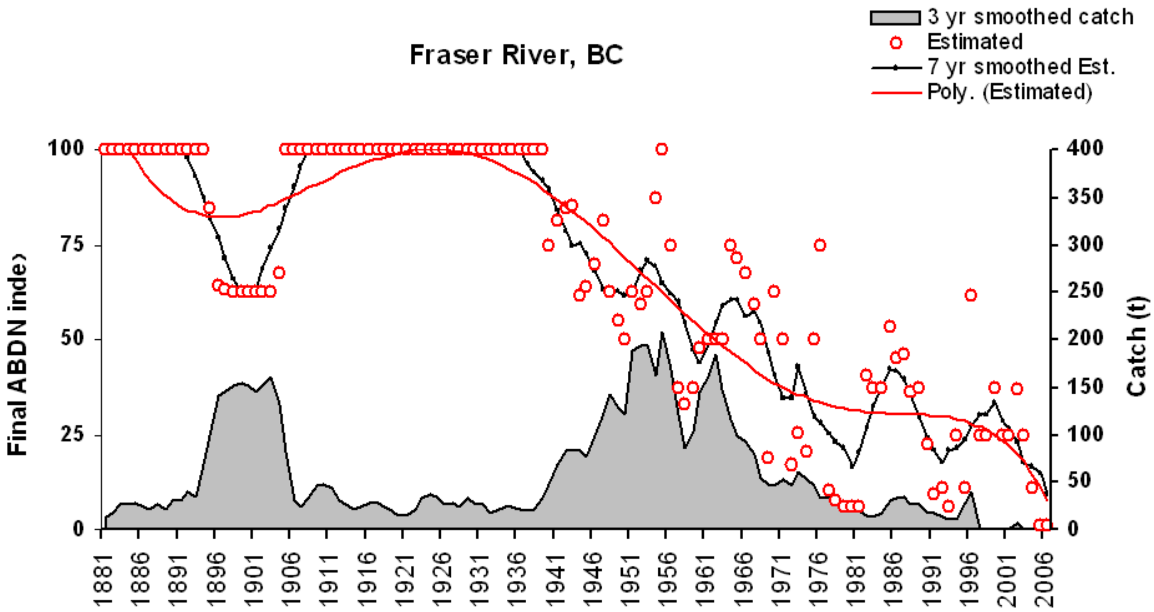
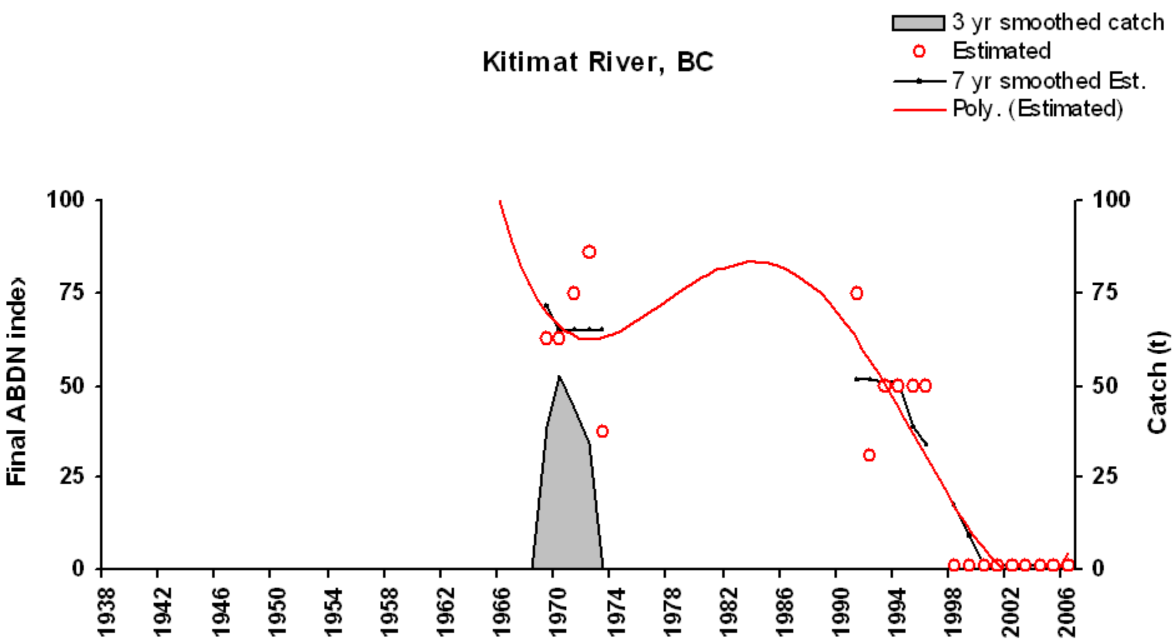


Figure 3 Fraser River, BC estimated eulachon abundance status (circles), 7 year smoothed abundance status estimations (black line), 3 yr. smoothed catch (grey fill) and a polynomial fitted trend line (red line) from Moody (2008).



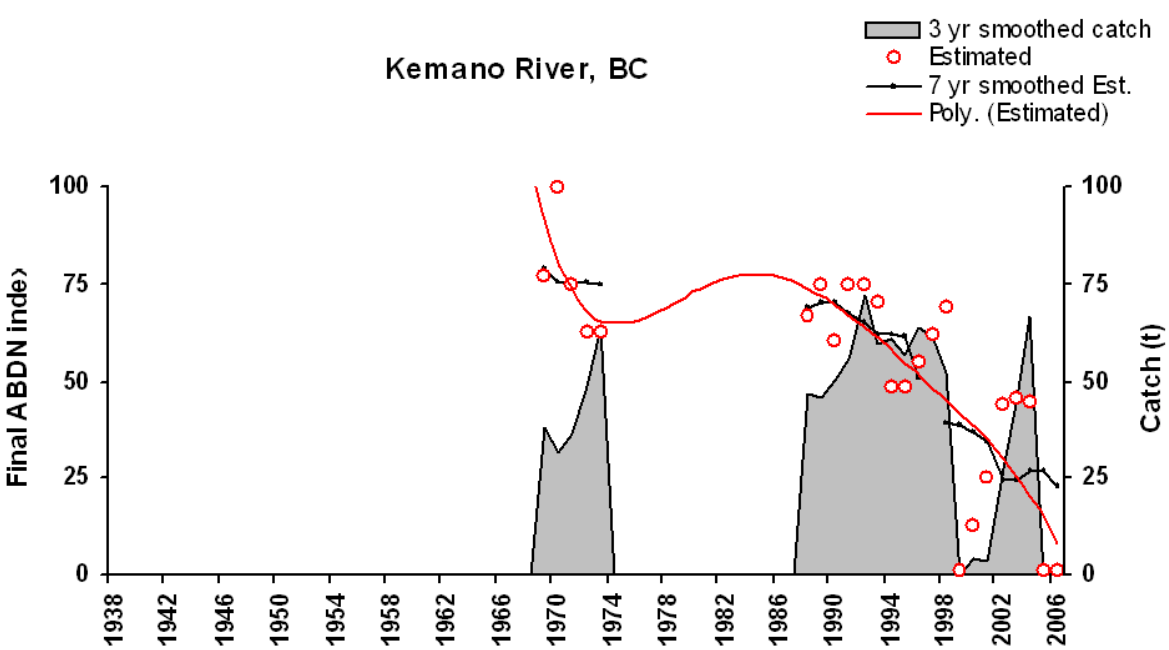
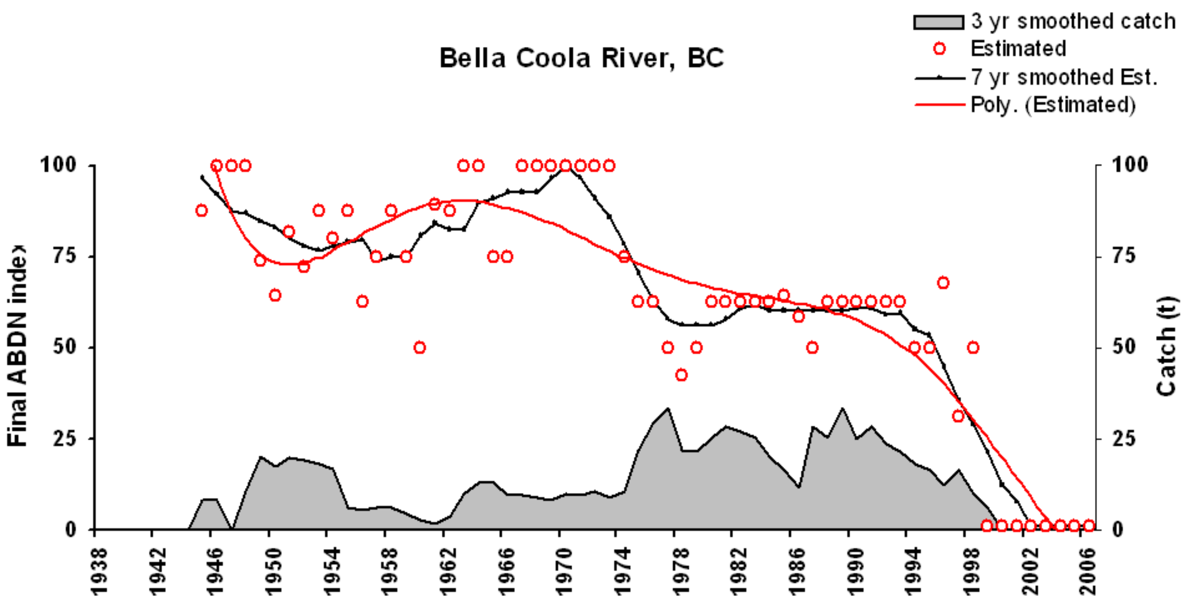


Figure 4 Kitimat River, BC (a) and Kemano River, BC (b) estimated eulachon abundance status (circles), 7 year smoothed abundance status estimations (black line), 3 yr. smoothed catch (grey fill) and a polynomial fitted trend line (red line) from Moody (2008).



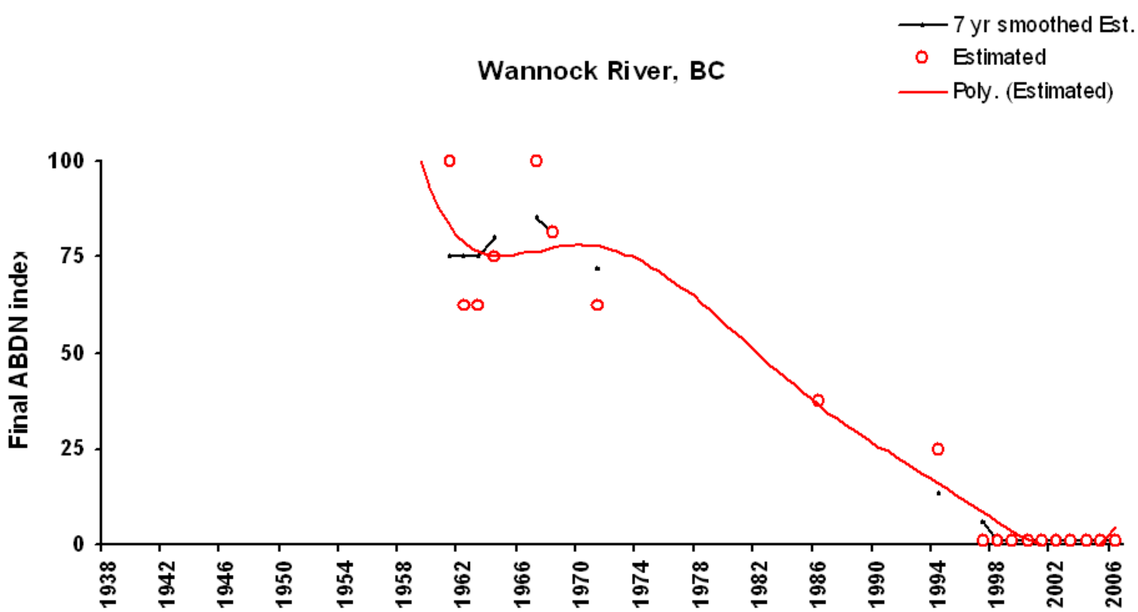
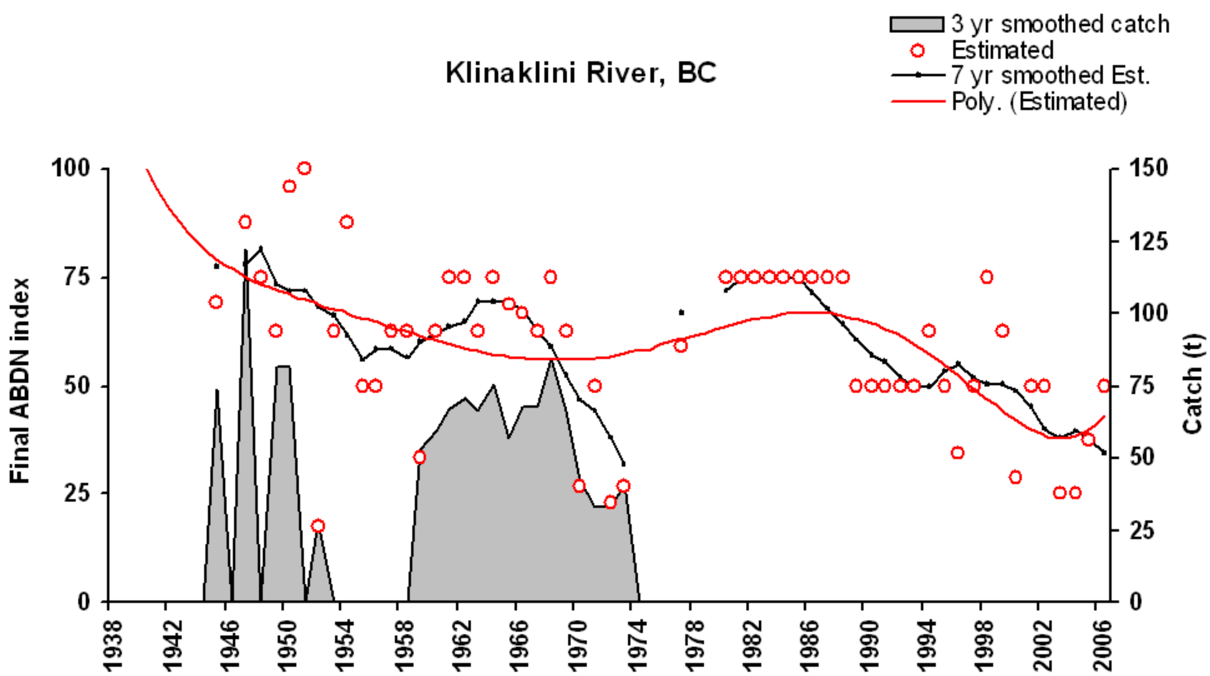


Figure 5 Bella Coola River, BC (a) and Whannock River, BC (b) estimated eulachon abundance status (circles), 7 year smoothed abundance status estimations (black line), 3 yr. smoothed catch (grey fill) and a polynomial fitted trend line (red line) from Moody (2008).



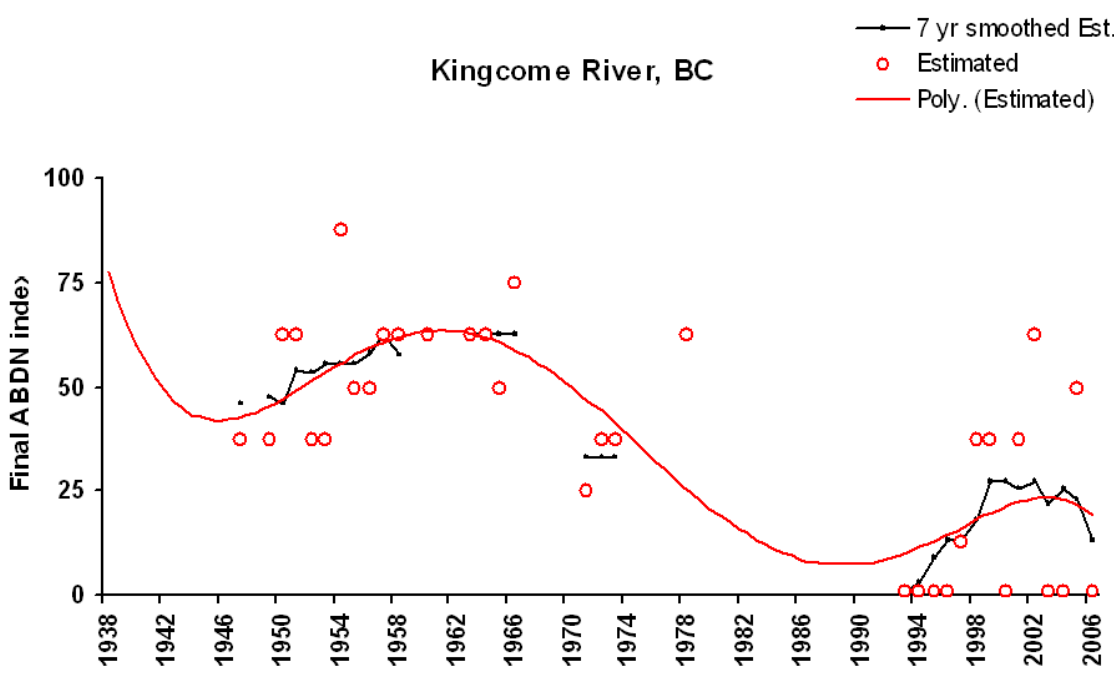
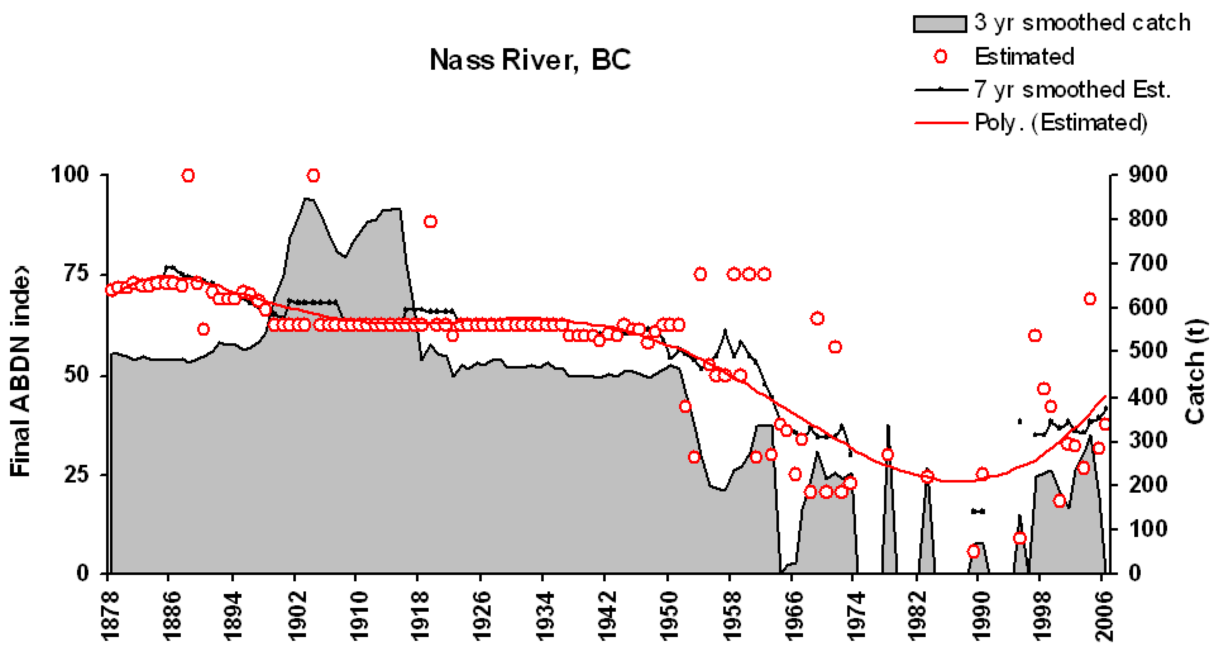


Figure 6 Klinaklini River, BC (a) and Kingcome River, BC (b) estimated eulachon abundance status (circles), 7 year smoothed abundance status estimations (black line), 3 yr. smoothed catch (grey fill) and a polynomial fitted trend line (red line) from Moody (2008).



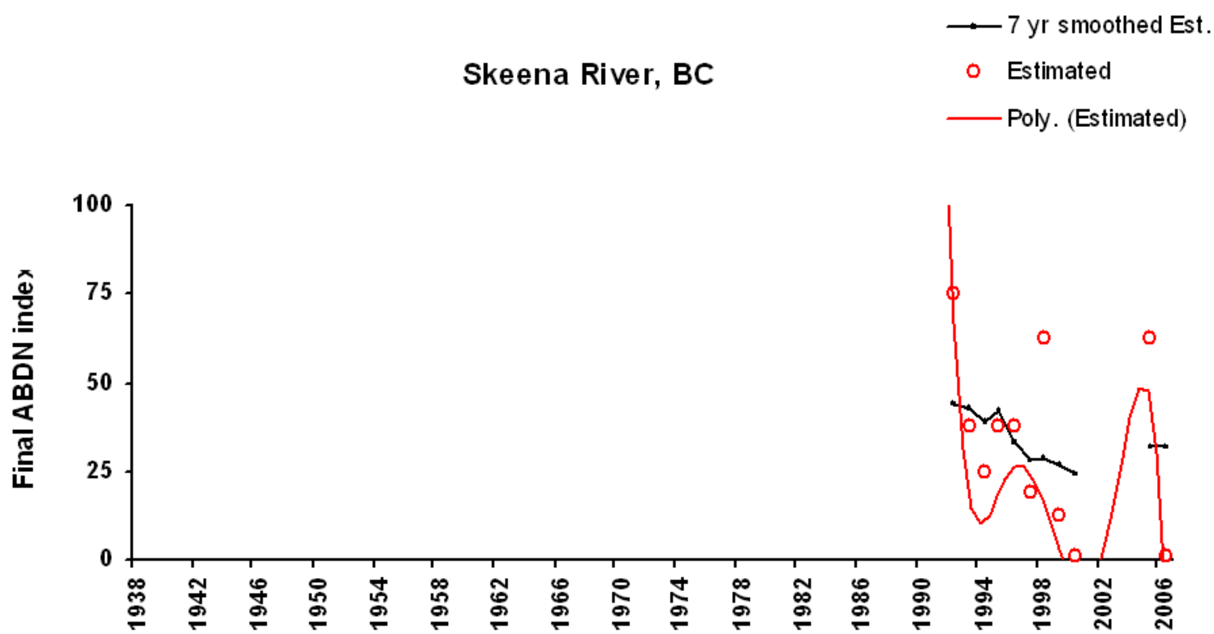


Figure 7 Nass River, BC (a) and Skeena River, BC (b) estimated eulachon abundance status (circles), 7 year smoothed abundance status estimations (black line), 3 yr. smoothed catch (grey fill) and a polynomial fitted trend line (red line) from Moody (2008).

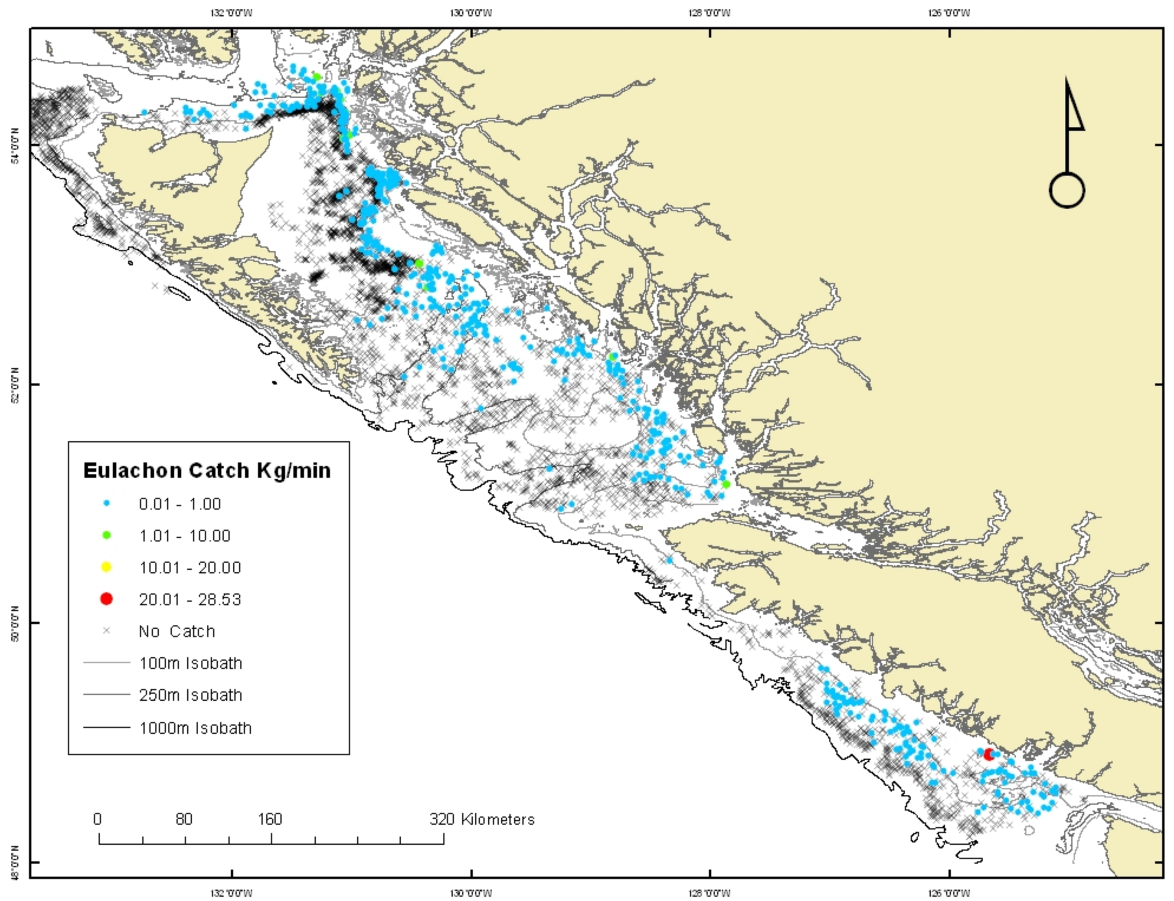


Figure 8 Eulachon catches from groundfish research surveys conducted in various areas of the BC coast from 2002-2010.

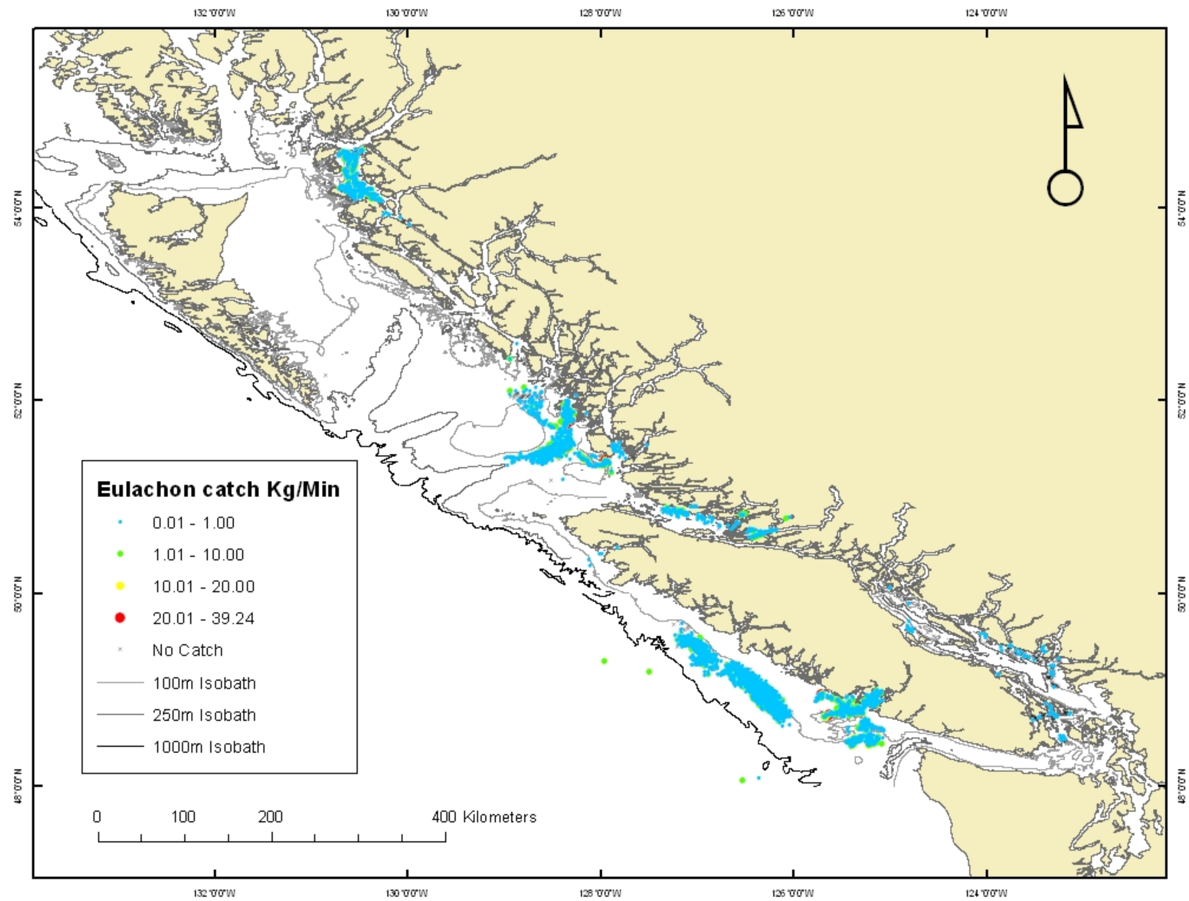


Figure 9 Eulachon catches from multispecies small mesh trawl research surveys conducted in various areas of the BC coast from 1967-2011.

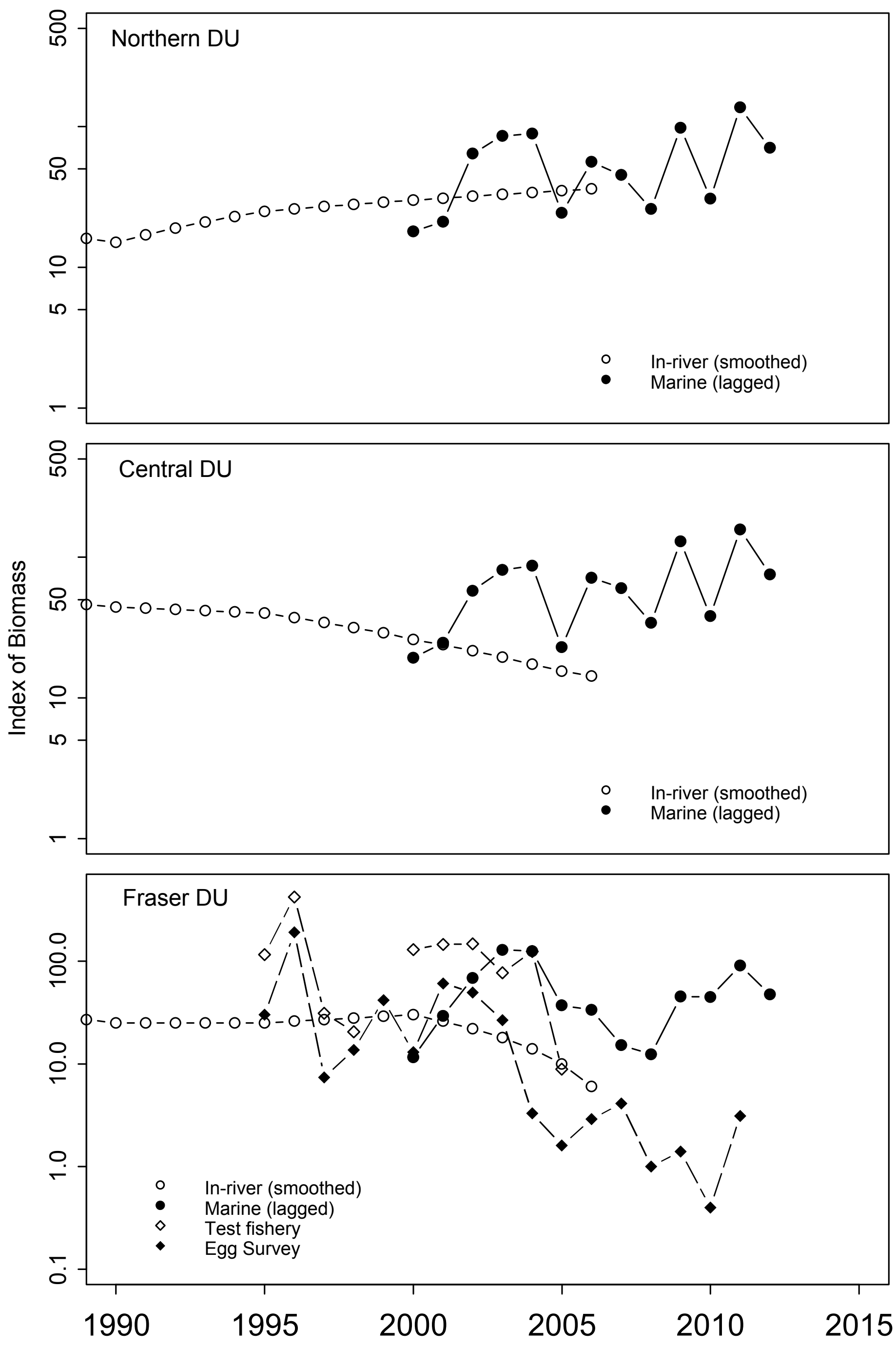


Figure 10 Comparison of trends in marine and in-river indices of eulachon biomass by DU from 1989-2011. Note log scale on y-axis. The marine index is lagged forward one year to reflect the pre-spawner abundance in the summer survey. The in-river smoothed index is from Moody (2008). Egg and larval survey and gillnet test fishery indices are also shown.

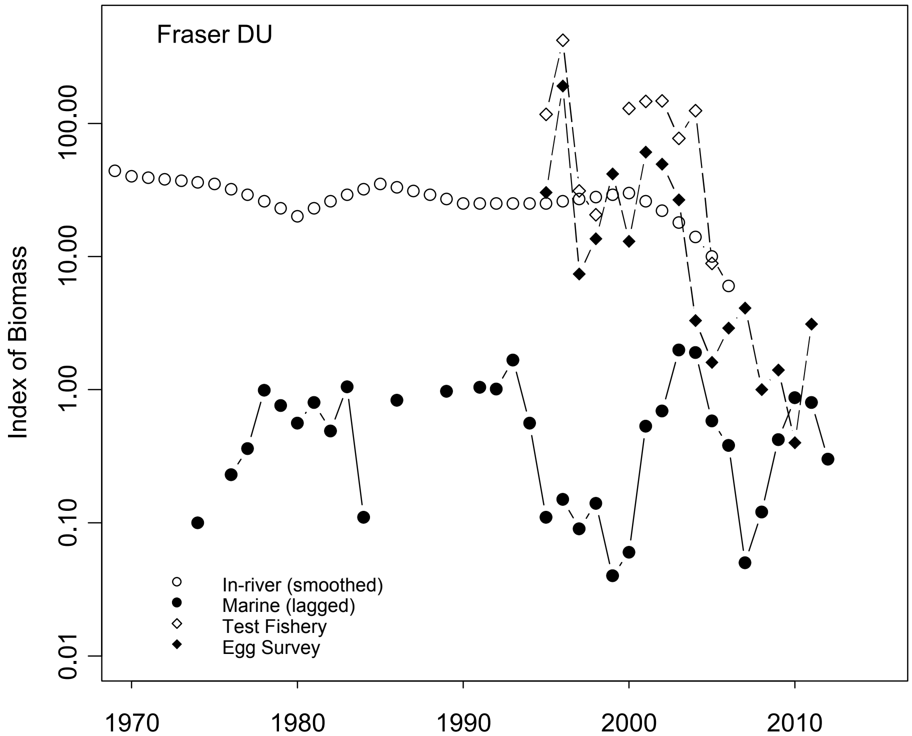


Figure 11 Comparison of trends in WCVI marine survey index and three in-river indices of Fraser River eulachon biomass from 1969-2011. Note log scale on y-axis. The in-river smoothed index is from Moody (2008). Egg and larval survey and gillnet test fishery indices are also shown.

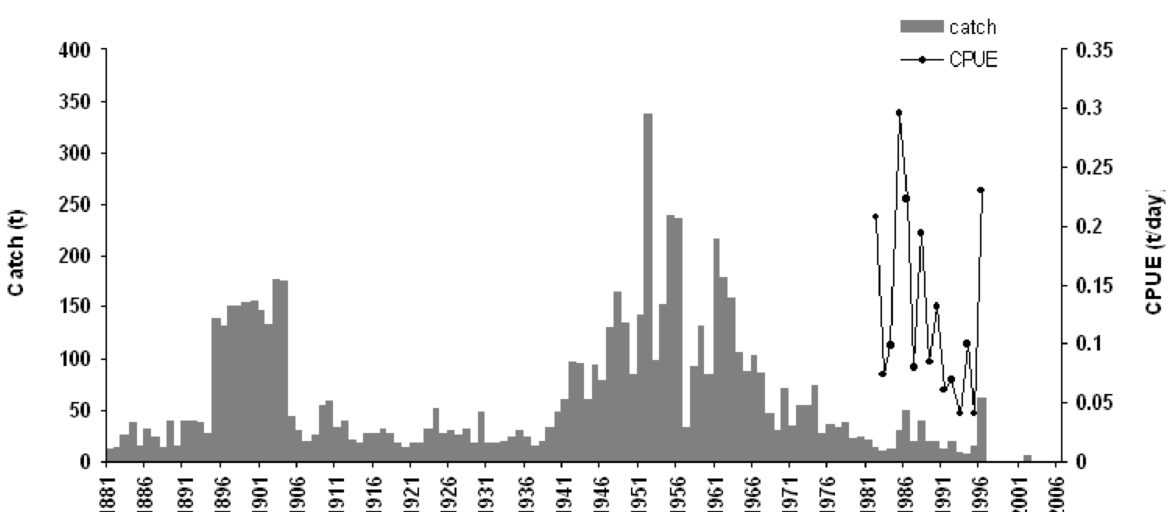


Figure 12 Commercial eulachon catch and CPUE from the Fraser River. Sources: catch 1881-1940 Clemens and Wilby 1946; catch 1941-1953 (Ricker et al. 1954); catch 1954-2000 (Hay and McCarter 2000); catch 2001-2006 (DFO 2007); and CPUE data (DFO 2008) from Moody (2008).

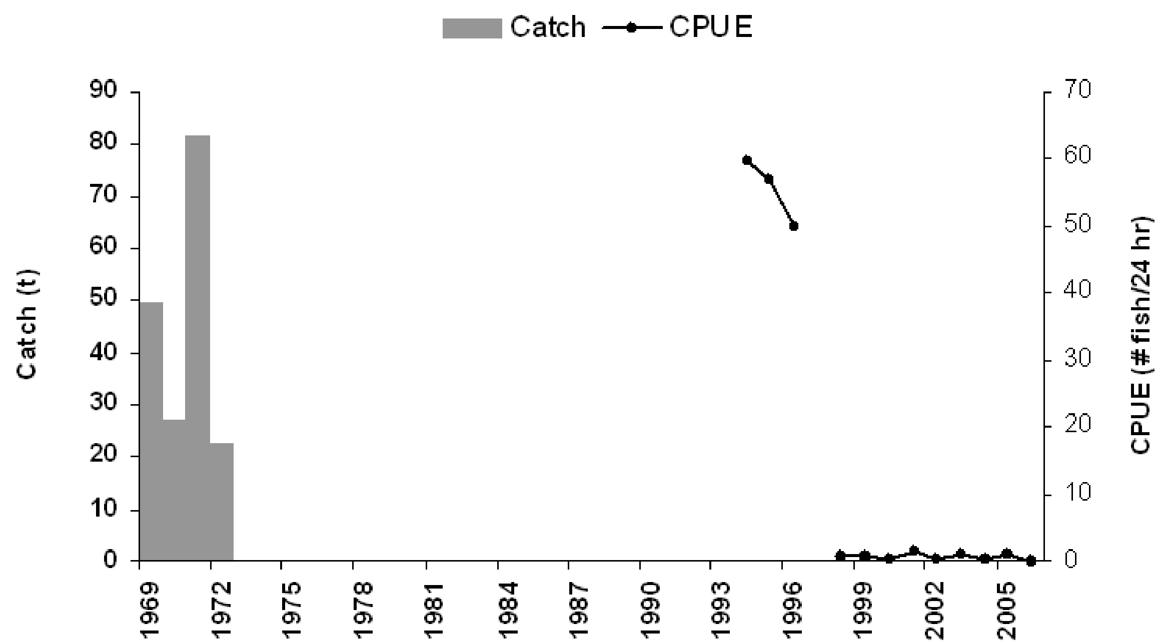


Figure 13 First Nation eulachon catch and CPUE from the Kitimat River. Source: DFO 1969-1973; Pedersen et al. 1995; EcoMetrix 2006 from Moody (2008).

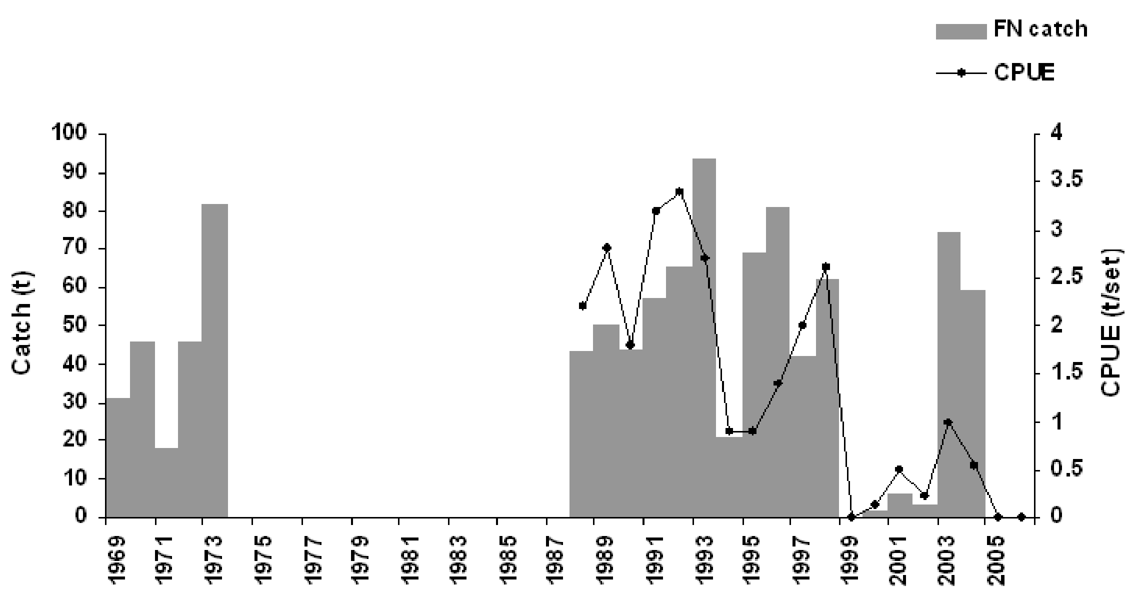


Figure 14 Eulachon catch and CPUE from the Kemano River Source: DFO 1969-1973; Lewis et al. 2002; Lewis and Ganshorn 2004 from Moody (2008).

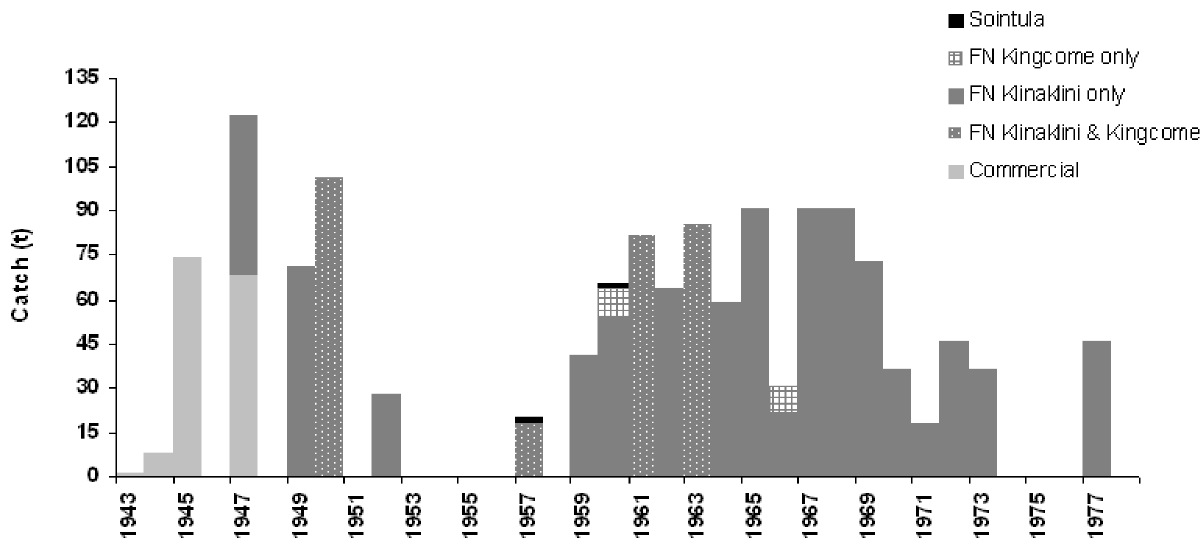


Figure 15 FN and commercial eulachon catches recorded in Knight and Kingcome Inlets. Commercial catch (light grey), Klinaklini First Nation (FN) catch (dark grey), Kingcome FN catch (grey checkered), Klinaklini and Kingcome FN catch (dark grey with spots) and Sointula fishers (black). Source: Common Resources Consulting Ltd. 1998 from Moody (2008).

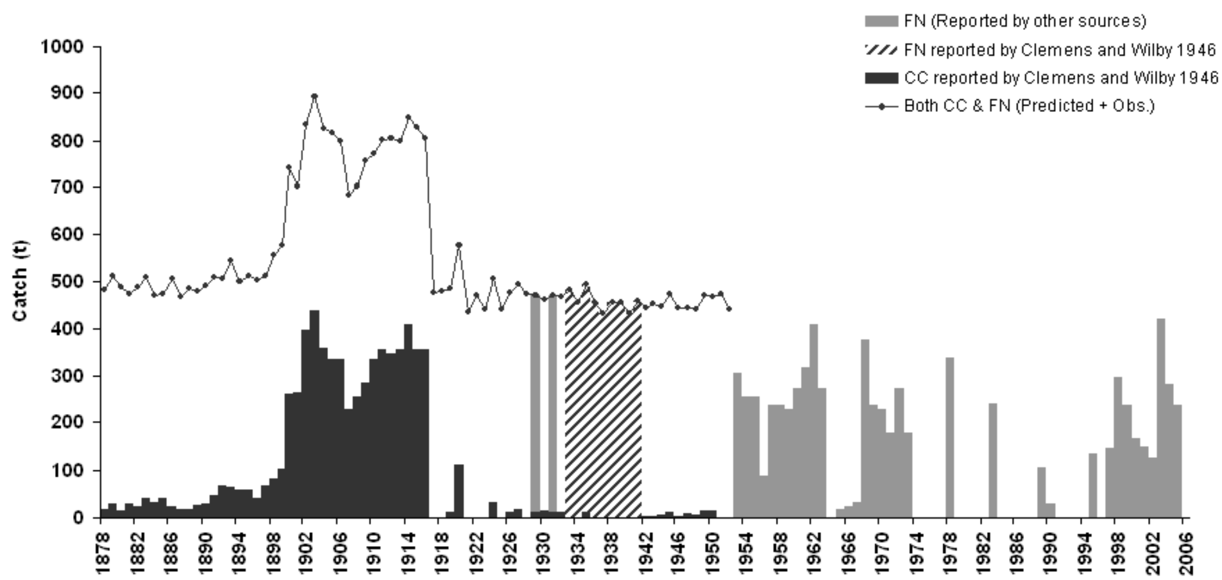


Figure 16 Eulachon catch from the Nass River. First Nation (FN) catch (diagonal stripes) and commercial catch (dark bars), Clemens and Wilby 1946. FN catch reported in "other" sources (light grey bars). Estimated catch = FN estimated + commercial catch, Clemens and Wilby 1946 (line) from Moody (2008).

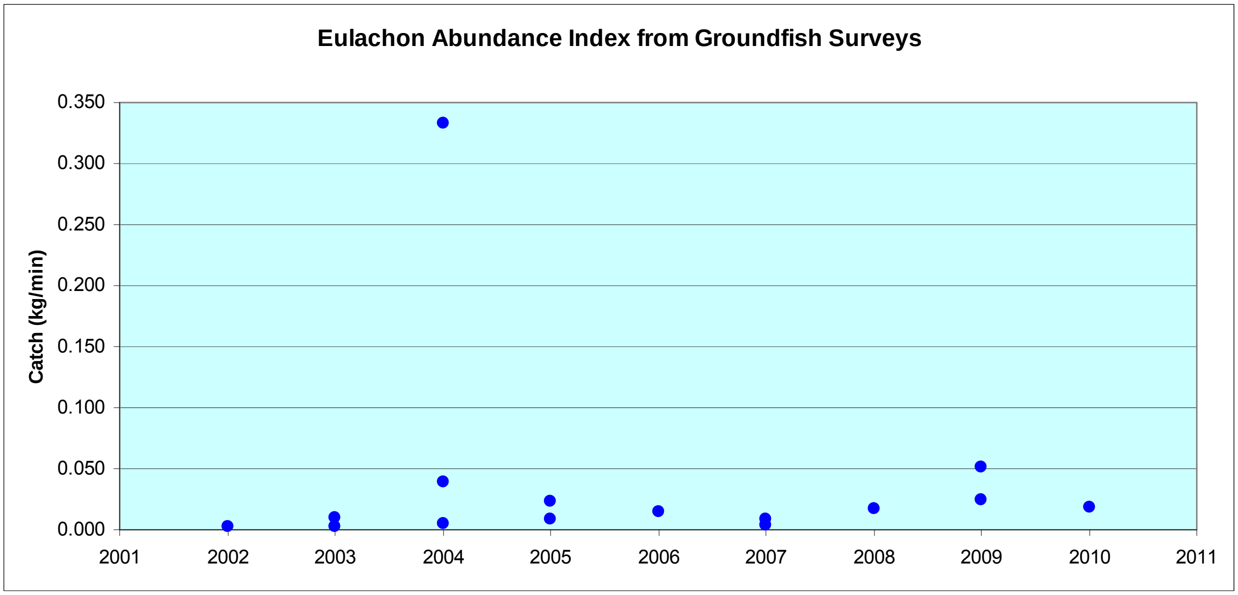


Figure 17 Estimated catch rate (kg/min) of eulachon from DFO Groundfish research surveys conducted in all three regions from 2002-2010.

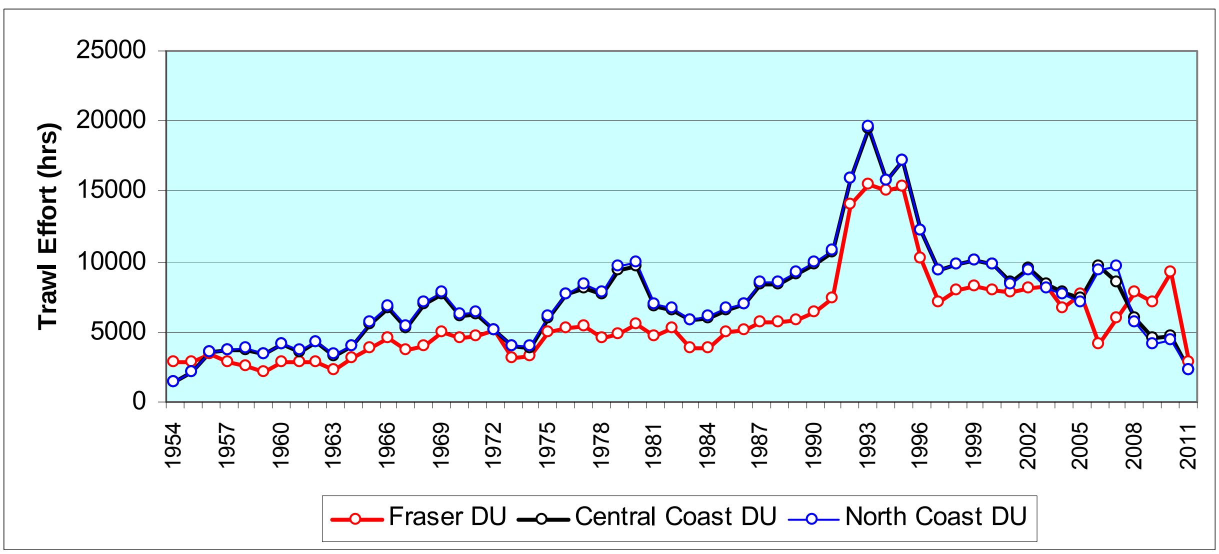


Figure 18 Estimated commercial groundfish trawl fishery effort (0-500m depth range) for each eulachon DU based on adjusting the observed effort by the genetic proportions of eulachon. Note that the lines for the Central and North coast largely overlap.

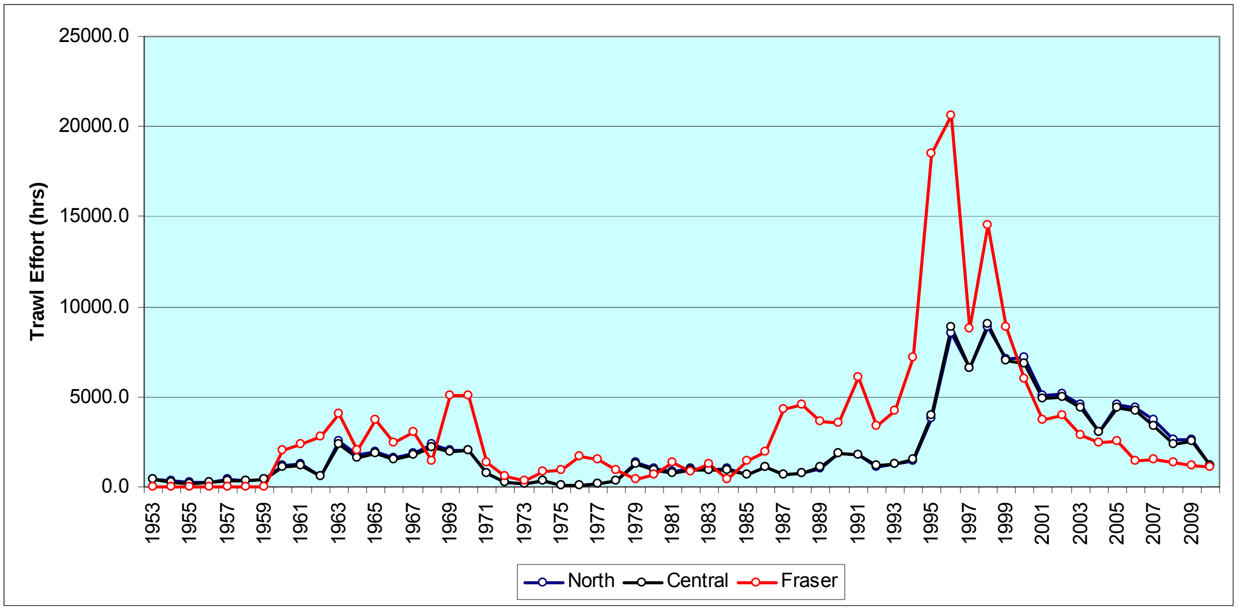


Figure 19 Estimated commercial shrimp trawl fishery effort (0-500m depth range) for each DU based on the proportion of eulachon by DU from the genetic samples. Note that the lines for the North and Central DU largely overlap.

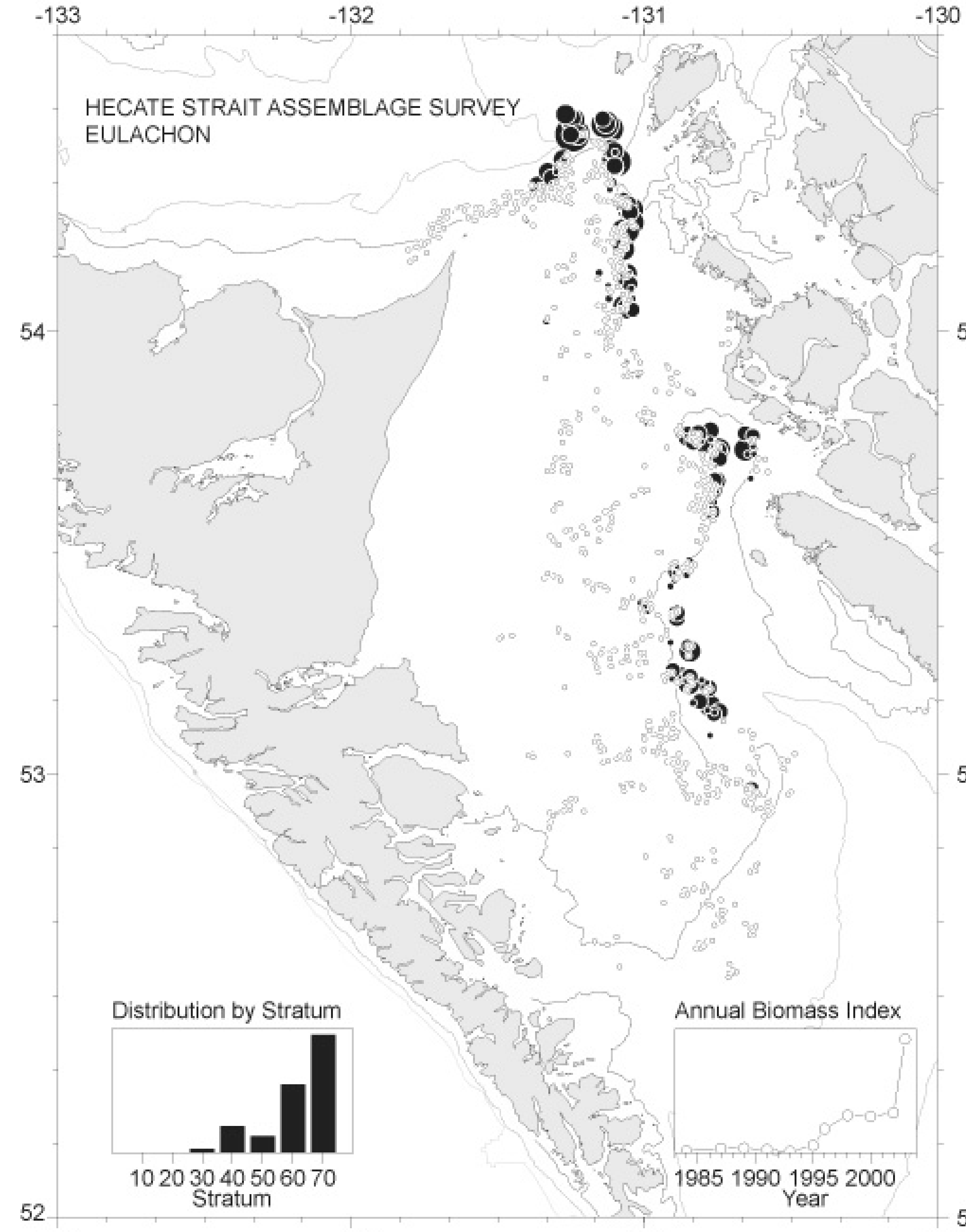


Figure 20 Catch distribution of EULACHON in the Hecate Strait Assemblage Survey, 1984-2003. The symbols are scaled linearly to the CPUE in the tow, from the 0.025 -0.975 percentiles of the distribution of non-zero catches. The relative distribution of catch by 10-fm depth stratum (lower left plot) and trends in the biomass index (kg•hr-1, lower right plot) are provided (from Sinclair et al. 2007).

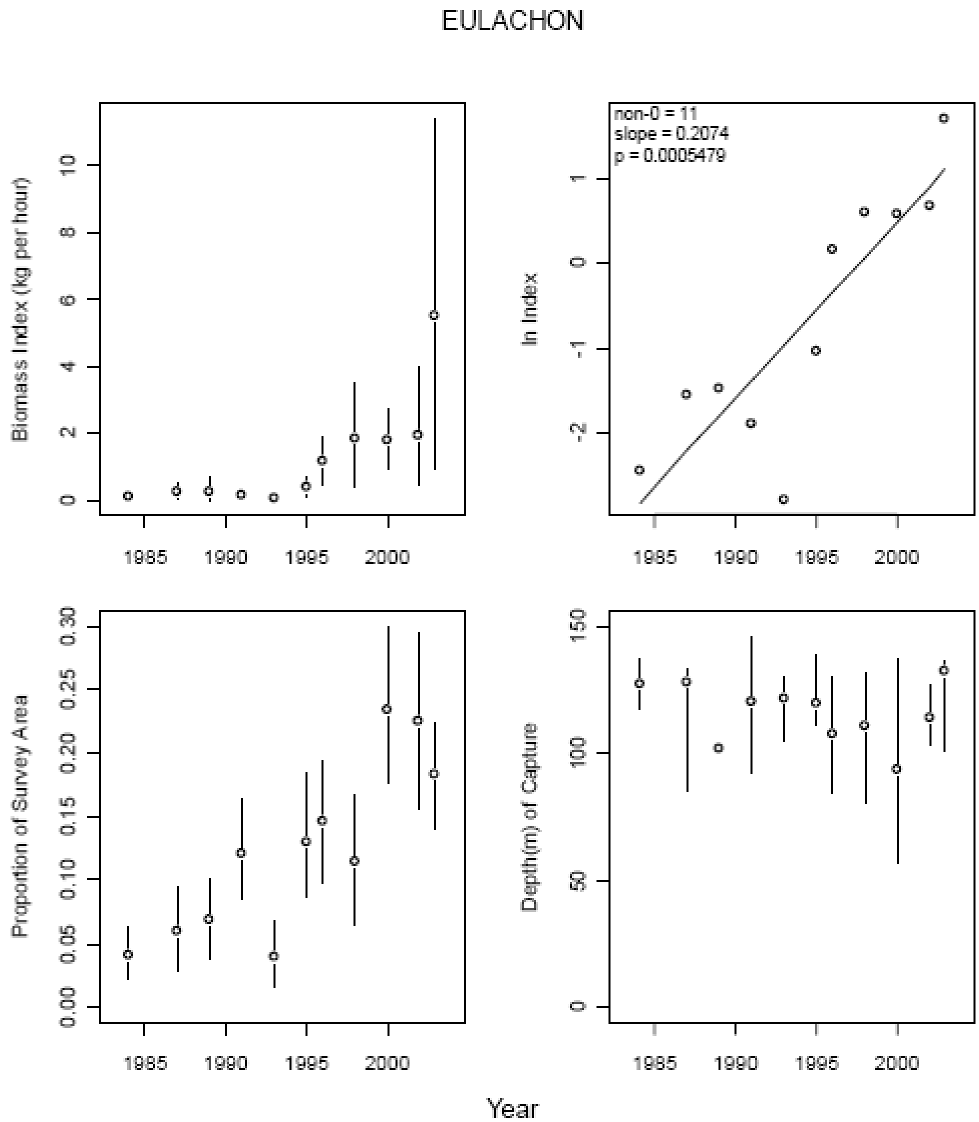


Figure 21 Annual indices for EULACHON from the Hecate Strait Assemblage Survey,1984 - 2003. The upper left panel gives the biomass index (kg•hr-1) and the 90% confidence intervals. The upper right panel gives the linear regression of the index vs. year. The number of non-zero observations, the slope estimate and its probability level are indicated. Regressions were performed for species with at least 8 non-zero observations. The lower left panel gives the stratified area occupied by the species, expressed as a proportion of the total survey area. The lower right panel gives the mean depth of capture (m, circles) and the depth range of 95% of the catch (from Sinclair et al 2007).

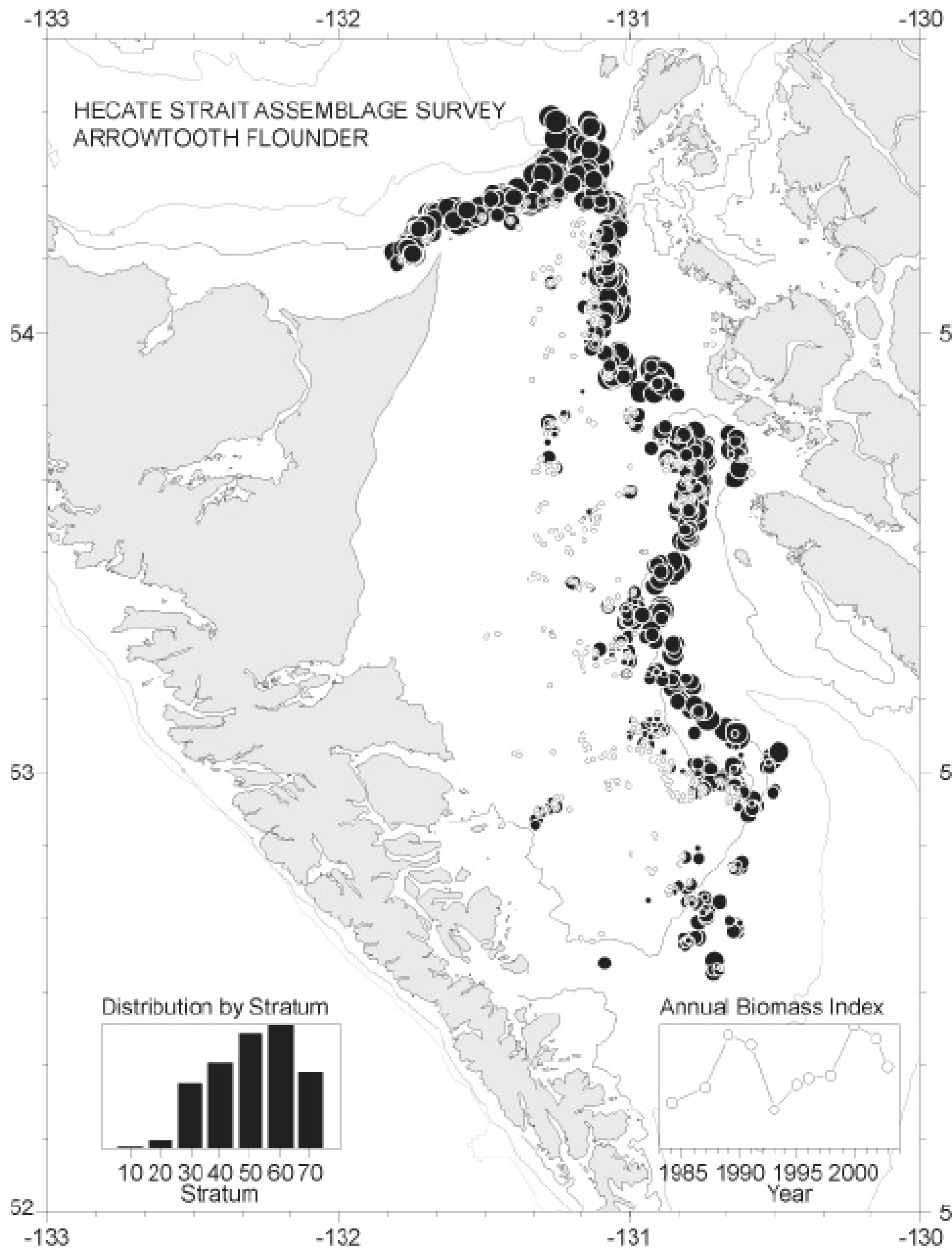


Figure 22 Catch distribution of ARROWTOOTH FLOUNDER in the Hecate Strait Assemblage Survey, 1984-2003. The symbols are scaled linearly to the CPUE in the tow, from the 0.025 - 0.975 percentiles of the distribution of non-zero catches. The relative distribution of catch by 10-fm depth stratum (lower left plot) and trends in the biomass index (kg·hr-1, lower right plot) are provided (from Sinclair et al 2007).

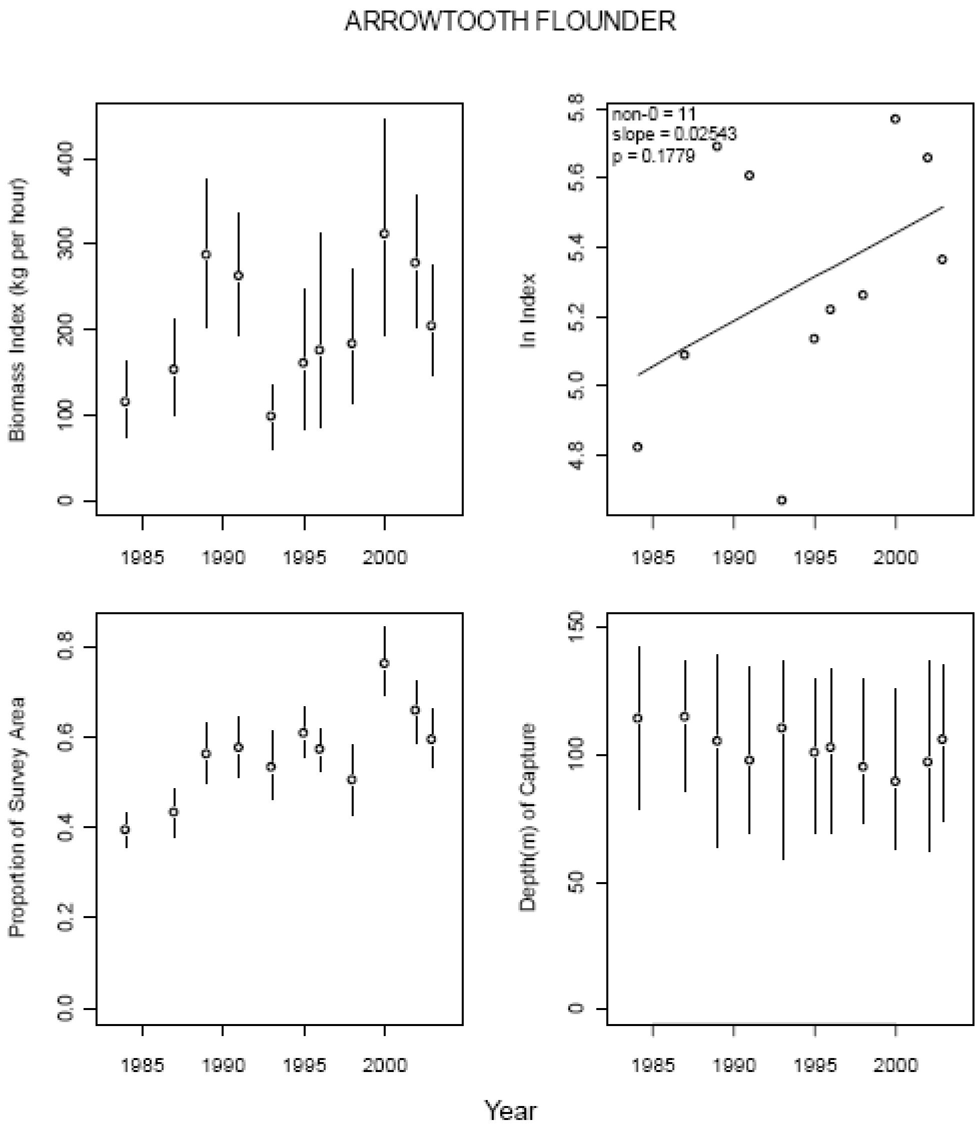


Figure 23 Annual indices for ARROWTOOTH FLOUNDER from the Hecate Strait Assemblage Survey, 1984 - 2003. The upper left panel gives the biomass index (kg•hr-1) and the 90% confidence intervals. The upper right panel gives the linear regression of the index vs. year. The number of non-zero observations, the slope estimate and its probability level are indicated. Regressions were performed for species with at least 8 non-zero observations. The lower left panel gives the stratified area occupied by the species, expressed as a proportion of the total survey area. The lower right panel gives the mean depth of capture (m, circles) and the depth range of 95% of the catch (from Sinclair et al 2007).

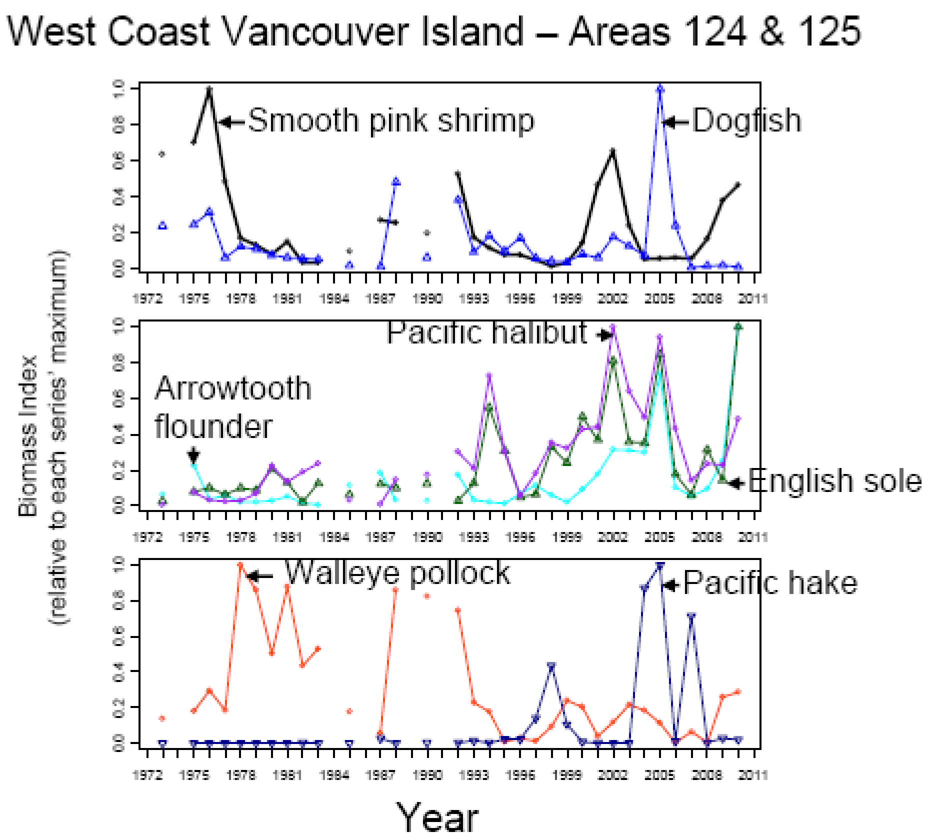


Figure 24 Time series of normalised (to maximum biomass) survey catches of smooth pink shrimp, dogfish, Pacific halibut, Arrowtooth flounder, English sole, Pacific hake and walleye pollock. Sampling was conducted in May of each year (from Crawford and Irvine 2011).

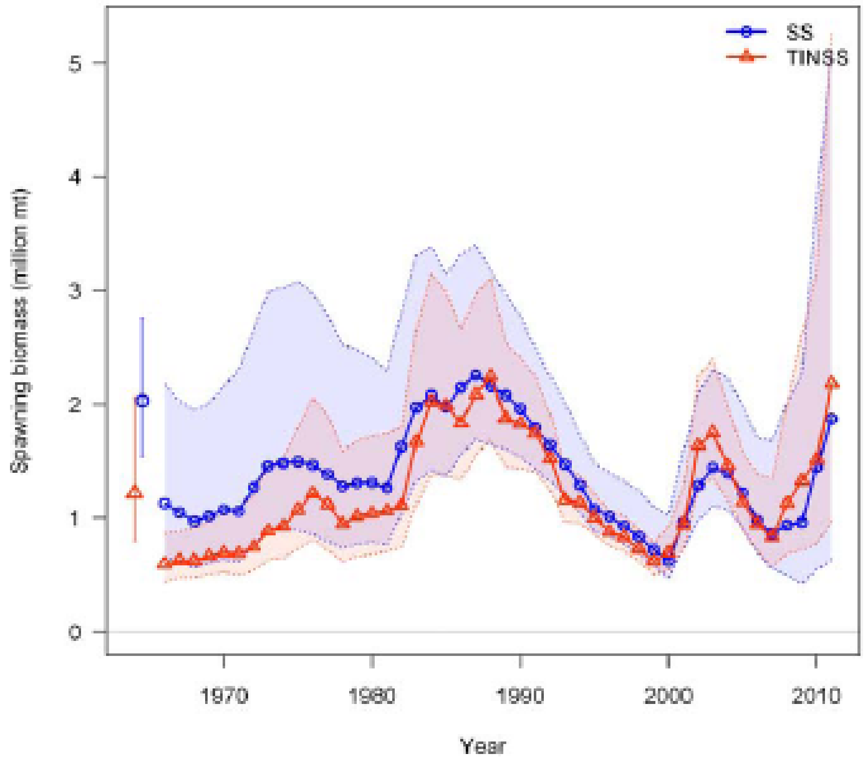


Figure 25 Estimated female spawning biomass (million mt) with 95% posterior credibility intervals from the 2011 Pacific hake stock assessment. Blue and red series represent estimates from two age-structured Bayesian models (SS and TINSS). Points (and confidence) intervals at the beginning of the series represent estimates of equilibrium unfished female spawning biomass. Source: Joint U.S. and Canadian Hake Technical Working Group 2011 (from Crawford and Irvine 2011).

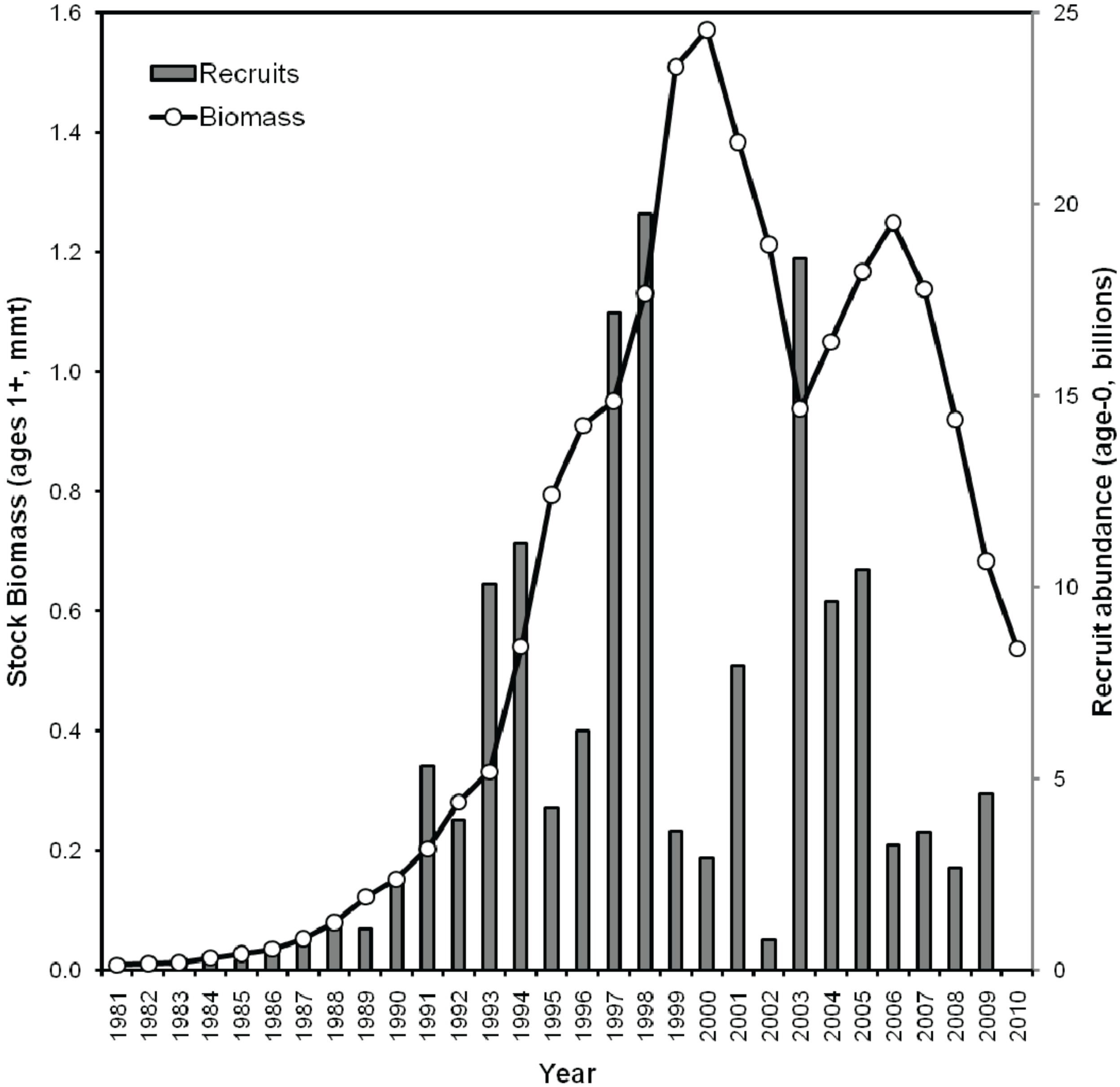


Figure 26 Pacific sardine stock biomass (ages 1+) and recruits (age 0) from the 2010 update model '10w' from Hill et al. (2010).

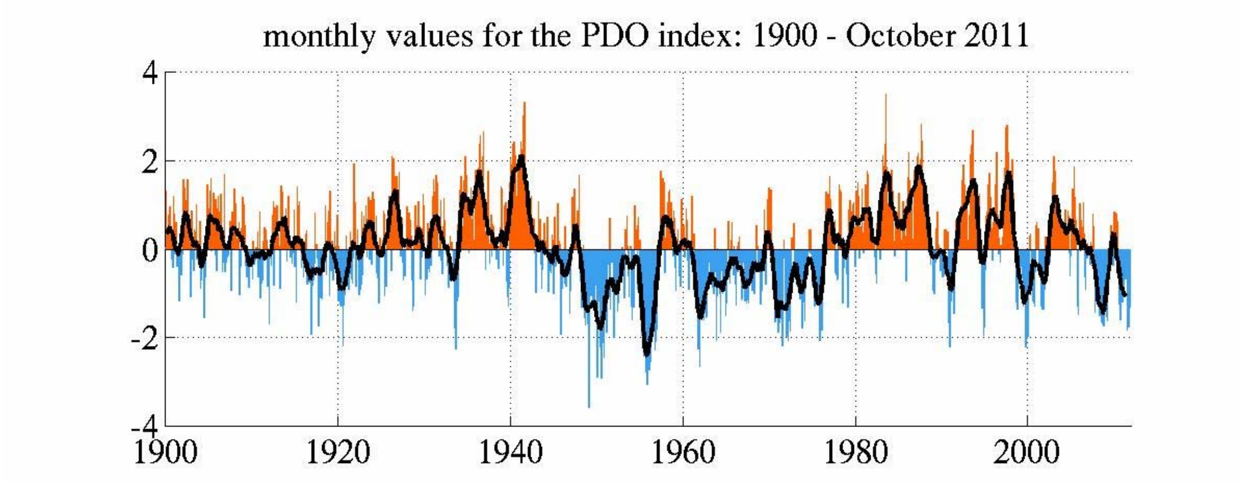


Figure 27 Pacific Decadal Oscillation time series from 1900 to 2011. Figure and data available from http://jisao.washington.edu/pdo/.

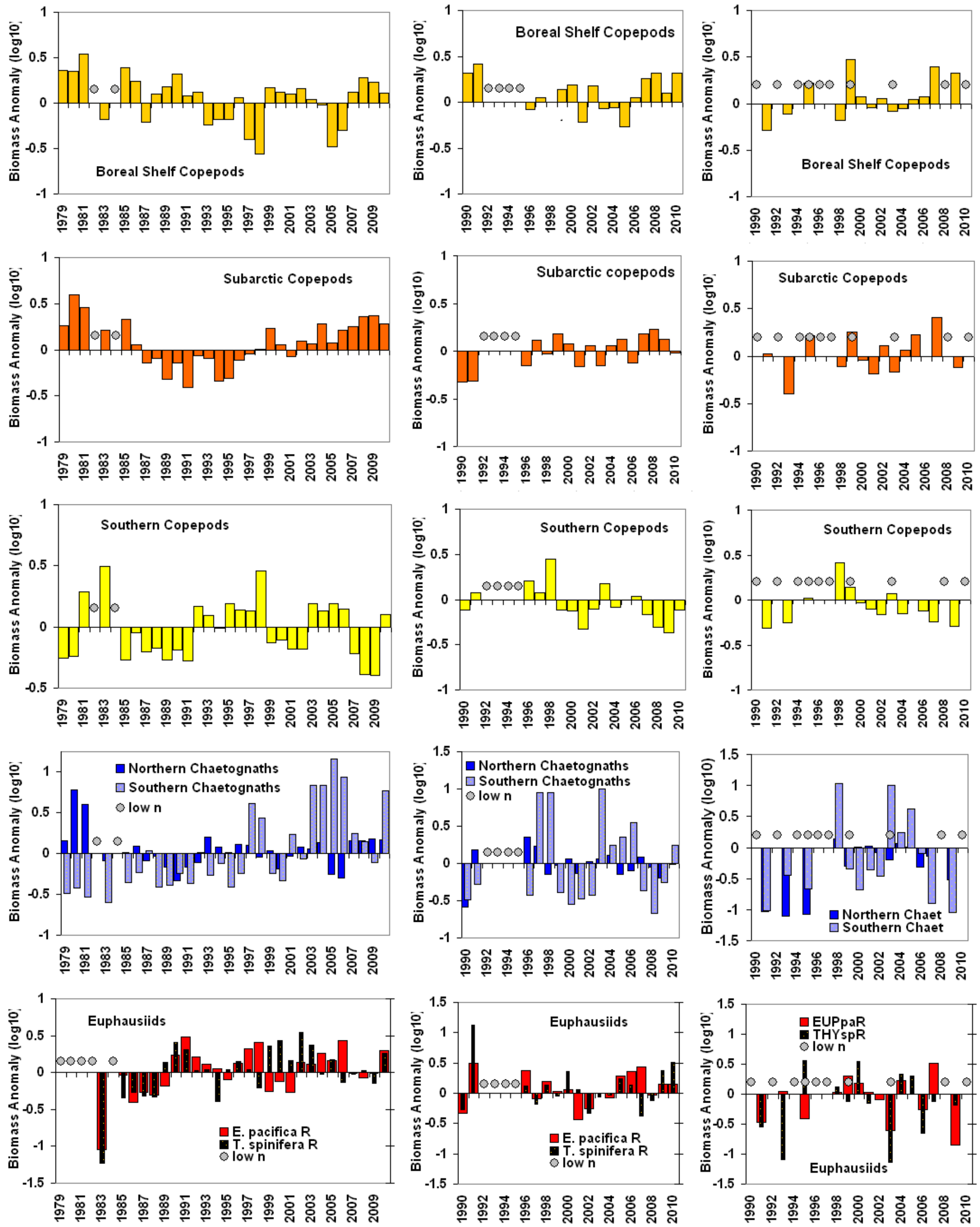


Figure 28 Zooplankton species-group anomaly time series (vs climatological baseline) for the Southern Vancouver Is., Northern Vancouver Is. and Hecate Strait regions. Bar graphs are annual log scale anomalies. Circles indicate years with no or very few samples from that region. Cool years favor endemic 'northern' taxa (boreal shelf, subarctic copepods, euphausiids) and , warm years favour colonization by 'southern' taxa (southern chaetognaths and copepods). (from Crawford and Irvine 2011).

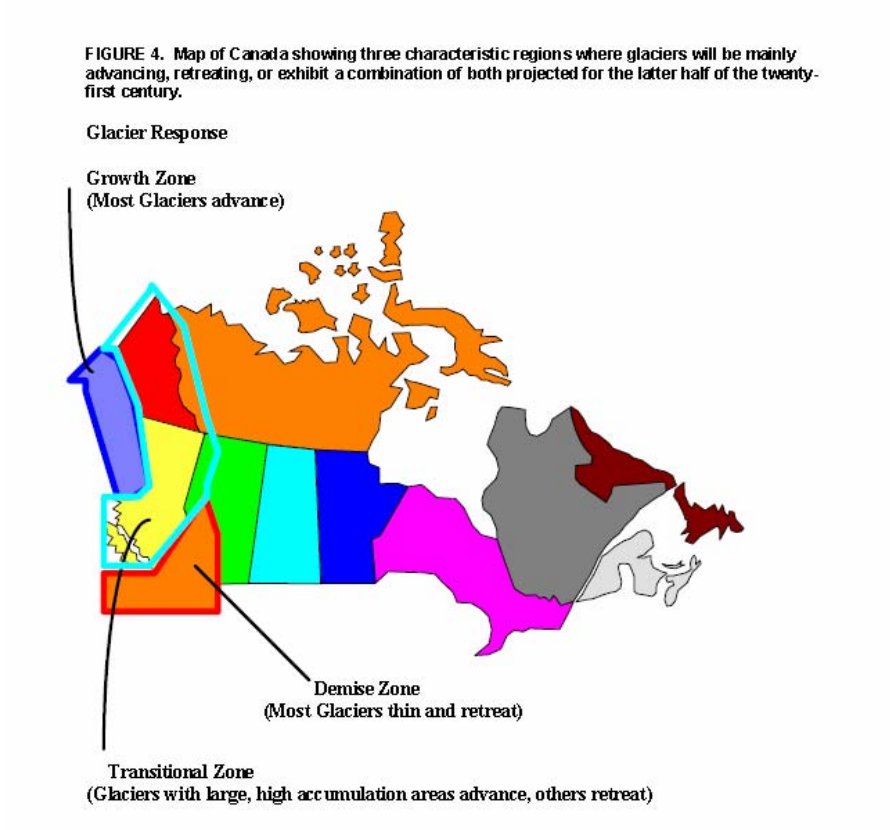


Figure 29 Projections of glacier changes for the latter half of the century as a result of climate warming (Figure 4 from Taylor and Taylor 1997).

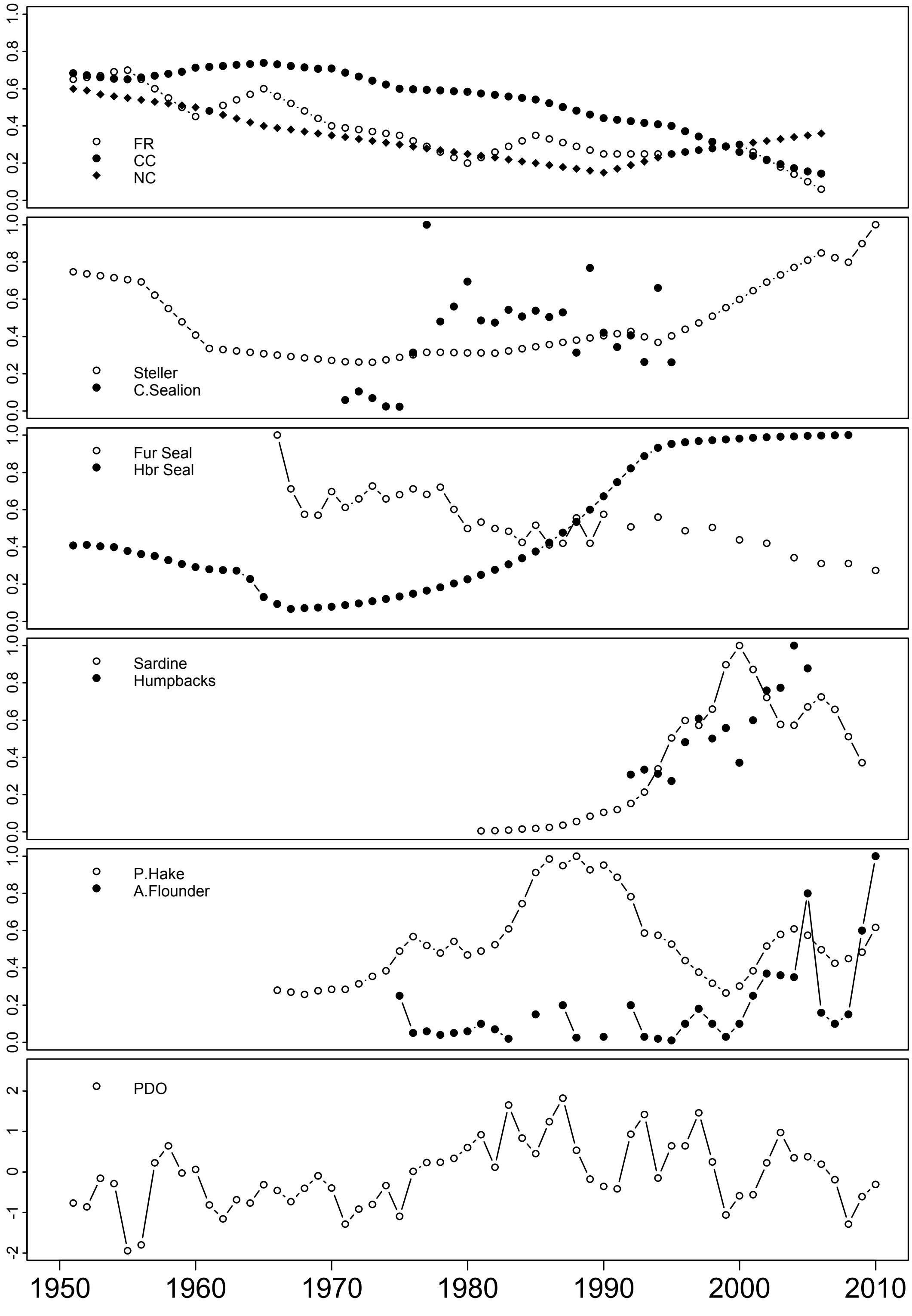


Figure 30 Estimated abundance trends for the three BC eulachon DUs (top panel) and associated potential coastwide threats to population recovery. The y-axis has been scaled frpm 0 to 1 in each panel except for PDO where it is the deviation from the average.

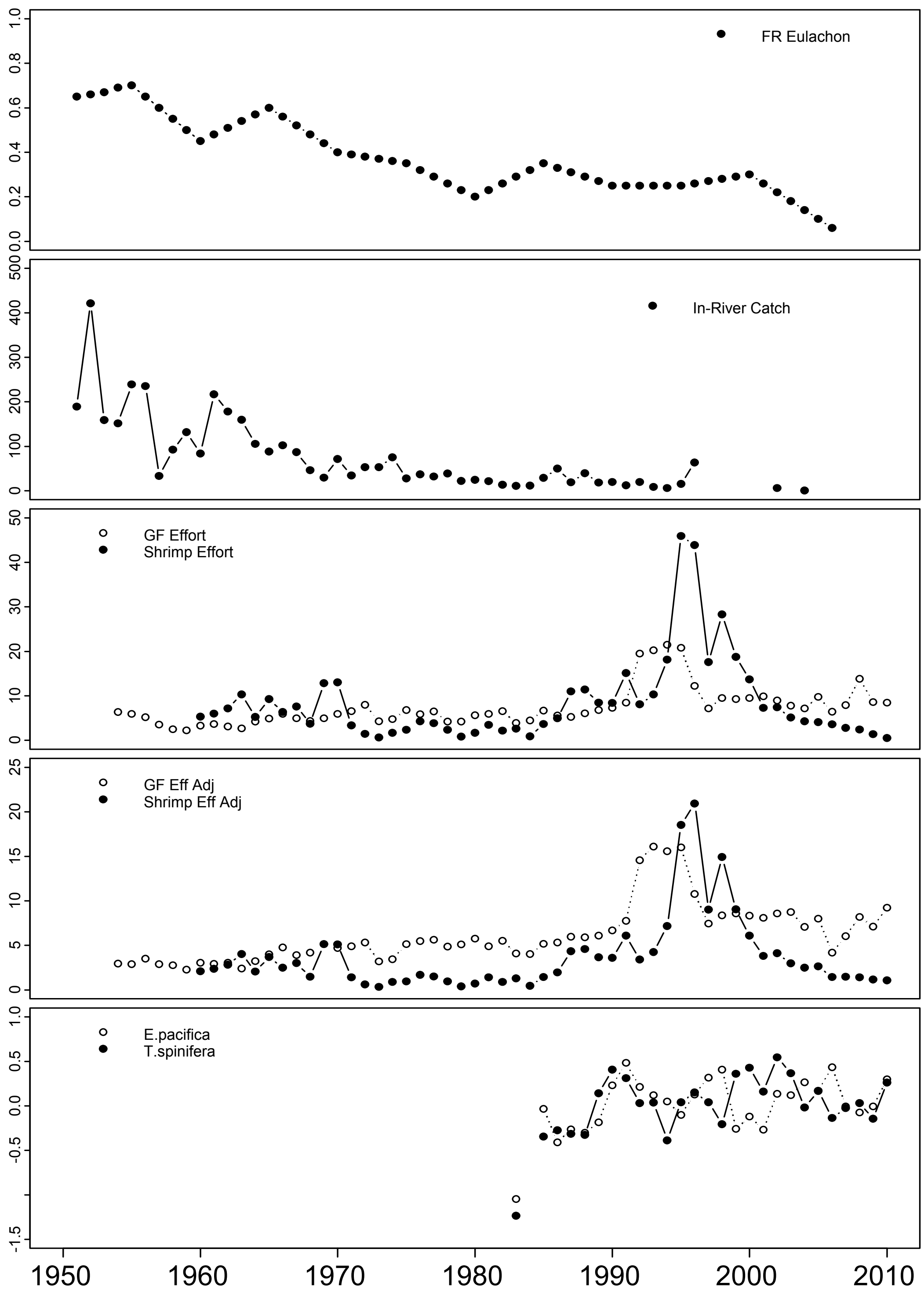


Figure 31 Eulachon abundance trend in the Fraser river and associated in-river catch (t) and offshore shrimp and groundfish raw trawl effort (thousands of hours) and adjusted for DU specific interception, and euphausiid relative abundance deviations off southwest Vancouver Island.

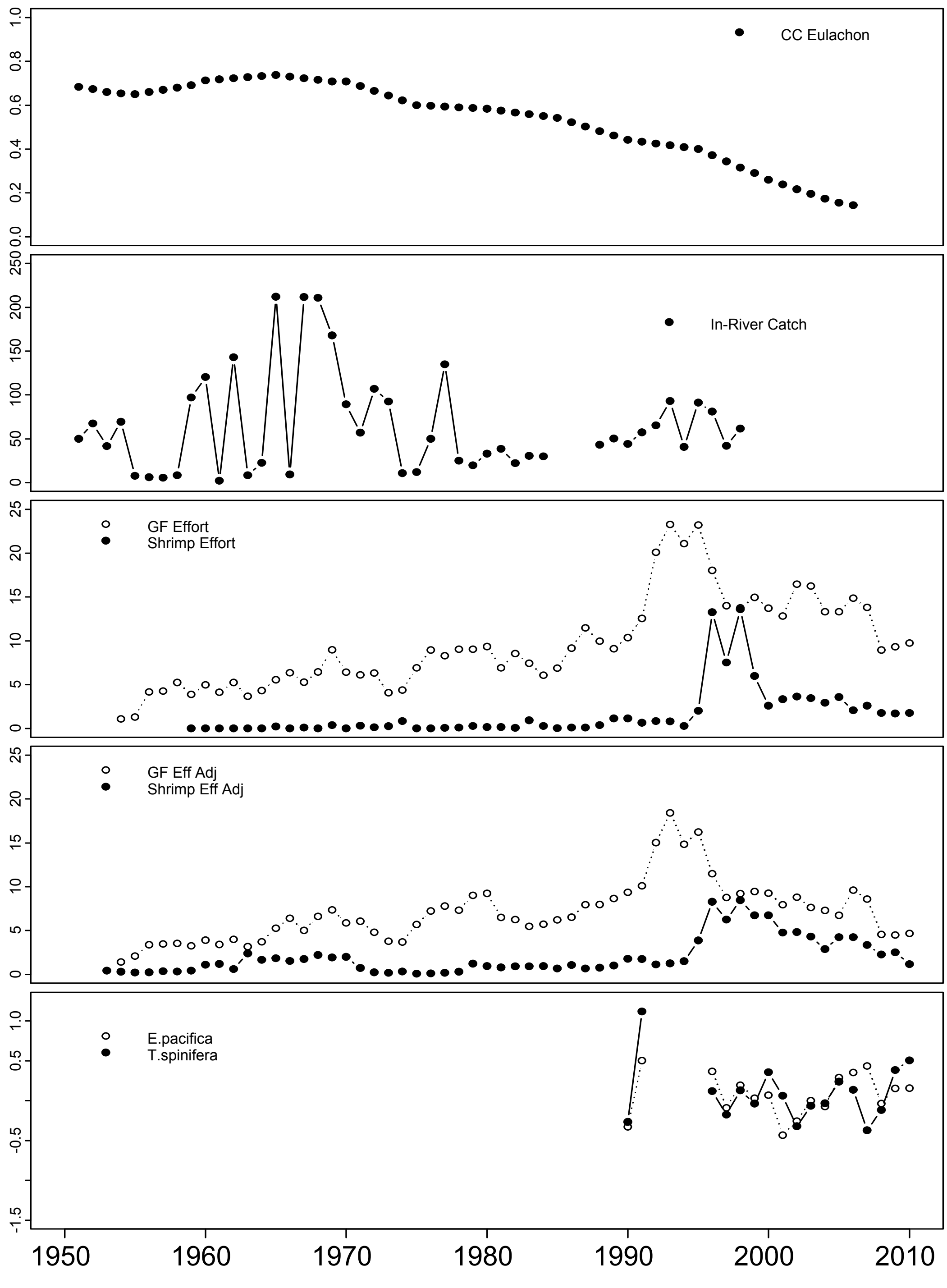


Figure 32 Eulachon abundance trend in the Central coast rivers and associated in-river catch (t) and offshore shrimp and groundfish raw trawl effort (thousands of hours) and adjusted for DU specific interception, and euphausiid relative abundance deviations off northwest Vancouver Island.

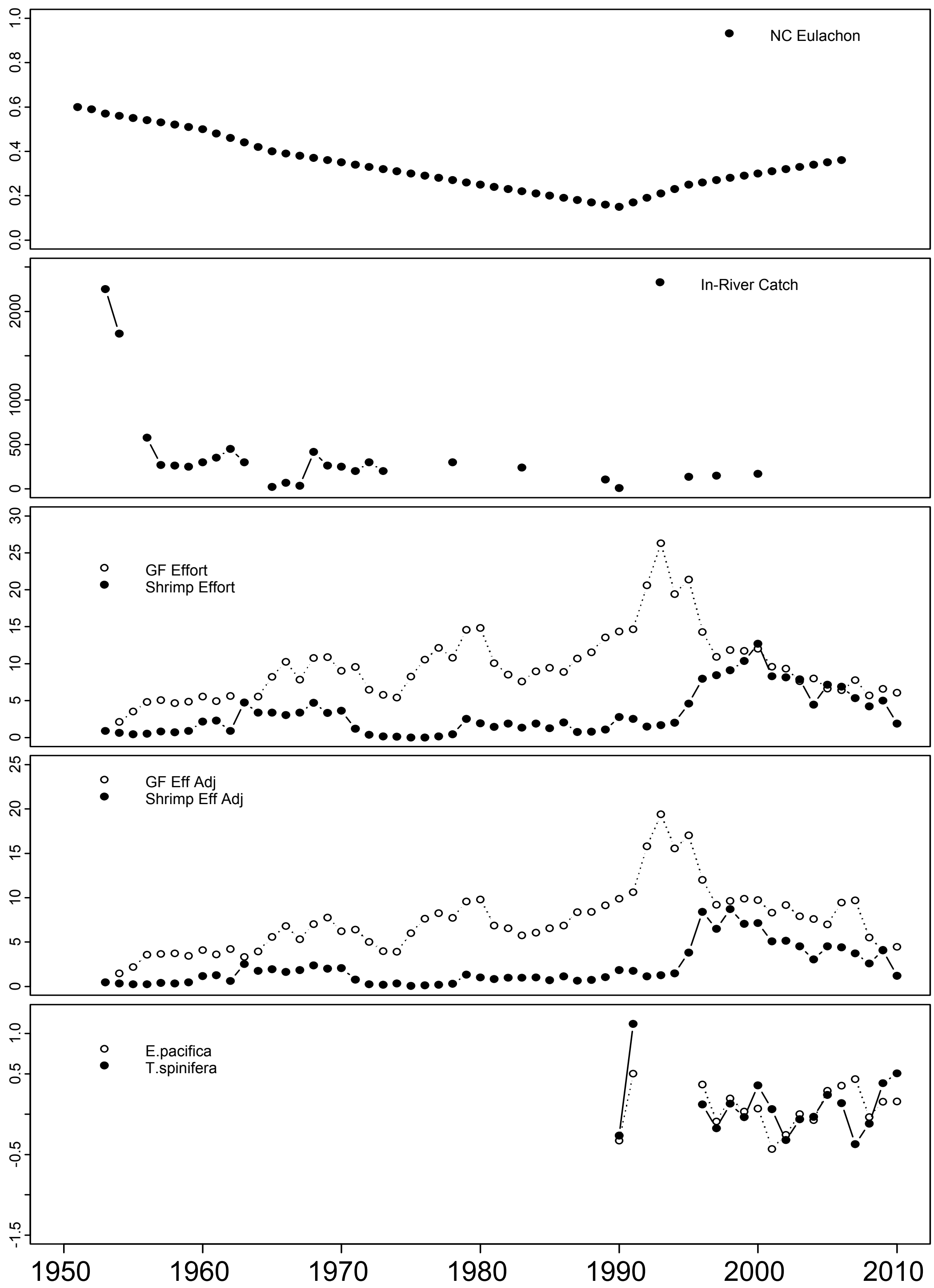


Figure 33 Eulachon abundance trend in the Nass River and associated in-river catch (t) and offshore shrimp and groundfish raw trawl effort (thousands of hours) and adjusted for DU specific interception, and euphausiid relative abundance deviations off northwest Vancouver Island.

APPENDIX 1 - RECOVERY POTENTIAL ASSESSMENT – FRASER RIVER DU

Assess current/recent species/ status

1. Evaluate present *[species/population/DU]* status for abundance and range and number of populations

Eulachon are known to spawn in the lower reaches of the North and South Arms of the Fraser River, and have extended upstream as far as Chilliwack in previous years.

Other

There are no known confirmed spawning rivers on coastal islands including Haida Gwaii and Vancouver Island (Hay and McCarter 2000). However, there are accounts of eulachon spawning in these other areas including: the Nimpkish and Kokish Rivers on the north end of Vancouver Island (Hay and McCarter 2000), the Somass River (in 1955) that drains into the Alberni Inlet on the west coast of Vancouver Island (Hay et al. 1997).

2. Evaluate recent species trajectory for abundance (i.e., numbers and biomass focusing on matures) and range and number of populations.

Abundance of eulachon in the Fraser River is at an historic low based on the results of recent egg and larval surveys. Relative abundance is available from Moody (2008) and presented in Figures 28 and 29.

3. Estimate, to the extent that information allows, the current or recent life-history parameters for *[species/population/DU]* (total mortality, natural mortality, fecundity, maturity, recruitment, etc.) or reasonable surrogates; and associated uncertainties for all parameters.

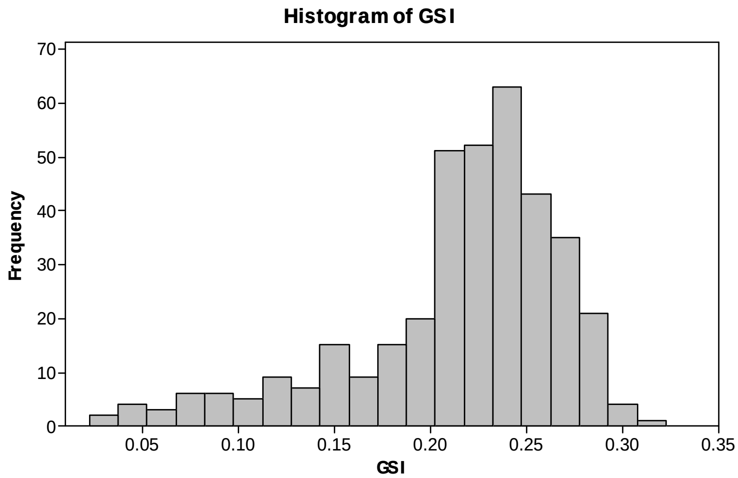
Mortality

Eulachon are semelparous. It appears that most die after spawning at age of 36 months, but probably some spawn a year earlier and a year later, at age 24 and 48 months respectively.

Fecundity

All fecundity data were collected between 1993 and 1998. There are fewer than 100 measurements of fecundity from the combined rivers in the Central DU (Kitimat, Kemano and Bella Coola) and none from the Nass DU. There are over 500 measurements from the Fraser DU. When fecundity is compared by the origin of the fish the more northern samples appear to have a lower relative (eggs/gm) and absolute fecundity but this may partially reflect an error attributable to sampling. Fraser River fish were captured several days prior to spawning whereas some or most of the fish in the northern samples could have been actively spawning and already released some of their eggs. Therefore the fecundity data from the Fraser River probably is the most reliable to apply to all DU's. This is explained further below.

The GSI (or 'gonosomatic index') is the proportion of total body weight made up of ovaries. When ripe, or actively spawning eulachon are captured there may be a risk of egg loss that cannot be detected during later analysis in a laboratory. Very low GSI estimates indicate probable loss of eggs, either from spawning or later when fish are inadvertently squeezed or compressed in sampling containers. Most of the low GSI eulachon were from Northern rivers when eulachon were captured at times and places close to spawning grounds, whereas in the Fraser River most eulachon were captured prior to spawning.



Absolute and relative fecundity was determined for eulachon from the Central and Fraser DU's. To avoid under-estimation related to loss of eggs the analyses were confined to fish that had a GSI of 0.18 or greater.

	Fecundity Mean	Rel Fecund Mean	Fecundity N	RelFecund N
Central	27700	599.0	41	41
Fraser	32208	787.2	512	512
All	31873	773.2	553	553

Sex ratios of individual samples can vary markedly but the composite ratios of all Fraser River fish is very close to an even split between males and females. Therefore, assuming that males weigh approximately the same as females the estimate of relative fecundity for the eulachon population (males and females) is 0.5 times the female estimate. For the Central coast this would be about 300 eggs/g and for the Fraser it would be about 390 eggs/g of eulachon weight.

Maturity

Eulachon are semelparous. It appears that most spawn at an age of 36 months, but probably some spawn a year earlier and a year later, at age 24 and 48 months respectively. Like other fish species in the North Pacific there may be a latitudinal cline in age-at-maturity with fish in the southern part of the range spawning at younger ages (many at age 2 in the Columbia, Gustafson et al. 2010) and at slightly older ages in Alaskan rivers.

Recruitment

The age of 'recruitment' is uncertain but for eulachon the definition of recruitment depends on the context of the question. If recruitment can refer to the age when young eulachon join older eulachon in offshore (shelf) waters, then the answer could be as young as 3-6 months and as old as 18 months. Probably the exact age depends on the DU. If recruitment depends on the age when eulachon are captured by First Nation fisheries, then recruitment is identical to age-at-maturity.

4. Estimate expected population and distribution targets for recovery, according to DFO guidelines (DFO 2005).

Based on these guidelines, recovery could imply more widespread spawning with the lower reaches of the Fraser to historical sites such as Mission. DU-specific abundance targets have not been established but it may be possible to estimate population sizes that would support sustainable catches that approximate the combined First Nations, commercial and recreational catches of eulachon taken from the Fraser River of about 200 tons/year. Levesque and Therriault (2011) propose a recovery target or lower stock reference level of 382t. Bayesian modeling (Appendix 3) estimated that the maximum sustainable yield (MSY) for this population is 112mt (90% C.I. 34-309)

5. Project expected *[species/population/DU]* population trajectories over three generations (or other biologically reasonable time), and trajectories over time to the recovery target (if possible to achieve), given current *[species/population/DU]* population dynamics parameters and associated uncertainties using DFO guidelines on long-term projections (Shelton *et al.* 2007).

The population dynamics model developed in Appendix 3 indicates that the population should rebuild to 20% of the unfished abundance level with a 50% probability that it will exceed this level.

6. Evaluate residence requirements for the species, if any.

Not applicable for eulachon.

Assess the Habitat Use of *[species/population/DU]*

7. Provide functional descriptions (as defined in DFO 2007b) of the properties of the aquatic habitat that *[species/population/DU]* needs for successful completion of all life-history stages.

The properties of the freshwater and marine habitats required by eulachon are described at length in Gustafson et al. (2010) and Levesque and Therriault (2011).

The characteristics of the freshwater environment have been well described but are variable whereas those for the marine environment are less clear. Finney (unpublished data) noted some of the variables that describe the marine areas where eulachon are normally observed:

Table B - 1. Minimum, median, and maximum values of the seven environmental variables at locations where eulachon were found.

Environmental variable	Minimum	Median	Maximum
Depth (m)	41	162	292
Slope (degrees)	0	0.29	7.1
Chlorophyll *a* concentration (ml/cm^3)	1.21	3.31	14.62
Summer salinity (psu)	31.37	33.73	34.04
Summer temperature (^{o}C)	5.11	6.25	9.13
Tidal velocity (m/s)	0.0418	0.0824	0.145
Summer current speed (m/s)	0.000387	0.0245	0.201

8. Provide information on the spatial extent of the areas in *[species/population/DU]*'s range that are likely to have these habitat properties.

The spatial extent of eulachon distribution within the Fraser River has been well described by Levesque and Therriault (2011) and model results for the marine environment provide an indication of where eulachon are normally observed (Finney, unpublished data). DFO research surveys also provide an indication of the marine distribution of eulachon (Figures 8 and 9).

9. Identify the activities most likely to threaten the habitat properties that give the sites their value, and provide information on the extent and consequences of these activities.

Pickard and Marmorek (2007) describe a wide variety of activities that could threaten eulachon within freshwater. These include pollution (industrial effluents, sewage, and agricultural runoff), dredging activity, changes to the discharge patterns of rivers affecting the availability of suitable spawning substrates, debris from log handling and booming in rivers, shoreline construction (roads, dykes changing available spawning habitat), diversion and dams affecting water volume, temperature and sediment levels. However, there is limited information on the extent of these activities within the Fraser DU.

Activities that threaten eulachon habitat within the marine environment are primarily associated with bottom trawling and estuary alteration or development. Other activities would include marine transportation of oil, natural gas, or toxic chemicals.

10. Quantify how the biological function(s) that specific habitat feature(s) provide to the species varies with the state or amount of the habitat, including carrying capacity limits, if any.

It is not possible to quantify the biological functions of habitat features or carrying capacity limits with existing information.

11. Quantify the presence and extent of spatial configuration constraints, if any, such as connectivity, barriers to access, etc.

We are not aware of any constraints to the species for spawning within the Fraser River.

12. Provide advice on how much habitat of various qualities / properties exists at present.

We do not believe that habitat is limiting for eulachon within the Fraser River for spawning. Available information does not permit an estimate of the overall change in the Fraser River through dredging, foreshore alteration, etc. since pre-contact. We do not believe that the marine environment has been reduced although the available data on hypoxia within the area normally occupied by eulachon is incomplete.

13. Provide advice on the degree to which supply of suitable habitat meets the demands of the species both at present, and when the species reaches biologically based recovery targets for abundance and range and number of populations.

We do not believe that habitat is limiting the abundance of the species at this time. However, it is not possible to quantify the habitat requirements at the upper stock reference level with existing information.

14. Provide advice on feasibility of restoring habitat to higher values, if supply may not meet demand by the time recovery targets would be reached, in the context of all available options for achieving recovery targets for population size and range.

It is not possible to address this with existing information.

15. Provide advice on risks associated with habitat "allocation" decisions, if any options would be available at the time when specific areas are designated as Critical Habitat.

Not applicable.

16. Provide advice on the extent to which various threats can alter the quality and/or quantity of habitat that is available.

Pickard and Marmorek (2007), Gustafson et al. (2010) and Levesque and Therriault (2011) identify and comment on the impact of various threats to the quality of available habitat in a qualitative manner. It is not possible to advise specifically on the extent of these impacts except in a speculative sense.

Scope for Management to Facilitate Recovery of *[species/population/DU]*

17. Assess the probability that the recovery targets can be achieved under current rates of *[species/population/DU]* population dynamics parameters, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

Appendix 3 (Table 9a,b,c) indicates that there is a high probability that the Fraser eulachon population will increase over 4, 8, and 17 year time horizons but the extent of the increase decreases as the extent of in-river catch increases from 0.1 to 30 tonnes.

18. Quantify to the extent possible the magnitude of each major potential source of mortality identified in the pre-COSEWIC assessment, the COSEWIC Status Report, information from DFO sectors, and other sources.

Assuming that the marine indices of eulachon abundance are representative, and if the apparent low abundance of eulachon spawning in rivers is an accurate reflection (qualitative and quantitative) of their abundance in freshwater, then there must be a period during their lives when they are subject to intense mortality, either from predation, disease or anthropogenic factors.

The marine surveys usually occur between April and May and encounter eulachon that are too large to represent progeny hatched in the same year as the survey. Instead the eulachon captured at sea are at least one year old (probably about 14-16 months) or two years old (probably 26-28 months). The two-year-old eulachon constitute the majority of eulachon (by weight) and represent fish that probably will spawn in the next 8-10 months when they reach an age of 36 months. Therefore, given that both marine and freshwater indices of abundance were correct, then there must be a major source of mortality on eulachon between the ages of 26 and 36 months of age. If comparisons can be made between the offshore marine environment on the west coast of Vancouver Island and the in-river spawning in the Fraser, then the mortality during this time would be in excess of 90%. However, it is not possible to attribute this mortality to the particular threat sources identified.

Appendix 3 (Table 8) indicates that maximum sustainable yield for the Fraser River eulachon population is 112 tonnes yet estimated total mortality from all sources during the early to mid-1990s exceeded this value for a number of years. The bulk of the mortality appears to have been associated with bycatch in the shrimp trawl fishery.

19. Quantify to the extent possible the likelihood that the current quantity and quality of habitat is sufficient to allow population increase, and would be sufficient to support a population that has reached its recovery targets.

Although there are instances of habitat loss it does not appear that habitat loss is a limiting factor causing widespread population declines at this time. There is no evidence that available spawning habitat within the Fraser River has been reduced to the extent that it would limit population increases from the present low levels. Similarly, there is no evidence that the range of eulachon in the marine environment has been reduced as determined from their presence in DFO trawl surveys. However, as eulachon populations recovered there may be instances where habitat loss could inhibit or slow further recovery.

20. Assess to the extent possible the magnitude by which current threats to habitats have reduced habitat quantity and quality.

As above we conclude that habitat is not limiting for eulachon at this time when populations are a very low levels.

Scenarios for Mitigation and Alternative to Activities

21. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all feasible measures to minimize/mitigate the impacts of activities that are threats to the species and its habitat (Steps 18 and 20).

See mitigation section in the main text.

23. Using input from all DFO sectors and other sources as appropriate, develop an inventory of activities that could increase the productivity or survivorship parameters (Steps 3 and 17).

Most of these activities are described in the mitigation within the main text. The only other approach would be the artificial rearing of eulachon. Although technically feasible this would require expensive and time consuming research to devise a method of establishing the success of a hatchery approach. A method to identify the progeny reared and released from a hatchery would also be required. In effect, the only available methods involve marking (or tagging) the larvae and juveniles prior to release. Chemical tags/marks are available but the technology to apply and recover marks would need to be developed for eulachon. The approach would require at least 5-10 years of expensive, preliminary research and would cost millions of dollars, without a confirmed chance of success. In addition, the issue of disease in intensely reared marine fish would need to be addressed and solved.

24. Estimate, to the extent possible, the reduction in mortality rate expected by each of the mitigation measures in step 21 or alternatives in step 22 and the increase in productivity or survivorship associated with each measure in step 23.

It is not possible to determine the reductions in mortality or increases in productivity that might be expected from these proposed alternatives at this time.

25. Project expected population trajectory (and uncertainties) over three generations (or other biologically reasonable time), and to the time of reaching recovery targets when recovery is feasible; given mortality rates and productivities associated with specific scenarios identified for exploration (as above). Include scenarios which provide as high a probability of survivorship and recovery as possible for biologically realistic parameter values.

Appendix 3 (Figure 8) presents the expected population trajectory for Fraser River eulachon relative to the unfished biomass level through 2030 under a variety of small harvest scenarios.

26. Recommend parameter values for population productivity and starting mortality rates, and where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts of listing the species.

Appendix 3 (Table 6) presents some of the life history parameters that were used for the population reconstruction and alternative scenario development. The basis of the modeling approach is described in Appendix 3.

Allowable Harm Assessment

27. Evaluate maximum human-induced mortality which the species can sustain and not jeopardize survival or recovery of the species.

Appendix 3 (Table 8) indicates that the human-induced mortality consistent with maximum sustainable yield is 0.1 for the Fraser River eulachon population and would permit population maintenance. Mortality rates below this level would be consistent with population recovery. The current replacement level for the population is 29 tonnes, well below the level consistent with maximum sustainable yield of 112 tonnes.

APPENDIX 2 - RECOVERY POTENTIAL ASSESSMENT – CENTRAL PACIFIC COAST DU

<u>Assess current/recent species/ status</u>

1. Evaluate present *[species/population/DU]* status for abundance and range and number of populations

Key eulachon spawning rivers are the Kitimat, Kildala, Kemano, Kitlope and Kowesas in the Gardner Canal. In the Dean Canal the Bella Coola River is the major spawning river. In Rivers Inlet eulachon are known from the Wannock River, Kilbella and Clyak. The other two major rivers are the Kingcome River from Kingcome Inlet and the Klinaklini from Knight Inlet. There are about 20 more potential spawning rivers that were identified based on the density and lengths of eulachon larvae found in adjacent estuaries or inlets during ichthyoplankton surveys conducted in the Central Coast in 1994 and 1996-1997 (McCarter and Hay 1999). Others were noted by Moody (2008).

Other

There are no known confirmed spawning rivers on coastal islands including Haida Gwaii and Vancouver Island (Hay and McCarter 2000).

2. Evaluate recent species trajectory for abundance (i.e., numbers and biomass focusing on matures) and range and number of populations.

Abundance of eulachon in the Central Coast systems is variable with some such as the Bella Coola at all time low levels whereas others such as the Kingcome and Klinaklini Rivers appear to have moderate spawning runs in some years. Relative abundance is available from Moody (2008) and presented in Figures 28 and 29.

3. Estimate, to the extent that information allows, the current or recent life-history parameters for *[species/population/DU]* (total mortality, natural mortality, fecundity, maturity, recruitment, etc.) or reasonable surrogates; and associated uncertainties for all parameters.

Mortality

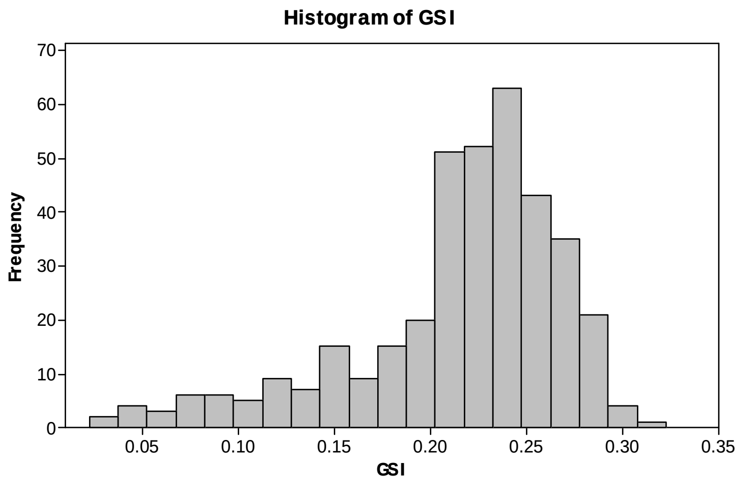
Eulachon are semelparous. It appears that most die after spawning at age of 36 months, but probably some spawn a year earlier and a year later, at age 24 and 48 months respectively.

Fecundity

All fecundity data were collected between 1993 and 1998. There are fewer than 100 measurements of fecundity from the combined rivers in the Central DU (Kitimat, Kemano and Bella Coola) and none from the Nass DU. There are over 500 measurements from the Fraser DU.

When fecundity is compared by the origin of the fish the more northern samples appear to have a slightly lower relative fecundity (eggs/gm) and absolute fecundity but this may partially reflect an error attributable to sampling. Fraser River fish were captured several days prior to spawning whereas some or most of the fish in the northern samples could have been actively spawning and already released some of their eggs. Therefore the fecundity data from the Fraser River probably is the most reliable to apply to all DU’s. This is explained further below.

The GSI (or ‘gonosomatic index’) is the proportion of total body weight made up of ovaries. When ripe, or actively spawning eulachon are captured there may be a risk of egg loss that cannot be detected during later analysis in a laboratory. Very low GSI estimates indicates probable loss of eggs, either from spawning or later when placed in containers during sampling efforts. Most of the low-GSI eulachon were from Northern rivers when eulachon were captured at time and places close to spawning grounds, whereas in the Fraser River most eulachon were captured prior to spawning.



Absolute and relative fecundity was determined for eulachon from the Central and Fraser DU’s. To avoid under-estimation related to loss of eggs the analyses were confined to fish that had a GSI of 0.18 or greater.

	Fecundity Mean	Rel Fecund Mean	Fecundity N	RelFecund N
Central	27700	599.0	41	41
Fraser	32208	787.2	512	512
All	31873	773.2	553	553

Sex ratios of individual samples can vary markedly but the composite ratios of all Fraser River fish is very close to an even split between males and females. Therefore, assuming that males weigh approximately the same as females the estimate of relative fecundity for the eulachon population (males and females) is 0.5 times the female estimate. For the Central coast this would be about 300 eggs/g and for the Fraser it would be about 390 eggs/g of eulachon weight.

Maturity

Eulachon are semelparous. It appears that most spawn at an age of 36 months, but probably some spawn a year earlier and a year later, at age 24 and 48 months respectively. Like other fish species in the North Pacific, there may be a latitudinal cline in age-at-maturity with fish in the southern part of the range spawning at younger ages (many at age 2 in the Columbia, Gustafson et al. 2010) and at slightly older ages in Alaskan rivers.

Recruitment

The age of 'recruitment' is uncertain but for eulachon the definition of recruitment depends on the context of the question. If recruitment can refer to the age when young eulachon join older eulachon in offshore (shelf) waters, then the answer could be as young as 3-6 months and as old as 18 months. Probably the exact age depends on the DU. If recruitment depends on the age when eulachon are captured by First Nation fisheries, then recruitment is identical to age-at-maturity.

4. Estimate expected population and distribution targets for recovery, according to DFO guidelines (DFO 2005).

Based on these guidelines, recovery could imply more widespread spawning with the lower reaches of all of the known eulachon bearing systems in the Central DU. DU-specific abundance targets have not been established but it may be possible to estimate population sizes that would support sustainable catches that approximate the combined First Nations and commercial catches of eulachon.

5. Project expected *[species/population/DU]* population trajectories over three generations (or other biologically reasonable time), and trajectories over time to the recovery target (if possible to achieve), given current *[species/population/DU]* population dynamics parameters and associated uncertainties using DFO guidelines on long-term projections (Shelton *et al.* 2007).

It is not possible to provide population projections with the available data for the Central DU.

6. Evaluate residence requirements for the species, if any.

Not applicable for eulachon.

Assess the Habitat Use of *[species/population/DU]*

7. Provide functional descriptions (as defined in DFO 2007b) of the properties of the aquatic habitat that *[species/population/DU]* needs for successful completion of all life-history stages.

The properties of the freshwater and marine habitats required by eulachon are described at length in Gustafson et al. (2010) and Levesque and Therriault (2011).

The characteristics of the freshwater environment have been well described but are variable whereas those for the marine environment are less clear. Finney (unpublished data) noted some of the variables that describe the marine areas where eulachon are normally observed:

Table B - 1. Minimum, median, and maximum values of the seven environmental variables at locations where eulachon were found.

Environmental variable	Minimum	Median	Maximum
Depth (m)	41	162	292
Slope (degrees)	0	0.29	7.1
Chlorophyll *a* concentration (ml/cm^3)	1.21	3.31	14.62
Summer salinity (psu)	31.37	33.73	34.04
Summer temperature (^{o}C)	5.11	6.25	9.13
Tidal velocity (m/s)	0.0418	0.0824	0.145
Summer current speed (m/s)	0.000387	0.0245	0.201

8. Provide information on the spatial extent of the areas in *[species/population/DU]*'s range that are likely to have these habitat properties.

The spatial extent of eulachon distribution within the Central Coast rivers has been described by Moody (2008) and Levesque and Therriault (2011) and model results for the marine environment provide an indication of where eulachon are normally observed (Finney, unpublished data). DFO research surveys also provide an indication of the marine distribution of eulachon (Figures 8 and 9).

9. Identify the activities most likely to threaten the habitat properties that give the sites their value, and provide information on the extent and consequences of these activities.

Pickard and Marmorek (2007) describe a wide variety of activities that could threaten eulachon within freshwater. These include pollution (industrial effluents, sewage, and agricultural runoff), dredging activity, changes to the discharge patterns of rivers affecting the availability of suitable spawning substrates, debris from log handling and booming in rivers, shoreline construction (roads, dykes changing available spawning habitat), diversion and dams affecting water volume, temperature and sediment levels. However, there is limited information on the extent of these activities within the Central DU.

Activities that threaten eulachon habitat within the marine environment are primarily associated with bottom trawling and estuary alteration or development. Other potential transient activities would include marine transportation of oil, natural gas, or toxic chemicals.

10. Quantify how the biological function(s) that specific habitat feature(s) provide to the species varies with the state or amount of the habitat, including carrying capacity limits, if any.

It is not possible to quantify the biological functions of habitat features or carrying capacity limits with existing information.

11. Quantify the presence and extent of spatial configuration constraints, if any, such as connectivity, barriers to access, etc.

We are not aware of any constraints to the species for spawning within the Central Coast systems.

12. Provide advice on how much habitat of various qualities / properties exists at present.

We do not believe that habitat is limiting within the Central Coast for eulachon spawning. Available information does not permit an estimate of the overall change in the Central Coast rivers through dredging, foreshore alteration, etc. since pre-contact. We do not believe that the marine environment has been reduced although the available data on hypoxia within the area normally occupied by eulachon is incomplete.

13. Provide advice on the degree to which supply of suitable habitat meets the demands of the species both at present, and when the species reaches biologically based recovery targets for abundance and range and number of populations.

We do not believe that habitat is limiting the abundance of the species at this time. However, it is not possible to quantify the habitat requirements at the upper stock reference level with existing information.

14. Provide advice on feasibility of restoring habitat to higher values, if supply may not meet demand by the time recovery targets would be reached, in the context of all available options for achieving recovery targets for population size and range.

It is not possible to address this with existing information.

15. Provide advice on risks associated with habitat "allocation" decisions, if any options would be available at the time when specific areas are designated as Critical Habitat.

Not applicable.

16. Provide advice on the extent to which various threats can alter the quality and/or quantity of habitat that is available.

Pickard and Marmorek (2007), Gustafson et al. (2010) and Levesque and Therriault (2011) identify and comment on the impact of various threats to the quality of available habitat in a qualitative manner. It is not possible to advise specifically on the extent of these impacts except in a speculative sense.

Scope for Management to Facilitate Recovery of *[species/population/DU]*

17. Assess the probability that the recovery targets can be achieved under current rates of *[species/population/DU]* population dynamics parameters, and how that probability would vary with different mortality (especially lower) and productivity (especially higher) parameters.

The available information on population dynamics parameters for the Central DU is inadequate to assess the probability of achieving proposed recovery targets.

18. Quantify to the extent possible the magnitude of each major potential source of mortality identified in the pre-COSEWIC assessment, the COSEWIC Status Report, information from DFO sectors, and other sources.

Assuming that the marine indices of eulachon abundance are representative, and if the apparent low abundance of eulachon spawning in rivers is an accurate reflection (qualitative and quantitative) of their abundance in freshwater, then there must be a period during their lives when they are subject to intense mortality, either from predation, disease or anthropogenic factors.

The marine surveys usually occur between April and May and encounter eulachon that are too large to represent progeny hatched in the same year as the survey. Instead the eulachon captured at sea are at least one year old (probably about 14-16 months) or two years old (probably 26-28 months). The two-year-old eulachon constitute the majority of eulachon (by weight) and represent fish that probably will spawn in the next 8-10 months when they reach an age of 36 months. Therefore, given that both marine and freshwater indices of abundance were correct, then there must be a major source of mortality on eulachon between the ages of 26 and 36 months of age. If comparisons can be made between the offshore marine environment on the west coast of Vancouver Island and the in-river spawning in the Fraser, then the mortality during this time would be in excess of 90%. However, it is not possible to attribute this mortality to the particular threat sources identified.

19. Quantify to the extent possible the likelihood that the current quantity and quality of habitat is sufficient to allow population increase, and would be sufficient to support a population that has reached its recovery targets.

Although there are instances of habitat loss it does not appear that habitat is a limiting factor causing widespread population declines at this time. There is no evidence that available spawning habitat within the Central Coast Rivers has been reduced to the extent that it would limit population increases from the present low levels. Similarly, there is no evidence that the range of eulachon in the marine environment has been reduced as determined from their presence in DFO trawl surveys. However, as eulachon populations recovered there may be instances where habitat loss could inhibit or slow further recovery.

20. Assess to the extent possible the magnitude by which current threats to habitats have reduced habitat quantity and quality.

As noted above we conclude that habitat is not limiting for eulachon at this time when population levels are very low.

Scenarios for Mitigation and Alternative to Activities

21. Using input from all DFO sectors and other sources as appropriate, develop an inventory of all feasible measures to minimize/mitigate the impacts of activities that are threats to the species and its habitat (Steps 18 and 20).

Mitigation measures are discussed in the main text.

26. Recommend parameter values for population productivity and starting mortality rates, and where necessary, specialized features of population models that would be required to allow exploration of additional scenarios as part of the assessment of economic, social, and cultural impacts of listing the species.

We do not have information on parameter values for determining population productivity for the Central DU at this time.

Allowable Harm Assessment

27. Evaluate maximum human-induced mortality which the species can sustain and not jeopardize survival or recovery of the species.

We are not able to determine the maximum human induced mortality that the eulachon populations in the Central DU can sustain at this time. Comparable analysis for the Fraser DU indicates that the fishing mortality rate that provides the maximum sustainable yield is 0.10 and could be lower for the Central DU given suspected lower productivity.

APPENDIX 3 - STOCK ASSESSMENT OF FRASER RIVER EULACHON (*THALEICHTHYS PACIFICUS*)

Prepared by Murdoch McAllister, PhD

1-156 West 14th Avenue,

Vancouver, B.C.

Abstract

An age-structured stock assessment model for Fraser River eulachon (*Thaleichthys pacificus*) was fitted to abundance index data using a Bayesian estimation framework. Bycatch of Fraser River eulachon in B.C.shrimp fisheries was accounted for by using shrimping effort in Fraser River eulachon designatable unit marine areas as a covariate for shrimping bycatch. Catch records from 1900 to 2009 were used to estimate exploitation rates from the Fraser River commercial fishery for eulachon. To enable parameter estimation, it was necessary to consider some alternative hypotheses for the ratio of the constant of proportionality (q) for the commercial gillnet and test fishery gillnet indices from the 1940s and 1990s, respectively. The population biomass (B) is scaled by the parameter q to each annual index of abundance (I), where I = q B. When q was estimated separately for the two gillnet indices, the probability intervals (PIs) for quantities of interest were very wide. For example the 80% PI for stock biomass in 2011 to average unfished biomass (depletion) ranged from about 9% to 90%. Under some alternative fixed assumptions about this ratio, the posterior median value for depletion ranged from about 6% to 11% and the reference case probability interval for depletion ranged from 2 to 15%. It was also necessary to estimate deviates from the Ricker stock recruit function for years from the early 1990s because the model could not fit the sharp correlated variation in the abundance indices after 1995. The correlation coefficient for the larval and gillnet test fishery indices was quite high (0.89) indicating that the two indices appeared to be sufficiently consistent in trends and annual deviates and plausible as indices of abundance for the population of interest. Posterior median values for fishing mortality rates suggested that the commercial fishery exploitation rates exceed the exploitation rate at MSY (U_{msy}) in the 1950s and early 1960s and that the shrimping mortality rates exceed the U_{msy} in the mid-1990s and combined with the commercial fishery were up to about 1.6 of the U_{msy}. However, the commercial fishery ended in 1997 and shrimping effort declined after 2000 to about 5% of the maximum effort in 1995 after 2010. The substantial drop in abundance in 2005, thus occurred well after shrimping and commercial fishing had dropped to very low levels and suggest that some other sources of mortality are responsible for the severe decline in Fraser River eulachon in 2005 and continued low abundance. Stock recruit deviates for 1992-2011 were found to be uncorrelated with several different covariates including Pacific hake abundance in B.C. waters, zooplankton prey species *E. pacifica* and *T. spinifera*, and the Pacific Decadal Oscillation Index (PDO) (for lags of 0-3 yr all P-values > 0.1). With the large increase in the larval index from 4 to 39 t between 2010 and 2011, the model suggests that surplus production could have increased to about 30 t in 2011. Projections up to three generations (18 years) under annual catch removals ranging from 0.1 t to 30 t and current shrimping effort levels were carried out for the three cycle lines, 2009, 2010 and 2011. An annual catch removal of 30 t yr^{-1} over three generations (18 yr) for the 2011 cycle line gave probabilities of population increase and exceeding 20% of average unfished biomass (B_0) of 57% and 51%, respectively. The 2009 cycle line was considerably less resilient. A 10 t constant annual catch over three generations gave values for these probabilities of 60% and 52%, respectively. The 2010 cycle line was the weakest and a 5 t constant annual catch after three generations gave values for these probabilities of 63 % and 51%, respectively. These results suggest that there may be some

scope for the resumption of the Fraser River gillnet test fishery for eulachon to improve monitoring of abundance and that harvest levels to achieve stock recovery may be highly dependent on the cycle line.

Introduction

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has designated Fraser River eulachon (*Thaleichthys pacificus*) as an endangered species due to perceived large drops in abundance over the last few decades. Bryan and Christensen (unpublished report of the UBC Fisheries Centre) attempted to fit an age-structured population dynamics model to abundance index data for this population to quantitatively evaluate stock status. The model formulated was age-structured, allowed for iteroparity and was found to produce reliable estimates of population parameters and stock status when fitted to simulated data. However, Bryan and Christensen (unpublished report of the UBC Fisheries Centre) were unable to reliably evaluate actual stock status using their model due to numerical difficulties when fitting their model to the actual data for Fraser River eulachon. Moreover, the approach did not account for the potential impact of bycatch of eulachon in B.C. shrimp fisheries.

To enable estimation of parameters using a fisheries population dynamics model, it is often necessary for abundance indices for a given population to show some decreases following observed catch removals. For each of the abundance indices for Fraser River eulachon this is not the case. The commercial gillnet catch per unit effort index in the 1940s increased as catches peaked. For 1995-2005, the gillnet test fishery and larval indices decreased after catches and fishing intensity sharply decreased. A second condition that could permit estimation when fitting a model to abundance indices relates to the constant of proportionality (q) that scales the model predicted abundance (B) to an abundance index (I), i.e. $I = q B$. Estimation could also be made possible should the values for q for the 1940s and 1990s gillnet indices be considered to be the same or similar. While there could be many reasons for differences, similarity in q between these indices could be plausible because the gillnet gear applied in both instances was nearly identical and both indices were derived from data obtained throughout each year's spawning run. Bryan and Christensen (unpublished report of the UBC Fisheries Centre) however assumed that q for the 1940s and the 1990s gillnet indices were different and unrelated.

In this report I have taken an alternative approach to Bryan and Christensen (unpublished report of the UBC Fisheries Centre) in formulating model structure and fitting the model to data for Fraser River eulachon. To facilitate estimation of population dynamics model parameters, I have considered some alternative hypotheses for the relatedness in q between the Fraser River gillnet catch per unit effort time series in the 1940s and the 1990s. I have also developed my stock assessment model to evaluate the potential impacts of bycatch of Fraser River eulachon in B.C. shrimp fisheries.

In this report, I have compiled Fraser River catch, B.C. shrimping effort and Fraser River relative abundance index data and analyzed these data using an age-structured population dynamics model. The model projected the population from lightly exploited conditions in 1900 to 2011 and was fitted to the relative abundance index data using a Bayesian estimation framework. The ratio of stock biomass in recent years to average unfished stock size and the roles in the decline of the stock of commercial harvests and bycatch in B.C. shrimp trawl fisheries were evaluated. Deviates in annual recruitment from the stock recruit function were estimated for years from 1992 to 2011. Projections were carried out to evaluate the potential consequences of alternative future scenarios for harvest removals of mature fish in the lower Fraser River assuming that shrimping effort stays at its current low level (i.e. at 5% of the maximum in 1996).

Data

Records of Fraser River Eulachon Catch

The annual catch biomass of mature eulachon in the Fraser River commercial fishery for eulachon from 1900 to 2009 was obtained from Fisheries and Oceans Canada records provided by C. Levesque and J. Schweigert (Table 1). In most years after 1996 catches were close to zero due to the closure of the commercial fishery in 1997. Records of aboriginal harvest were not available and thus were not included in this analysis. Rather than assuming that the Fraser River harvest was zero in years with recorded zero harvest, a value of 0.1 tons was applied. Also it is noted that an error in the catch records initially supplied for the years 1941 to 1954 was detected. Values initially provided were identical to Ricker et al.'s (1954) catch per unit effort values. It is possible that this error could have gone unnoticed in some previous studies. These incorrect catch values were replaced with the total commercial catch records for these years in Ricker et al. (1954) since it was believed that these values were the most accurate records that were available.

Reconstruction of shrimping effort on the B.C. coast

Effort data for the B.C. shrimp trawl fishery for years 1987 to present were obtained from the SHTRAWL database maintained by the Shellfish Data Unit, Pacific Biological Station, Nanaimo, B.C. Historical effort data from 1953 to 1986 were obtained from the British Columbia Catch Statistics report produced by Fisheries and Oceans Canada. The 1953 to 1986 effort data were based on sales slip reports and the 1987 to present based on logbook reports. Data on shrimp effort by gear type are only available for year 1987 to present. Two different roll-ups of the shrimp effort data were used in the analysis. The first data roll-up (source: D. Rutherford) represents the combined shrimping effort from beam and otter trawl gears in management areas found by genetic analyses (Beacham et al. 2005) to have included Fraser DU eulachon (Figure 1, Table 2). The combined series of shrimping effort ranges from 1953 to 2010. This shows some low to moderate effort in the 1960s a low period in the 1970s and a substantial increase to a peak in the mid 1990s. Shrimping effort on the Fraser River eulachon DU drops to low levels after the year 2000. This combined shrimping effort time series was applied in the stock reduction analysis as a covariate for eulachon fishing mortality rates in B.C. shrimp fisheries (see below).

The second data roll-up of shrimping effort data (provided by C. Levesque), provided detailed records of shrimping effort by gear type (i.e. otter trawl and beam trawl) and management areas for the years 1987 to the present. Some of these records for each area include effort not differentiated by gear type. The records undifferentiated by gear type for each area were split into effort by gear type for each area by applying the average percentage of recorded effort by gear type in the period from 1987-2009. Values by area were imputed using the combined effort time series from the first data roll-up. For years prior to 1987 to determine effort by gear the following method was applied. The effort in each year divided by the maximum of the first data roll-up (Rutherford effort series) ($E_{R,y}$/ $E_{R,max}$) was first computed. The maximum effort for a given area and gear type in the Levesque series from years 1987-2009 was multiplied by ($E_{R,y}$/ $E_{R,max}$) to impute the effort for each gear and area in years from 1953-1986. The compiled imputed values for shrimping effort by gear type and area are also presented in Table 2 and Figure 1.

Eulachon bycatch in B.C. shrimp trawl fisheries

I used the eulachon bycatch estimates for each shrimp trawl gear type in each fishery management area from Hay et al. (1999a) for May-December 1997. These estimates were obtained by analysis of bycatch records made available by hail-ins in 1997 from May - December. Approximations of the bycatch of the Fraser River stock of eulachon in each management area were obtained with the use of the estimates of eulachon stock composition in shrimp trawl bycatch that were provided in Beacham et al. (2005) for the year nearest to the bycatch estimate, i.e. 2000 (Table 3). The estimates of the total and Fraser River eulachon bycatch for 1997 obtained using the stock composition estimates are provided in Table 4. The total estimated Fraser River eulachon bycatch summed across areas and gears in 1997 was applied to estimate the catchability coefficient for bycatch in B.C. shrimp fisheries. Additional estimates of eulachon bycatch in B.C. shrimp fisheries for 1997-1999 are provided in Olsen et al. (2000) but we were unable to resolve some discrepancies in these two estimates. We chose to conduct our analysis using the Hay estimate and followed this with sensitivity runs using the Olsen estimates.

Indices of relative abundance for Fraser River Eulachon

I have compiled three different time series of relative abundance for the Fraser River eulachon spawning population. These included the Fraser River gillnet commercial fishery catch rate (CPUE) records for 1941-1953 made available in Ricker et al. (1954). The units for these CPUE are provided as the average catch of eulachon in pounds per hour of fishing by 100 square fathoms of net. The size of mesh varied from about 1 inch to 1 ¾ inches and nets were commonly about 200 meshes deep (Ricker et al. 1954). These data show considerable inter-annual variability but no apparent trend (Table 5).

The Fraser River eulachon gillnet test fishery from 1995 to 2005 also provided estimates of total catches and days fished. The test fishery gillnets were similar to the gillnet gear used in the commercial Fraser River gillnet fishery for eulachon. The nets were 380 meshes deep, had a mesh size of 1.25 inches, and were 50 fathoms long (Hay et al. 2003). The test fishery vessel fished off of New Westminster on the low slack tide. The soak time was for 15 minutes. The test fishery starting in late March or early April depending on when the eulachon showed up and fished every day until the eulachon spawning stopped in early to mid-May. I converted the total catch per year obtained in the gillnet test fishery to the same units of pounds caught per hour of fishing by 100 square fathoms of net. To obtain an estimate of the depth of the test gillnet in fathoms I used the estimate of 2.2 fathoms net depth per 1.25 inch mesh of a 200 mesh net provided in Ricker et al. (1954). I multiplied the estimate of fathoms per mesh by the 380 meshes in the test fishery gillnet to obtain a depth of 4.18 fathoms. The total area of the gillnet was computed as 209 fathoms^2. The pounds caught per year was computed as the product of the number of eulachon caught per year in the gillnet test fishery and the average mass in grams of the eulachon sampled from the test fishery catches. In 1995 there was no estimate of average fish size. Thus for 1995, the average size was imputed from the average of the sample means for mean body size from 1995-1998 and 2000-2004. The hours fished each year was computed by multiplying the number of days fished per year with the soak duration of 0.25 hours for each day fished.

The average annual gillnet test fishery CPUE values are provided in Table 5. These show a net decline over the period from 1995-2005. The lowest CPUE occurs in 2005 with more than a 10-fold drop in CPUE occurring from 2004 to 2005. The average of the CPUE from the 1940s and 1950s was approximately 2.6 times higher than the average gillnet test fishery CPUE from 1995-2005. While the average values for the constant of proportionality, q, between Fraser River eulachon spawning stock biomass and the CPUE from the commercial gillnet fishery and the test gillnet fishery will be different, it is likely that they are similar given that the gear used was very similar and both the commercial and test fisheries operated over most weeks of each year's spawning run. While the catch rates of commercial fishermen may be higher due to targeting, there are other factors that could make the test fishing gear more efficient. For example, the net material in the 1940s was cotton and that used in the 1990s and 2000s was monofilament which may be more efficient than cotton. Moreover, from 1995-2005, especially in the later years, there was either no or very little commercial fishing effort. Catch rates of gillnets may be less when there is considerable fishing activity on the water.

The egg and larval survey estimate of Fraser River spawning stock biomass from 1995-2010 is also used as a relative abundance index (Table 5). This shows a progressive decline from 300, 1900 and 74 tons in 1995-1997 to 10, 14 and 4 tons in 2008-2010 and an increase to 31 tons in 2011. For the years where both the larval index and the gillnet test fishery index are available, there is a strong positive correlation of 0.89. This supports the interpretation that both of the indices have tracked spawning stock biomass in the period.

Methods

An age structured model with a Ricker stock-recruit function was fitted to the relative abundance indices using a stock reduction analysis estimation framework (Kimura and Tagart 1982; Walters et al. 2006). The Sampling/Importance Resampling (SIR) was employed to obtain posterior distributions for model parameters and other quantities of interest (McAllister et al. 1994). Clarke et al. (2007) conclude from their analysis of otilith microchemistry in Fraser River eulachon that this population is predominantly semelparous. Clarke et al. (2007) concluded that all mature fish were three years of age based on two pieces of evidence. First, only two barium annuli were observed in all otiliths sampled from mature Fraser River eulachon. As sample size was relatively small (i.e. otoliths from 17 fish), it is possible that other ages of maturity exist, but the relative frequency of individuals with other ages of maturity could be expected to be quite small and ignoring them can be expected to be of little consequence in this analysis. Clarke et al. (2007) also based their conclusions that the predominant age of maturity is three years on the existence of only two length modes in all West coast Vancouver Island samples from shrimp trawl bycatch of eulachon. The model applied thus assumes semelparity and a single age of maturity at age three years. Life history parameter estimates are shown in Table 6. This assumption creates three separate cycle lines analogous to the even and odd year lines for pink salmon. Due to differences in harvesting rates between the cycle lines across the three cycle lines, this could give rise to apparent dominance and sub-dominance in the three cycle lines.

Initial Conditions

The biomass of unfished three year old recruits (R_0), the number of age 1 recruits ($N_{0,1}$), and spawner biomass (S_0) predicted in the first year is given by:

$$R_0 = b_i \beta$$

$$S_0 = R_0$$

$$N_{0,1} = R_0 \phi$$

$$\phi = \gamma \frac{l_1}{l_3}$$

$$\gamma = \frac{1}{m_3 * 1000}$$

$$l_a = \exp(-(a-1))$$

where

b_i is the ratio of initial recruited mature biomass to long-term average unfished mature recruited stock biomass.

β is the long-term average unfished mature stock biomass.

ϕ is the ratio of the number of average unfished age 1 recruits per ton of average unfished mature stock biomass at the beginning of the third year of life.

γ is the average number of mature fish per ton of mature fish at the beginning of the third year of life.

m_3 is the mass in grams of a mature fish at the beginning of the third year of life.

l_a is the survivorship of fish to age *a* from age 1 year.

Population dynamics equations for years after the initial year

The predicted number of age 1 recruits in year *y* + 1 produced from spawning stock biomass S_y in year *y* is obtained from:

$$N_{y+1,1} = \phi\, S_y \exp\left(\alpha\left(1 - \frac{S_y}{\beta}\right) + \varepsilon_y\right)$$

where ε_y is the recruitment anomaly in year y. I assumed that ε_y was normally distributed with a mean of zero and applied a prior standard deviation of 1, a relatively high though not uncommon value for the prior standard deviation in recruitment anomalies (e.g. Francis 1992). Due to the paucity of data, we fixed ε_y at zero for years up to 1992 and estimated ε_y for years 1993-2011. In an earlier set of analyses ε_y were fixed for years prior to 1938, and 1951-1992 and estimated for the years 1939-1951 and 1993-2008. However, this latter option frequently led to indeterminacy in the approximation of posterior distributions and thus had to be abandoned.

The number of immature age 2 fish in year y is given by:

$$N_{2,y} = N_{1,y-1} \exp\left(-\left(M + v_1 F_{1,y-1}\right)\right)$$

$$F_{1,y} = \sum_{i=1}^{n_s} g_i E_{i,y}$$

where

$F_{1,y}$ is the total bycatch fishing mortality rate in year y in B.C. shrimp fisheries;

g_i is the catchability coefficient for immature Fraser River eulachon in shrimp fishery i;

v_a is the vulnerability of age group a to the shrimp fishery;

$E_{i,y}$ is the effort of shrimp fishery i in year y where a shrimp fishery is defined by a combination of a given coastal area or region and shrimp trawl gear type.

Age 3 spawner biomass in year y is given by:

$$S_y = m_3\, N_{2,y-1} \exp\left(-\left(M + v_2 F_{1,y-1}\right)\right) - C_{2,y}$$

where

m_3 is the mass of age 3 fish,

$C_{2,y}$ is the Fraser River commercial gillnet catch biomass of eulachon in year y.

Vulnerability at age to the shrimp trawl fishery was fixed at 1 for both ages. See below for the sensitivity analyses on this parameter.

The spawner abundance that gives maximum sustainable yield (S_{MSY}) is approximated (Hilborn and Walters 1992) by:

$$S_{MSY} = \beta\ (0.5 - 0.07 * \alpha)$$

Likelihood functions and prior probability distributions

The log likelihood function of the relative abundance data was obtained from a lognormal density function:

$$\mathrm{LogLik}(I_{j,y}) = c_{j,y} - \ln(I_{j,y} / (q_j S_y))^2 / (2\ \sigma_j^2))$$

where

$I_{j,y}$ is the index of abundance for series j in year y,

q_j is the constant of proportionality for index j

$c_{j,y}$ is a likelihood function constant that is independent of the estimated parameters.

σ_j is the standard deviation in the deviation in the natural logarithm of the index and its model predicted value for series j.

Fixed values of σ_j were applied and the values were obtained by iterative re-weighting whereby in each iteration a fixed set of values was applied and the empirical estimates obtained using the fixed values were then adjusted upwards slightly and reentered as fixed values in the maximum posterior mode estimation. The fixed values applied and the empirical estimates obtained from iterative re-weighting for the reference case run are shown in Table 7. A non-informative prior was applied for q_j, i.e. uniform over the natural logarithm of q_j. The approximation for the marginal posterior result from Walters and Ludwig (1994) was applied to make the computation of marginal posteriors for quantities more efficient.

Three different approaches were taken to fit the population dynamics model to the commercial and gillnet test fishery CPUE data. For model parsimony, the reference case approach assumed that the catchability for these two gears was identical. In the second approach some different fixed values for the difference in catchability were applied. In the third approach, an informative prior was placed on the difference in catchability between the two series. In the fourth approach, the constants of proportionality q_j for these two series were considered to be unrelated and estimated as two separate parameters as was done in Bryan and Christensen (unpublished report of the UBC Fisheries Centre).

The Fraser River eulachon bycatch of fish of age a in shrimp fishery r in 1997 is predicted by:

$$C_{r,a,y} = \left(m_a N_{a,y}\right)\frac{v_a F_{1,r,y}}{Z_{r,a,y}}\left(1 - \exp\left(-Z_{r,a,y}\right)\right)$$

$$Z_{r,a,y} = M + v_a F_{1,r,y}$$

$$C_{r,y} = C_{r,1,y} + C_{r,2,y}$$

where $F_{1,r,y}$ is the bycatch fishing mortality rate in shrimp fishery r. The value for the catchability coefficient for each shrimp fishery is estimated using a likelihood function for the empirically derived estimate of shrimp bycatch in 1997. The partial log likelihood for each shrimp bycatch estimate for Fraser River eulachon in each shrimp fishery is given by:

$LogLik(C_{y,1,r(o)}) = c_{y,1,r} - ln(C_{y,1,r(o)} / (C_{y,1,r}))^2 / (2\ \sigma_r^2))$

where $c_{y,1,r}$ is a constant for shrimp fishery *r* that is independent of the estimated parameters, and

$C_{y,1,r(o)}$ and $C_{y,1,r}$ are the observed and model predicted bycatch of Fraser River eulachon in year y and shrimp fishery r.

We applied a prior distribution for the α parameter based on the mean and standard deviation in values for α in Myers et al. (1999) for anadromous semelparous species. The only species for which both mean values and cross population standard deviations were available were chum, pink and sockeye salmon. Stock-recruit datasets for smelt-like fishes were obtained from web-linked sources for three additional fish stocks. The mean value for α across the six stocks was 1.1 and the cross population variance in α was 0.54. The prior for B_0 was uniform over the natural logarithm of B_0.

The negative log of the prior density function for α, B_0 and ε_y was obtained from:

$$-\ln(\text{prior}) = c_{\text{prior}} + \frac{(\alpha - \mu_\alpha)^2}{2\sigma_\alpha^2} + \sum_{y=1992}^{2010} \frac{(\varepsilon_y)^2}{2\sigma_\varepsilon^2} + \ln(B_0)$$

where

μ_α is the prior mean for α,

σ_α^2 is the prior variance for α, and

σ_ε^2 is the prior variance for the recruitment anomalies.

A non-informative prior was applied for g_i, i.e. exponential for each parameter g_i, with the coefficient for each density function being the shrimping effort in the year (or year and area) of the bycatch observation (Stanley et al. 2009). Constraints were placed on the stock biomass and fishing mortality rate coefficients to prevent the taking of the log of zero or non-negative numbers within the computer model.

Reference Case Stock Assessment Model

The reference case stock assessment model utilizes the most credible set of model inputs and structures, given the available options. The reference case for this stock assessment includes the following:

The standard deviation in log annual stock-recruit function deviates is to be set at 0.8, to account for uncertainty in stock dynamics processes. This was the minimum value that enabled the modeled population biomass to follow the abrupt trends in the test fishery gillnet and larval survey indices from 1995-2011.

Non-informative priors for *q* are to be applied due to a paucity of expert judgment on the alternative values for factors that scale swept area biomass estimates to total population biomass.

A uniform prior on the natural logarithm of B_0 was the base case prior for B_0; this for example assigns equal credibility to values for B_0 between 100 and 1000 tons as between 1000 and 10000 tons.

Positive lag 1 autocorrelation in process error deviates set to 0.5 and starting to be simulated in 2011, the first year for which there is no information in the data about historic process error. The autocorrelation coefficient was computed from the posterior median deviates for years since 1992 up to 2010 and found to be very small at only 0.33, despite the large negative deviates in the last few years. The presumed value of 0.5 though larger than the empirical estimate would appear to be within the upper bounds of plausibility.

In summary the reference case has the following specifications:

Prior mean α = 1.1, prior standard deviation (SD) α = 0.74.

Three stock trend indices:

1941-1954 Fraser River commercial gillnet CPUE,

1995-2005 Fraser River test fishery gillnet CPUE.

1995-2011 Fraser River larval survey index of spawner abundance.

The value for the constant of proportionality for the two gillnet indices is the same.

The deviation between observed and predicted Fraser River eulachon bycatch value for 1997 is treated as lognormal in the estimation of the coefficient, *g*, used to impute historic bycatch from historic shrimp fishing effort with σ_s set at 0.1.

The Ricker stock-recruit function is applied.

The standard deviation in the natural logarithm of stock recruit deviates, σ_r = 0.8.

Prior mean value for B_{1900}/ B_0 = 1.0

Non-informative priors for *q* are applied.

The lag 1 autocorrelation starts in 2011 and the autocorrelation coefficient ρ has a value of 0.5.

The value for σ_j for abundance indices obtained by iterative reweighting.

Evaluation of sensitivity of results to alternative inputs and assumptions

As there exists considerable uncertainty over several of the model inputs and assumptions, numerous evaluations of the sensitivity of model results to several inputs and assumptions were carried out. These include the following:

Prior for Ricker alpha – Prior means were set at 33% lower and 33% higher than the reference case prior mean.

Initial stock size - The prior mean for the ratio of initial stock size to B_0 was adjusted 33% lower and 33% higher.

Historic catches in the Fraser River – The time series of historic eulachon catches in the Fraser River were adjusted 33% lower and 33% higher.

Assumptions about the difference in catchability between the commercial and test fishery gillnet CPUE – The ratio of q for the gillnet test fishery CPUE was set as 33% higher and 33% lower than the reference value of 1. In a third analysis, the ratio of q between these two CPUE series was estimated with a prior mean of 1 and a prior standard deviation of 0.1. In a fourth analysis, the two CPUE series were treated as separate abundance indices and their q's were estimated separately in the same population dynamics model.

Extent of recruitment anomalies – The standard deviation in stock recruit deviates was set at 0.6 and then 1.0.

Vulnerability of age 1 fish to shrimping – The vulnerability of age 1 to shrimping becoming shrimp bycatch was first assumed to be 50% of that of age 2, and then 25% of that of age 2.

Influence of apparent outliers – The 1996 larval index value was removed from one analysis and this index and the 1996 gillnet test fishery index was removed to evaluate the extent to which these large outliers have influenced the estimation of current stock status.

The magnitude of eulachon bycatch in 1997 – The presumed observed eulachon bycatch value in 1997 was changed from Hay et al.'s estimate to Olsen et al.'s (2000) estimate. The value was also increased to 1.33, 2, 3 and 4 times Hay et al.'s estimate.

The value for the autocorrelation coefficient in future deviates from the stock-recruit function - To evaluate the impact on stock status and projection results, the autocorrelation coefficient was set to zero in one run. In two additional runs, the value was again set at 0.5 but the initial year in which the autocorrelation was turned on was set at 2009, and then 2008. The second strongest negative recruitment deviate of -1.23 occurred in 2008. By setting the autocorrelation to start in 2008, this enables an evaluation of the impact on projection results of linking future deviates to the most strongly negative deviate within the last few years.

See Table 9 for further details on the sensitivity analyses.

Bayes factor is the ratio of the probability of the data for an alternative model (e.g. for the low B_{1918}/K case) to the probability of the same data for the reference case model. We computed Bayes factors for each alternative model run referenced to the reference case run to indicate the relative plausibility of the different model runs when different models or models with different priors were fitted to the same data. The average of the importance function for each model run was used as an approximation of the probability of the data for each model given the model (Kass and Raftery 1995; McAllister and Kirchner 2002).

Projections

Under the reference case analysis projections of alternative constant catch policy options were carried out under the presumption that the 2010 levels of shrimping effort will persist into the future. The 2010 effort was about 5% of the maximum effort in 1996. The stock was projected six generations, i.e. 18 years, into the future.

Results

An initial attempt was made to fit a deterministic Ricker model to the abundance indices (results not shown). This led to very poor fits to the Fraser River Gillnet test fishery and larval abundance indices with the model predicting either stable stock size or increases in the last decade while both indices show marked decreases in the past decade (Table 5). The approach of considering the constant of proportionality for the two gillnet CPUE time series as unrelated was also tried as was done in a recent attempt at fitting a population dynamics model to Fraser River eulachon (Bryan and Christensen unpublished report of the UBC Fisheries Centre). The results obtained from my analysis confirmed that unless hypotheses are considered about the degree of similarity in q for the two gillnet CPUE series, stock status results obtained from fitting a population dynamics model to data will remain highly uncertain with extremely wide probability intervals. See below for further details.

Attempts were made to free up the entire time series of stock-recruit deviates from 1900 to 2011. However, it was not possible to find a numerically stable solution in the time available. Therefore, in the reference case model, annual recruitment anomalies were estimated from 1992-2010 only, and the value for σ_r was increased until the model predicted biomass closely followed the trends in the two abundance index data series for 1995-2011 (Figs 2 and 3). Several very strong negative recruitment anomalies were estimated for years from the mid-1990s to 2008 (Fig. 4) and these enabled the model to fit the marked declines in the Fraser river gillnet test fishery and larval index data since the mid-1990s.

The high degree of variation in the indices from 1995-2011, made Bayesian importance sampling highly inefficient and difficult to get to run. Over a period of about five months of trials, a numerically reliable approach was developed but the SIR algorithm still required fairly long runs of three to five hours. 36 million draws were taken from the importance function applied in SIR. The diagnostics applied indicated that the posterior approximations were quite stable. In the reference case, for example, the maximum weight that any one draw took up was about 0.8% of the posterior distributions obtained.

The marginal posterior distributions for model parameters showed considerable updating from their prior distributions (Fig. 5). Posterior distributions for model parameters and key variables of interest still yet showed moderate amounts of uncertainty (Fig. 5, 6, Table 8). The posterior median estimate of average unfished stock size was about 2500 tons (80% probability interval (PI): 1200, 5000 t) (Fig. 5, Table 8). Hereon, the posterior median is taken as the estimate and 80% probability intervals are shown in parentheses. The estimate of 0.19 (0.04, 0.51) for the maximum rate of increase parameter, α, was considerably lower than the prior mean of 1.1 (Fig. 5, Table 8). This resulted in a low estimate for the fishing mortality rate at MSY (F_{msy}) of 0.10 (0.02, 0.27) and relatively low value for MSY at 112 t (34, 309 t) and relatively high value for B_{msy}/B_0 of about 0.487 (0.464, 0.497) (Table 8). The plotted stock recruit curve from the posterior modal estimates shows relatively little recruitment compensation and low harvest rate at MSY (Fig. 7).

The assumption of semelparity with a strict age at maturity of three years creates three independent cycle lines of Fraser River eulachon. The model predicts some apparent cycling (i.e. persistence of stronger and weaker lines) after the 1950s due to the large interannual variability in catches in these decades and the persistence of consistently small catches for the spawning line starting in 1958 (Fig. 2). As there are no relative abundance data between the mid-1950s and mid-1990s, this cycling could be an artifact of model structure (e.g. assumption of semelparity when in fact there could be some iteroparity which may tend to reduce interannual variability in spawning stock biomass (SSB)) and lack of relative abundance data over this period. In the 1990s, the cycling was diminished partly due to the increase in bycatch mortality rates from shrimping which simultaneously takes two lines and lack of cycling seen in the Fraser river gillnet test fishery and larval abundance indices for years 2000 and after (Fig. 2, 3). In the last three years, i.e. 2009-2011, stock biomass for each line is estimated at 141 t (44, 537t), 79 t (28, 212t) and 155 t (53, 437t) and stock biomass to unfished biomass values of 6% (2, 21%), 3 (1, 8%) and 6% (2, 15%) (Fig. 6, Table 8).

The commercial fishing mortality rates exceeded the MSY fishing mortality rate a few times in the 1950s and early 1960s (Figure 8). Since the fishery closed in 1997, the fishing mortality rates have diminished to close to zero since then. The bycatch mortality rates in the shrimp fisheries increased to low levels in the 1960s. With the large increase in shrimping effort in the Fraser River DU areas in the 1990s (Fig. 1) bycatch mortality rates far exceeded the commercial fishery mortality rates and MSY fishing mortality rate in the mid-1990s (Figure 8). The bycatch mortality rates peaked at about 0.30 yr^{-1} in the 1990s and since 2000 have diminished to very low levels as shrimping effort declined. With the largest bycatch values, the West coast Vancouver Island and Central Coast Otter trawling have contributed most to the bycatch mortality rates (Table 4).

About 90% and higher posterior probability for SSB is less than 20% of B_0 in all three of the most recent years to 2011 (Figs 2, 3, 6b, 9, Table 8). The 2011 replacement yield appears fairly substantial at 29 t (6, 121 t) (Table 8), indicating some potential for the population to increase in coming years (Fig. 6). This was supported by the substantial increase in the larval index from 4 to 39 t between 2010 and 2011. With very small catches applied in the model for the last decade, the marginal posteriors for catch relative to replacement yield and fishing mortality rate relative to F_{msy} show that most of the probability is well below 1% (Fig. 6).

Projections

With the median replacement yield in 2011 being about 29 t (Table 8), stock projections with annual catch removals of up to 30 tons for this cycle line gave no less than 57% probability of the stock increasing above the 2011 levels (Table 9a). After 18 years or six generations there was a 51% probability that the stock would exceed 20% of B_0 under 30t catch removals. Lower catch levels resulted in higher probabilities of increasing stock size and exceeding 20% B_0 within three generations. The 2010 cycle line was lower in abundance than the other two cycle lines in both 2009 and 2011. Thus, for example, catch removals of only 5t gave a 63% chance of population increase and a 51% probability of exceeding 20% of B_0 within three generations (Table 9b). The 2009 cycle line was also considerably lower in abundance than the 2011 cycle line and catch removals of 10 t yr^{-1} gave a 52% chance of increase and a 60% chance of exceeding B_0 within 3 generations (Table 9c). Thus the different cycle lines showed very different responses to the different catch removal options considered (Fig. 8).

Sensitivity analyses

Of the numerous alternative model runs carried out, only a few of them gave results on stock status different from the reference case run (Tables 10, 11). When it was assumed that the constant of proportionality (*q*) for the test fishery gillnet index was 67% of the commercial fishery index in the 1940s, the median value for B_{2011}/ B_0 increased from 6% to 11%. When it was assumed that q for the test fishery was 1.33 times higher than that for the commercial index, the median value for B_{2011}/ B_0 dropped to 4%. When the q for the gillnet test fishery and commercial CPUE indices were estimated separately, the marginal posterior for B_{2011}/ B_0 increased to 33%. However, the 80% probability interval for this quantity changed from 2 to 15% in the reference case to 9 to 88%. The very wide probability interval for stock status under the run in which q's for the three indices were estimated separately supports the presumption that it is necessary to treat the q's from the two gillnet indices as related when fitting the stock assessment model to the abundance index data. When a prior was placed on the ratio of q's for the two gillnet indices, the probability intervals for most quantities, e.g. B_0, B_{msy}, alpha parameter, and B_{2011}/ B_0, were considerably wider than the reference case values as expected. The median value for all quantities, e.g. for B_{2011}/ B_0 at 0.07 (0.03, 0.24), were also similar to the reference case values as expected. Other sensitivity analyses on issues that gave rise to considerable discussion showed that stock status results were insensitive to plausible alternative settings to the reference case ones. For example applying the 1997 shrimp bycatch value from the Olsen et al. (2000) study increased the posterior median for B_{2011}/B_0 to 8%. The total F/F_{msy} was less than the reference case and reached a maximum of about 1.3 as opposed to 1.6 under the reference case in 1995.

Increasing the inputed 1997 shrimp bycatch value by factors of 1.33 relative to the reference case, increased the posterior median alpha parameter quite substantially from about 0.19 to 0.33 under the factor of four increase. Though the fit to the data was better under more extreme shrimp bycatch scenarios, this led only to slightly smaller negative stock-recruit deviates in the mid 1990s (Fig. 4). All other stock status estimates were otherwise quite similar (Table 11). The implication is that the perceived capacity for stock recovery increases as the presumed recent bycatch amounts increase. The stock status and projection results were all completely insensitive to different settings for auto-correlation in future stock-recruit deviates. For example, when the correlation coefficient was reduced from 0.5 to zero, the same stock status and projection results were obtained as in the reference case. When the year in which autocorrelation is switched on was put to 2009 and 2008, identical results were also obtained. This is likely a result of the relatively low value for the auto-correlation coefficient of 0.5 and the fact that the last strong negative deviate was estimated to be in 2008. With the very large standard deviation for the stock-recruit deviates (0.8), the potential for carry overs of the strongly negative deviate in 2008 diminishes rapidly and disappears by 2011.

Bayes factors were computed for some of the runs to evaluate the relative credibility of different model runs against the reference case run (Table 12). In all instances, the Bayes factors were not much different from that obtained for the reference case run. This indicates that all comparable model runs remain credible against the data, though some runs appear to have lower credibility than others. For example, applying the total shrimp bycatch implied by the Olsen et al. (2000) report (low relative to the reference case) was seven times less credible compared to the run where shrimp bycatch was increased to four times the reference case. This indicates that the abundance index data are more closely consistent with high shrimp bycatch scenarios compared to low shrimp bycatch scenarios.

Evaluation of the relationship between recruitment and environmental covariates

The median estimates of the stock recruit deviates for 1992-2011 were found to be uncorrelated with several different covariates including an index of Pacific hake abundance in B.C. waters, zooplankton prey species *E. pacifica* and *T. spinifera*, and the Pacific Decadal Oscillation Index (PDO) (P-values for all two-tailed tests were larger than 0.1) (source of covariate data: J. Schweigert). The same goes for the euphausid abundance indices in Barkley Sound that were provided by R. Tanasichuk. In all instances, time lags of 0-3 years between the year of covariate and the estimated recruitment anomalies were evaluated, e.g. for a recruitment deviate estimated for age 3 recruits in 2005, potential correlations were evaluated for all covariates in 2002, 2003, 2004 and 2005. Despite the numerous evaluations of potential correlations between the recruitment deviates and the indices, no significant correlations were found for any of the covariates. The largest point estimate for any one covariate was only 0.4 for *T. spinifera* and -0.39 for Pacific hake for a lag of 1 year (Fig. 9). However, neither of these correlations was statistically significant (P-values of 0.13 and 0.15, respectively).

Discussion

The results of this analysis agree with the perception that the Fraser River eulachon population has recently collapsed with the estimated 2009-2011 stock sizes at only about 3-11% of the original unfished stock size, accounting for the range of estimates between the different cohorts and in the sensitivity analyses. The estimated productivity of the stock is low with a maximum sustainable harvest rate of only about 10% (with 80% PI of 2%-27%). The Fraser River eulachon fishery between the 1940s and 1970s depleted at least two of the lines of this population and on occasion took quite large harvests, e.g. up to over 400 t in a given year from a stock with a carrying capacity of about 2500 t (1200-5000 t).

Shrimping appears to have played a role in the decline with bycatch mortality rates far exceeding the MSY harvest rates for a period in the mid-1990s. It appears that the main cause of the systematic decline apparent in both the Fraser River gillnet test fishery catch rates and the larval survey abundance indices after the year 2000 is not fishing but some other factor that has negatively impacted recruitment after the year 2000. The model is able to fit the decline in the abundance index data after 2000 only by estimating very large negative recruitment anomalies for years after 2000. The large negative recruitment anomalies could be manifestations of increases in predation rates on pre-recruits or mature fish, possibly due to increases in predator abundances, such as harbour seals and sea lions since the 1960s in B.C.

waters. It could also be a result of declines in the availability of preferred prey such as euphausids.

A peculiar result of the analysis is the cycling between the three different cycle lines between the 1960s and 1990s. The model predicted this cycling due to the systematic low catches coinciding with the high spawning cycle line starting in 1958. The average catch for this line between 1951 and 1987 is 71 tons, the average catch for the 2nd line in this period is 110 tons and the average catch for the third line in this period is 83 tons. The much larger average catch on the 2nd cycle line is one possible reason for it being the weakest line in this period. However, the smaller catches on this apparent dominant line could conversely reflect a line with low abundance and relatively similar effort being applied across years.

Making use of any available Fraser River gillnet fisheries effort and reparameterizing the model to predict the commercial catches based on fishing effort could help to eliminate this anomalous behaviour and produce more realistic estimates of spawning stock biomass over this period. While it would appear that fishing effort in the 1950s to the 1990s should remain relatively constant between years, this was not the case for the period from 1941-1953. There were very large fluctuations in the annual commercial gillnet fishing effort, possibly due to variation in river discharge and other factors from year to year. Thus, it is credible that large fluctuations in effort, eulachon abundance and catchability between years could be one of the causes of the apparent large fluctuations in Fraser River eulachon catches for the majority of the years between the 1940s and the 1990s and the reconstructed stock biomass over this period.

Prior distributions were applied for the Ricker α parameter and the recruitment anomalies but these were applied only to help constrain the estimation of model parameters. The prior standard deviation for the recruitment anomalies was set to be quite large, being set at a value of 0.8. This was due to the large interannual variation in the stock trend indices. Given the similar pattern in interannual variability between the Fraser River eulachon gillnet test fishery index and the larval index, the large standard deviation in the prior distribution for recruitment anomalies appeared to be reasonable and permitted the model to fit the consistently low stock size estimates in the larval index time series between 2005 and 2010.

The results of this analysis of the Fraser River eulachon population contrast with those of Bryan and Christensen (unpublished report of the UBC Fisheries Centre). Bryan and Christensen (unpublished report of the UBC Fisheries Centre) presumed that the constant of proportionality for the commercial gillnet fishery and the test fishery were independent and thus lost information from the potential similarity in this parameter between the two abundance indices. This is especially so, given that the mean value of the catch rate has dropped by a factor of about 2.6 between the 1950s and the 1990s. The analysis in this paper in contrast presumes that the constant of proportionality between stock and the index for these two series is identical. While it is likely to be similar, it is unlikely to be identical. Due to the diminishing catches in the 1990s, the decline in the two most recent indices is not sufficient to permit abundance estimation. Thus Bryan and Christensen (unpublished report of the UBC Fisheries Centre) were unable to get their numerical analysis to work and could not provide any reliable estimates of abundance.

In contrast to the present analysis Bryan and Christensen (unpublished report of the UBC Fisheries Centre) presumed that eulachon is iteroparous. As Clark et al. (2003) conclude, there appears to be only a single 3-year age at maturity showing up in the set of Fraser River eulachon otoliths that they had analyzed. This study does not refute the hypothesis of iteroparity, since it was based on a sample size of only 17 animals apparently from a single year. However, as these appear to be the most rigorous findings yet, the assumption of semelparity is currently the most credible hypothesis. Should there actually be iteroparity, this would likely make the model projections more optimistic, since spawnings from weak cohorts could be supplemented with spawning from co-occurring cohorts. Should there actually be iteroparity, it is likely that the empirically derived value for the variance in stock-recruit deviates would become even higher given the high interannual variability in the abundance index data.

The numerous evaluations of sensitivity of results to alternative model specifications and variations in inputs showed that results were most sensitive to the assumptions about q for the two gillnet indices. For example, if q for the 1990s series was assumed to be 67% of the 1950s series, the ratio of B_{2011}/ B_0 increased from 6% in the reference case to 11%. If the ratio of q values was assumed instead to be 1.33, stock status decreased to 4%. If both q's were estimated as different parameters, the 80% posterior probability interval ranged from 9% to 90%, demonstrating that the abundance index data are uninformative unless hypotheses about the relatedness in q for the gillnet indices are considered. In contrast, results were very similar when the ratio of q's was estimated with an informative prior with mean of 1 and SD of 0.1. As mentioned, there are no data available with which to evaluate whether the test fishery CPUE q is higher or lower than the commercial fishery CPUE and there are different mechanisms that could work either way. We have thus chosen to apply the assumption of equal q in the reference case run, based mainly on the considerations of parsimony and numerical efficiency. We suggest that readers consider the results of the sensitivity analyses on the ratio of the gillnet index q's as alternative credible hypotheses for this ratio and reasonable bounds for uncertainty in the stock assessment results. The computed Bayes factors indicate that the different scenarios considered remain credible against the data though some scenarios, e.g. the high shrimp bycatch scenarios, appear to be more credible than others.

The lack of there being any significant correlations between recruitment deviates and various covariates that could impact recruitment does not suggest that recruitment anomalies are not affected by these different factors; there could be some form of mismatch in the measurement of the key factors in terms of their position in season and space in relation to the where the factors are having their impact. It remains plausible also that some other factor for example predation by some seal or sea lion population that has not yet been considered could also help to explain the recent stark trends in abundance of Fraser River eulachon.

Due to differences in the abundance between the three cycle lines in the most recent years, they respond differently to the different catch removal scenarios considered in the projections. Stock projections for the 2011 cycle line suggested that there would still be a higher than 50% chance of increase in abundance and exceeding 20% of unfished stock size within six generations with catch removals of up to 30 tons per year. This positive outlook was likely influenced by the large increase in the larval survey index in 2011. The 2010 cycle line was the least resilient and catch removals of 5t yr^{-1} and lower would result in no less than a 50% chance of exceeding 20% of B_0 within 3 generations. The 2009 cycle line was intermediate in abundance between the 2010 and 2011 cycle lines. These results suggest that there may be some scope for the resumption of the Fraser River gillnet test fishery for eulachon to enhance the monitoring of abundance. The results also suggest that cycle line responses to different harvest levels differ markedly and that any levels of permitted harvest should be tailored to the cycle line. Constant harvest rate policies (not evaluated in this report) could also be considered which may offer a more consistent harvest control rule across the different cycle lines.

Acknowledgments

Jake Schweigert, Bruce McCarter, Thomas Therriault, Dennis Rutherford and Chantal Leveque are thanked for their assistance in compiling information and data essential to the analyses. Jake Schweigert, Doug Hay, Chris Wood, Dennis Rutherford, and Bruce McCarter are thanked for comments on the analyses. Adrian Clarke is thanked for helpful discussions.

Table 1. Commercial fishery catch records for Fraser River Eulachon (tons) taken in the Fraser River during spawning.

Year	Catch	Year	Catch	Year	Catch	Year	Catch
1900	113.4	1931	6.3	1962	178.2	1993	8.7
1901	108.86	1932	5.03	1963	159.3	1994	6.1
1902	90.72	1933	6.94	1964	105.5	1995	15.1
1903	128.97	1934	10.25	1965	87.8	1996	63.2
1904	129.27	1935	15.47	1966	101.9	1997	0.1
1905	22.68	1936	10.07	1967	86.8	1998	0.1
1906	13.61	1937	4.08	1968	46	1999	0.1
1907	6.8	1938	7.67	1969	29.8	2000	0.1
1908	10.21	1939	20.59	1970	71.7	2001	0.1
1909	31.75	1940	34.16	1971	34.5	2002	5.76
1910	42.5	1941	50.14	1972	53.2	2003	0.1
1911	32.66	1942	60.0	1973	53.1	2004	0.44
1912	36.29	1943	97.0	1974	75.3	2005	0.1
1913	10.52	1944	95.3	1975	27.7	2006	0.1
1914	6.44	1945	60.2	1976	36.7	2007	0.1
1915	12.34	1946	93.2	1977	32.2	2008	0.1
1916	12.52	1947	77.2	1978	38.6	2009	0.1
1917	17.28	1948	129.2	1979	22.3	2010	0.1
1918	15.2	1949	164.7	1980	24.3	2011	0.1
1919	5.94	1950	135.2	1981	21.2	2012	0.1
1920	5.22	1951	85.6	1982	13.7		
1921	8.53	1952	141.2	1983	10.8		
1922	7.98	1953	337.5	1984	11.8		
1923	19.87	1954	151.6	1985	29.2		
1924	36.51	1955	238.8	1986	49.6		
1925	16.19	1956	235.5	1987	19.3		
1926	17.24	1957	33.2	1988	39.5		
1927	12.97	1958	92.1	1989	18.7		
1928	18.73	1959	132	1990	19.9		
1929	9.71	1960	84	1991	12.3		
1930	35.33	1961	216.9	1992	19.6		

Table 2. Shrimping effort[*] in B.C. waters. WCVI = west coast Vancouver Island; O=outside, I = Inside waters. Combined effort (D. Rutherford, pers. com.); Effort by gear and area source 1987-2010 (C. Levesque, pers. com.). See text for method for imputing Levesque effort prior to 1987.

Year	Combined FR DU	WCVI Otter	Central Coast Otter	WCO Beam	WCI Beam
1953	0.00020	0.0001	0.0000	0.0000	0.0001
1954	0.00001	0.0000	0.0000	0.0000	0.0000
1955	0.00001	0.0000	0.0000	0.0000	0.0000
1956	0.00001	0.0000	0.0000	0.0000	0.0000
1957	0.00001	0.0000	0.0000	0.0000	0.0000
1958	0.00001	0.0000	0.0000	0.0000	0.0000
1959	0.00026	0.0001	0.0001	0.0000	0.0002
1960	0.20665	0.0888	0.0435	0.0250	0.1456
1961	0.23480	0.1009	0.0495	0.0285	0.1654
1962	0.28113	0.1208	0.0592	0.0341	0.1980
1963	0.40313	0.1733	0.0849	0.0489	0.2839
1964	0.20534	0.0883	0.0433	0.0249	0.1446
1965	0.36831	0.1583	0.0776	0.0446	0.2594
1966	0.24881	0.1069	0.0524	0.0302	0.1752
1967	0.30006	0.1290	0.0632	0.0364	0.2113
1968	0.14611	0.0628	0.0308	0.0177	0.1029
1969	0.51058	0.2195	0.1076	0.0619	0.3596
1970	0.50856	0.2186	0.1071	0.0616	0.3582
1971	0.13856	0.0596	0.0292	0.0168	0.0976
1972	0.05906	0.0254	0.0124	0.0072	0.0416
1973	0.03191	0.0137	0.0067	0.0039	0.0225
1974	0.08676	0.0373	0.0183	0.0105	0.0611
1975	0.09287	0.0399	0.0196	0.0113	0.0654
1976	0.16748	0.0720	0.0353	0.0203	0.1180
1977	0.15058	0.0647	0.0317	0.0182	0.1061
1978	0.09472	0.0407	0.0200	0.0115	0.0667
1979	0.03900	0.0168	0.0082	0.0047	0.0275
1980	0.07007	0.0301	0.0148	0.0085	0.0494
1981	0.13881	0.0597	0.0292	0.0168	0.0978
1982	0.08698	0.0374	0.0183	0.0105	0.0613
1983	0.12615	0.0542	0.0266	0.0153	0.0889
1984	0.04291	0.0184	0.0090	0.0052	0.0302
1985	0.14427	0.0620	0.0304	0.0175	0.1016
1986	0.19554	0.0840	0.0412	0.0237	0.1377
1987	0.43270	0.1869	0.0000	0.2492	0.1165
1988	0.45637	0.2235	0.0000	0.1730	0.1321
1989	0.36142	0.1249	0.0000	0.0637	0.1651
1990	0.35681	0.2190	0.0000	0.0252	0.1300
1991	0.60692	0.3350	0.0022	0.2049	0.1332
1992	0.33683	0.1474	0.0000	0.0789	0.1274
1993	0.42247	0.4019	0.0000	0.0716	0.1092
1994	0.71555	0.6026	0.0002	0.1095	0.3676
1995	1.84716	0.7153	0.0096	0.1144	1.4486
1996	2.05673	0.8840	0.3045	0.0332	1.3975
1997	0.88030	0.4349	0.2213	0.0357	0.5782
1998	1.45627	0.4300	0.4333	0.0049	1.2637
1999	0.88672	0.3589	0.0278	0.0081	0.7576
2000	0.60115	0.1322	0.0004	0.0066	0.6793
2001	0.37165	0.1052	0.0000	0.0002	0.3324
2002	0.40024	0.1023	0.0000	0.0009	0.3363
2003	0.28816	0.0152	0.0000	0.0008	0.2874
2004	0.24090	0.0266	0.0000	0.0000	0.2249
2005	0.25247	0.0122	0.0000	0.0000	0.2313
2006	0.14352	0.0245	0.0000	0.0077	0.1747
2007	0.14789	0.0080	0.0001	0.0003	0.1593
2008	0.13229	0.0021	0.0000	0.0000	0.1420
2009	0.11597	0.0103	0.0000	0.0000	0.0723
2010	0.10586	0.0103	0.0000	0.0000	0.0723

[*]Effort measured in mil. of minutes of trawling. See Table 5 for list of the statistical areas in each named region.

Table 3. Fraction of the Fraser River Eulachon stock assumed in the Strait of Georgia, Central Coast waters and on the West Coast of Vancouver Island 1997-2000. The first two estimates reported in Beacham et al. (2005) were obtained from an analysis of DNA samples obtained between May 2000 and March 2001. We assume that all eulachon in the Strait of Georgia are Fraser River stock. This assumption is of little consequence because the eulachon bycatch in Strait of Georgia shimp fisheries is small.

Region	Fraser River Stock fraction
West Coast of Vancouver Island	0.375
Central coast	0.239
Strait of Georgia	1.000

Table 4. Estimates of eulachon bycatch (tonnes) in various B.C. shrimp fisheries from June to September in the year 1997 from Hay et al. (1999a) and Olsen et al. (2000). Estimates are provided for the total bycatch in each aggregate area and the bycatch of the Fraser River Eulachon stock based on the stock composition estimates in Table 3. SOG refers to Strait of Georgia, WCO refers to West Coast Outside, WCI refers to West Coast inside, WCVI refers to West coast Vancouver Island both inside and outside areas.

Region	WCVI Otter	Central Coast Otter	SOG Otter	WCO Beam	WCI Beam	Area 12 and SOG beam	
Statistical Areas	23, 123-125	10, 101, 108, 110, 111	14-19, 28-29	123-125	23-25	12, 14-19,28-29	Totals
Total annual eulachon bycatch (Olsen et al. 2000)	29.72	93.70	0.03	3.33	2.17	0.12	129.07
Total annual eulachon bycatch (Hay et al. 1999a)	51.90	90.37	0.02	17.40	4.43	0.05	164.17
Estimated Fraser River eulachon bycatch (Hay et al. 1999a)	11.15	22.39	0.03	1.25	0.81	0.12	35.75
Estimated Fraser River eulachon bycatch (Hay et al. 1999a)	19.46	21.60	0.02	6.53	1.66	0.05	49.32

Table 5. Relative abundance indices for the Fraser River Eulachon population. The commercial CPUE is the catch per unit effort obtained from the Fraser River commercial gillnet fishery. The Test fishery CPUE is the catch per unit effort obtained from the gillnet test fishery at New Westminster. For both indices the units are in pounds caught per hour fished and 100 square metres of net. The Larval survey index is the estimate of Fraser River eulachon spawner biomass (t) obtained from the Eulachon egg and larval survey in the lower Fraser River.

Year	Commercial C/E	Year	Test fishery C/E	Larval survey Index
1941	50	1995	13.94	302
1942	153	1996	41.05	1911
1943	155	1997	3.48	74
1944	66	1998	2.22	136
1945	74	1999	NA	418
1946	116	2000	13.21	130
1947	231	2001	11.70	609
1948	113	2002	17.77	494
1949	103	2003	10.37	266
1950	36	2004	16.19	33
1951	112	2005	1.27	16
1952	117	2006	NA	29
1953	160	2007	NA	41
		2008	NA	10
		2009	NA	14
		2010	NA	4
		2011	NA	31

Table 6. Life history parameter estimates for Fraser River eulachon that were applied in the stock assessment model.

	Source	Units	Parameter values		
Von Bertalanffy k	Fishbase	yr^{-1}	0.34		
Mortality coefficient	Jensen (1996)[1]	NA	1.5		
Rate of natural mortality	Jensen (1996)[1]	yr^{-1}	0.51		
Age		yr	1	2	3
Mean length	Hay and McCarter (2000)	cm	7.062	10.59	17.00
Mean mass	Hay and McCarter (2000) and Fraser River gillnet test fishery database	grams	4.5	30.0	41.5

[1] Based on Beverton-Holt life history invariant theory: $M = 1.5\ k$

Table 7. Applied and empirical estimates of the variance terms (i.e. sigma) in the estimation of population dynamics model parameters for Fraser River Eulachon CPUE refers to the 'catch per unit effort' from gillnet sets. Sigma is the standard deviation in the deviation between the natural logarithms of the index and the predicted index.

Stock trend data set	Applied value for sigma	Empirical sigma
Fraser river commercial gillnet CPUE	0.6	0.52
Fraser river gillnet test fishery CPUE	0.6	0.52
Larval survey index of spawning stock biomass	0.8	0.74

Table 8. Posterior median, 10th and 90th percentiles for model parameter and quantities of interest from fitting the age-structured model to the data.

Variable	10th Percentile	Median	90th Percentile
Ricker alpha	0.04	0.19	0.51
B_0	1173	2537	4977
MSY	34	112	309
B_{msy}	559	1220	2376
B_{2009}	44	141	537
B_{2010}	28	79	212
B_{2011}	53	155	437
B_{msy}/ B_0	0.464	0.487	0.497
B_{2011}/B_{msy}	0.05	0.12	0.31
B_{2009}/B_0	0.02	0.06	0.21
B_{2010}/B_0	0.01	0.03	0.08
B_{2011}/B_0	0.02	0.06	0.15
F_{MSY}	0.02	0.10	0.27
F_{cur}	0.004	0.007	0.018
F_{cur}/F_{MSY}	0.03	0.09	0.35
REPY	6	29	121
Catch/REPY	0.0008	0.0034	0.0182
$P(B_{cur} > 0.4B_{msy})$	0.06		
$P(B_{cur} > 0.8B_{msy})$	0.02		

Table 9a. Reference case model stock projection results under alternative constant catch removals for Fraser River eulachon for the 2011 cycle line.

Horizon	Catch taken (t)	Median B_{fin}/ B_0	Median(B_{fin}/B_{msy})	P(B_{fin}>0.2B_0)	P(B_{fin}>0.8 B_{msy})	P(B_{fin}>B_{2011})
6 -year	0.1	0.14	0.29	0.44	0.34	0.64
	2	0.14	0.29	0.43	0.33	0.64
	5	0.13	0.28	0.43	0.33	0.63
	10	0.13	0.28	0.43	0.33	0.63
	15	0.13	0.27	0.43	0.33	0.62
	20	0.13	0.26	0.43	0.33	0.61
	25	0.13	0.26	0.42	0.32	0.60
	30	0.12	0.25	0.41	0.32	0.59
9 -year	0.1	0.20	0.42	0.50	0.43	0.64
	2	0.20	0.41	0.50	0.42	0.64
	5	0.20	0.41	0.50	0.42	0.63
	10	0.19	0.39	0.49	0.41	0.62
	15	0.18	0.38	0.49	0.41	0.61
	20	0.17	0.36	0.48	0.41	0.60
	25	0.16	0.34	0.48	0.41	0.58
	30	0.15	0.31	0.48	0.41	0.58
18 –year	0.1	0.49	1.01	0.56	0.53	0.64
	2	0.47	0.98	0.56	0.52	0.64
	5	0.46	0.96	0.55	0.52	0.63
	10	0.43	0.89	0.55	0.51	0.62
	15	0.40	0.82	0.54	0.50	0.60
	20	0.37	0.76	0.53	0.49	0.59
	25	0.34	0.73	0.52	0.49	0.58
	30	0.32	0.67	0.51	0.49	0.57

Table 9b. Reference case model stock projection results under alternative constant catch removals for Fraser River eulachon for the 2010 cycle line.

Horizon	Catch taken (t)	Median B_{fin}/ B_0	Median(B_{fin}/B_{targ})	P(B_{fin}>0.2B_0)	P(B_{fin}>0.8 B_{targ})	P(B_{fin}>B_{2010})
5 –year	0.1	0.06	0.13	0.20	0.11	0.68
	2	0.06	0.13	0.20	0.11	0.67
	5	0.06	0.12	0.20	0.10	0.65
	10	0.05	0.11	0.19	0.10	0.58
	15	0.05	0.10	0.18	0.09	0.57
	20	0.04	0.09	0.18	0.09	0.50
	25	0.03	0.07	0.18	0.09	0.48
	30	0.03	0.06	0.18	0.09	0.46
8 -year	0.1	0.10	0.21	0.43	0.31	0.68
	2	0.10	0.20	0.42	0.31	0.67
	5	0.09	0.19	0.40	0.30	0.65
	10	0.09	0.17	0.39	0.30	0.59
	15	0.07	0.14	0.34	0.25	0.57
	20	0.06	0.12	0.34	0.24	0.54
	25	0.05	0.10	0.29	0.19	0.51
	30	0.02	0.04	0.28	0.19	0.42
17 -year	0.1	0.33	0.68	0.53	0.50	0.65
	2	0.31	0.65	0.52	0.48	0.65
	5	0.26	0.56	0.51	0.48	0.63
	10	0.15	0.32	0.49	0.45	0.58
	15	0.10	0.20	0.47	0.44	0.55
	20	0.08	0.16	0.45	0.42	0.52
	25	0.03	0.05	0.43	0.41	0.49
	30	0.01	0.02	0.38	0.36	0.43

Table 9c. Reference case model stock projection results under alternative constant catch removals for Fraser River eulachon for the 2009 cycle line.

Horizon	Catch taken (t)	Median B_{fin}/B_0	Median(B_{fin}/B_{targ})	P(B_{fin}>0.2B_0)	P(B_{fin}>0.8 B_{targ})	P(B_{fin}>B_{2009})
4 -year	0.1	0.10	0.21	0.36	0.20	0.67
	2	0.10	0.20	0.36	0.20	0.65
	5	0.10	0.20	0.36	0.20	0.64
	10	0.09	0.19	0.35	0.20	0.61
	15	0.09	0.18	0.35	0.20	0.60
	20	0.08	0.18	0.35	0.20	0.59
	25	0.08	0.17	0.34	0.20	0.57
	30	0.08	0.16	0.32	0.20	0.57
7 -year	0.1	0.14	0.29	0.44	0.35	0.67
	2	0.14	0.28	0.44	0.35	0.67
	5	0.13	0.26	0.43	0.35	0.65
	10	0.12	0.23	0.43	0.34	0.61
	15	0.10	0.21	0.42	0.34	0.58
	20	0.09	0.19	0.40	0.33	0.56
	25	0.08	0.16	0.40	0.32	0.54
	30	0.07	0.15	0.39	0.32	0.52
16 -year	0.1	0.41	0.84	0.56	0.52	0.64
	2	0.40	0.83	0.56	0.50	0.64
	5	0.39	0.79	0.55	0.50	0.63
	10	0.25	0.52	0.52	0.45	0.60
	15	0.18	0.37	0.48	0.44	0.58
	20	0.14	0.30	0.47	0.43	0.55
	25	0.11	0.22	0.46	0.42	0.52
	30	0.07	0.15	0.44	0.41	0.50

Table 10. Summary of sensitivity runs in the Fraser River eulachon stock assessment, including their categorization. Under the reference case model, the prior mean B_{init}/ B_0 was set at 1.0, f=1, □$_r$ = 0.8

Category Code	**Category Description**	**Table Code**	**Run Description**
Ref	Reference run	Ref.1	Reference run
A	α prior mean	A.3	Prior mean for α set at 67% of reference case
		A.4	Prior mean for α set at 133% of reference case
B	Initial stock size assumptions	B.3	prior mean B_{init}/ B_0 = 0.67
		B.4	prior mean B_{init}/ B_0 = 1.33
C	Uncertainty over catch records	C.3	Fixed catches are 67% of the reference case
		C.4	Fixed catches are 133% of the reference case
D	Uncertainty in the degree of similarity in the constant of proportionality for the commercial and test fishery gillnet cpue ($f = q_t / q_c$)	D.1	f = 1.33
		D.2	f = 0.67
		D.3	Prior for f ~ normal(1, 0.1^2)
		D.4	q_c, qt estimated separately
E	Alternative values for standard deviation (σ_r) in recruitment deviates	E.1	σ_r = 0.6
		E.2	σ_r = 1.0
F	Vulnerability of age 1 to shrimping gear relative to age 2	F.1	v_1 / v_2 set at 0.5
		F.2	v_1 / v_2 set at 0.25
G	Evaluating effects of the 1996 "outlier" index values:	G.1	Removing only the 1996 larval index
		G.2	Removing the 1996 larval index and the 1996 gillnet index
H	Uncertainty over the 1997 shrimp trawl bycatch estimate	H.1	Use of Olsen et al. 2000 bycatch estimate 0.72 x Hay et al. (1999a) estimate for 1997
		H.2	Use of bycatch estimate 1.33 x Hay et al. (1999a) estimate for 1997

Table 11. Summary of results from sensitivity runs in the Fraser River eulachon stock assessment.

	Ricker alpha			B_{msy}			B_{2011}			$RepY_{2011}$			B_{2011}/B_o			F_{2011}/F_{msy}			$Catch_{2011}/RepY_{2011}$		
	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Code	Reference run																				
Ref.1	0.042	0.186	0.51	559	1220	2376	53	155	437	6	29	121	0.023	0.061	0.154	0.026	0.09	0.354	0.012	0.074	0.472
	Ricker alpha prior mean 33% lower and 33% higher																				
A.1.1	0.027	0.176	0.504	539	1282	2517	57	160	476	5	28	119	0.021	0.068	0.160	0.027	0.1	0.485	0.011	0.071	0.508
A.1.2	0.023	0.207	0.56	540	1162	2839	51	152	436	5	24	127	0.022	0.059	0.154	0.025	0.101	0.399	0.012	0.086	0.483
	Initial stock size, 0.66 B_0 and 1.33 B_0																				
B.1.1	0.059	0.208	0.525	557	1249	2371	50	144	520	7	32	129	0.022	0.060	0.153	0.024	0.087	0.296	0.013	0.061	0.399
B.1.2	0.026	0.18	0.537	550	1211	2244	54	170	412	5	26	116	0.025	0.064	0.166	0.029	0.1	0.444	0.011	0.082	0.587
	Catches 2/3or 1 1/3 higher																				
C.1.1	0.058	0.235	0.588	390	885	2464	33	102	431	5	23	112	0.023	0.064	0.160	0.023	0.087	0.322	0.009	0.073	0.503
C.1.2	0.039	0.18	0.473	759	1657	3187	66	181	916	6	39	152	0.021	0.068	0.142	0.022	0.08	0.321	0.008	0.043	0.377
	Fraser River gillnet test fishery q is 1.33x, or 0.67x the commercial gillnet q, has the q factor estimated with a prior mean of 1, prior SD of 0.1, or has its q estimated separately.																				
D.1.1	0.017	0.157	0.432	547	1123	2020	34	86	252	3	11	44	0.018	0.039	0.101	0.076	0.188	1.108	0.028	0.139	0.932
D.1.2	0.069	0.262	0.836	458	1275	2519	66	228	806	9	66	305	0.036	0.113	0.214	0.012	0.04	0.193	0.006	0.032	0.23
D.1.3	0.087	0.31	0.731	311	669	3064	58	133	267	8	37	143	0.031	0.072	0.237	0.055	0.078	0.238	0.047	0.134	0.466
D.1.4	0.596	0.964	1.525	426	802	1322	123	532	1675	92	289	1456	0.09	0.33	0.88	0.008	0.012	0.028	0.007	0.028	0.068
	Standard deviation in recruitment deviates set at 0.6 and 1.0																				
E.1.1	0.034	0.135	0.366	617	1189	2418	46	136	474	4	16	79	0.023	0.058	0.148	0.041	0.148	0.424	0.022	0.116	0.618
E.1.2	0.08	0.269	0.703	580	1152	2078	52	122	608	7	36	197	0.025	0.059	0.210	0.014	0.072	0.209	0.007	0.049	0.399
	Vulnerability of age 1 to shrimping gear relative to age 2, set at 0.5 and 0.25																				
F.1.1	0.019	0.176	0.441	582	1260	2748	54	158	455	5	26	116	0.023	0.060	0.151	0.024	0.093	0.673	0.011	0.074	0.624
F.1.2	0.018	0.167	0.509	622	1286	2675	59	154	479	5	27	129	0.024	0.062	0.146	0.024	0.093	0.717	0.009	0.071	0.711
	Evaluating effects of the 1996 "outlier" index values: removing only the 1996 larval index and removing the 1996 larval index and the 1996 gillnet index																				
G.1.1	0.021	0.184	0.584	543	1262	2538	62	170	612	5	34	180	0.024	0.079	0.199	0.019	0.088	0.561	0.011	0.057	0.48
G.1.2	0.053	0.329	0.94	509	917	2237	47	137	487	7	34	473	0.022	0.066	0.270	0.014	0.078	0.287	0.004	0.056	0.484
	Use of Olsen et al. (2000) bycatch estimate (0.72 x Hay et al. (1999a) estimate) and a bycatch estimate 1.33, 2, 3, 4 x Hay et al. (1999a).																				
H.1.1	0.052	0.176	0.47	569	1395	2658	53	165	723	5	37	215	0.022	0.080	0.150	0.012	0.064	0.273	0.007	0.04	0.326
H.1.2	0.053	0.227	0.616	543	1169	2430	50	134	439	6	33	122	0.023	0.063	0.147	0.027	0.102	0.353	0.016	0.086	0.55
H.1.3	0.064	0.315	0.651	400	1232	2498	37	134	410	8	35	126	0.047	0.106	0.297	0.04	0.114	0.353	0.022	0.091	0.5
H.1.3	0.084	0.351	0.72	500	1421	2586	43	152	495	11	50	182	0.049	0.107	0.326	0.046	0.111	0.306	0.022	0.08	0.452
H.1.4	0.091	0.356	0.717	611	1502	2753	50	174	544	13	61	210	0.047	0.115	0.318	0.051	0.118	0.348	0.024	0.086	0.434

Table 12. Bayes factors computed for some of the alternative model runs.

Category Code	Category Description	Table Code	Run Description	Bayes factor relative to the reference case
Ref	Reference run	Ref.1	Reference run	1
A	α prior mean	A.3	Prior mean for α set at 67% of reference case	1.6
		A.4	Prior mean for α set at 133% of reference case	0.5
C	Uncertainty over catch records	C.3	Fixed catches are 67% of the reference case	0.6
		C.4	Fixed catches are 133% of the reference case	1.7
D	Uncertainty in the degree of similarity in the constant of proportionality for the commercial and test fishery gillnet cpue ($f = q_t / q_c$)	D.1	f = 1.33	0.7
		D.2	f = 0.67	1.4
		D.3	Prior for f ~ normal(1, 0.1^2)	0.006
		D.4	q_c, qt estimated separately	
H	Uncertainty over the 1997 shrimp trawl bycatch estimate	H.1	Use of Olsen et al. (2000) bycatch estimate (0.72 x Hay et al. (1999a) estimate for 1997)	0.7
		H.2	Use of bycatch estimate 1.33 x Hay et al. (1999a) estimate for 1997	1.4
		H.3	Use of bycatch estimate 2 x Hay et al. (1999a) estimate for 1997	2.2
		H.4	Use of bycatch estimate 3 x Hay et al. (1999a) estimate for 1997	3.0
		H.5	Use of bycatch estimate 4 x Hay et al. (1999a) estimate for 1997	3.5

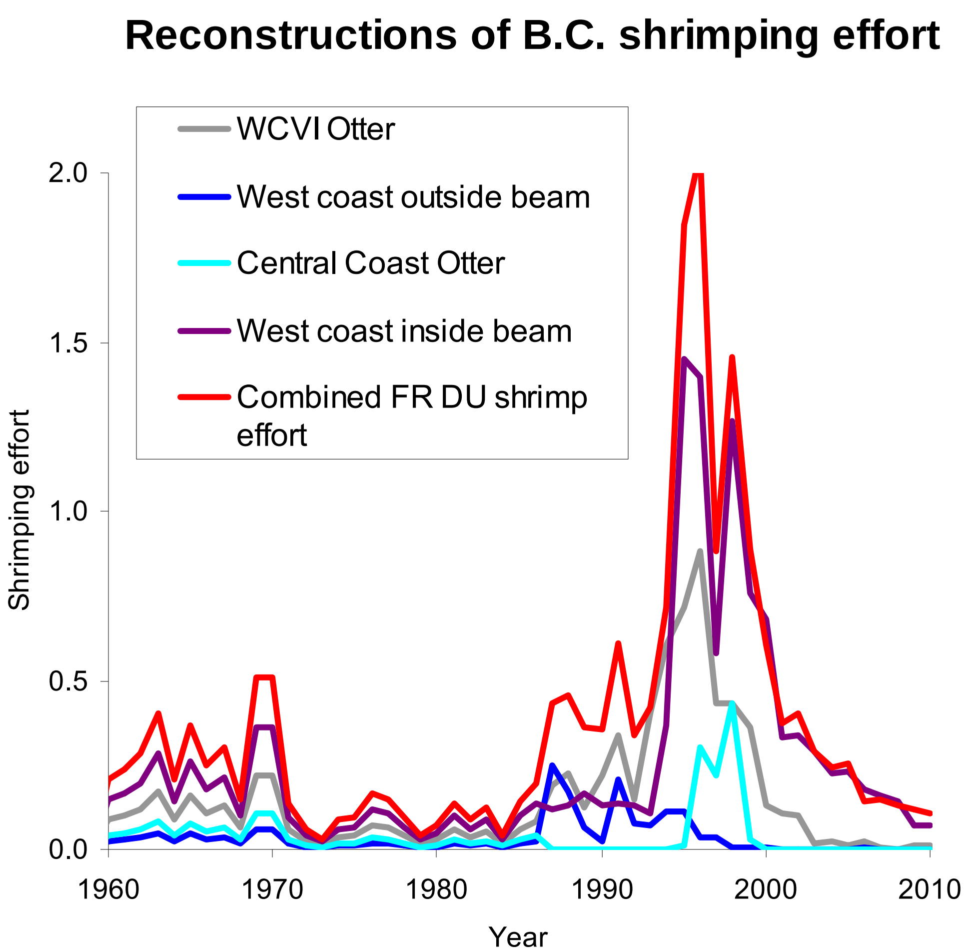


Figure 1. Reconstructions of shrimp fishing effort on the B.C. coast in different management areas by Otter and Beam trawl gear. The units are in millions of minutes trawled. The source of the data for years from 1987 to the present is obtained from mandatory logbook records. From 1987 to 2009, records are available by area and gear type (C. Levesque and D. Rutherford, pers. comm).

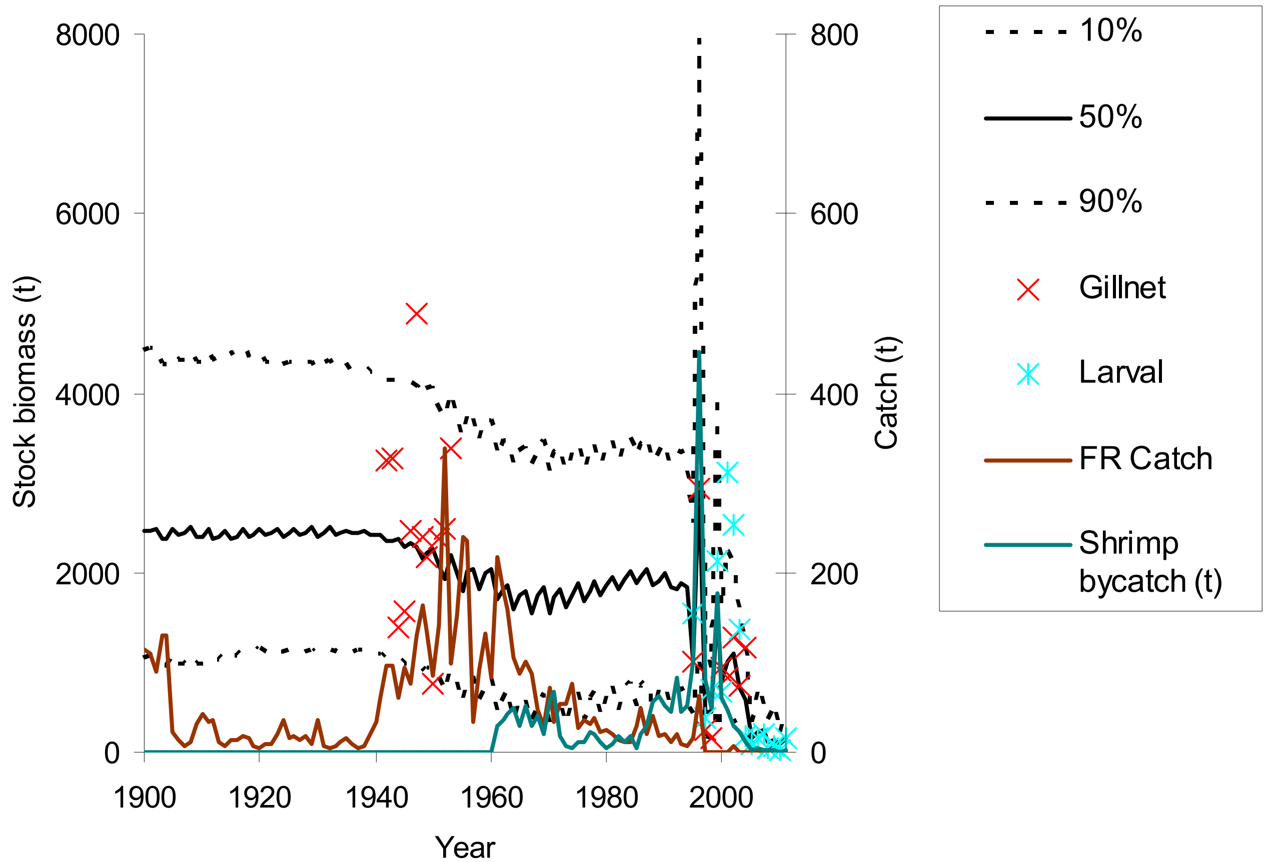


Figure 2. Estimated spawning stock biomass, commercial catch in the Fraser River, shrimp bycatch and abundance indices divided by their constants of proportionality for years 1930 to 2010.

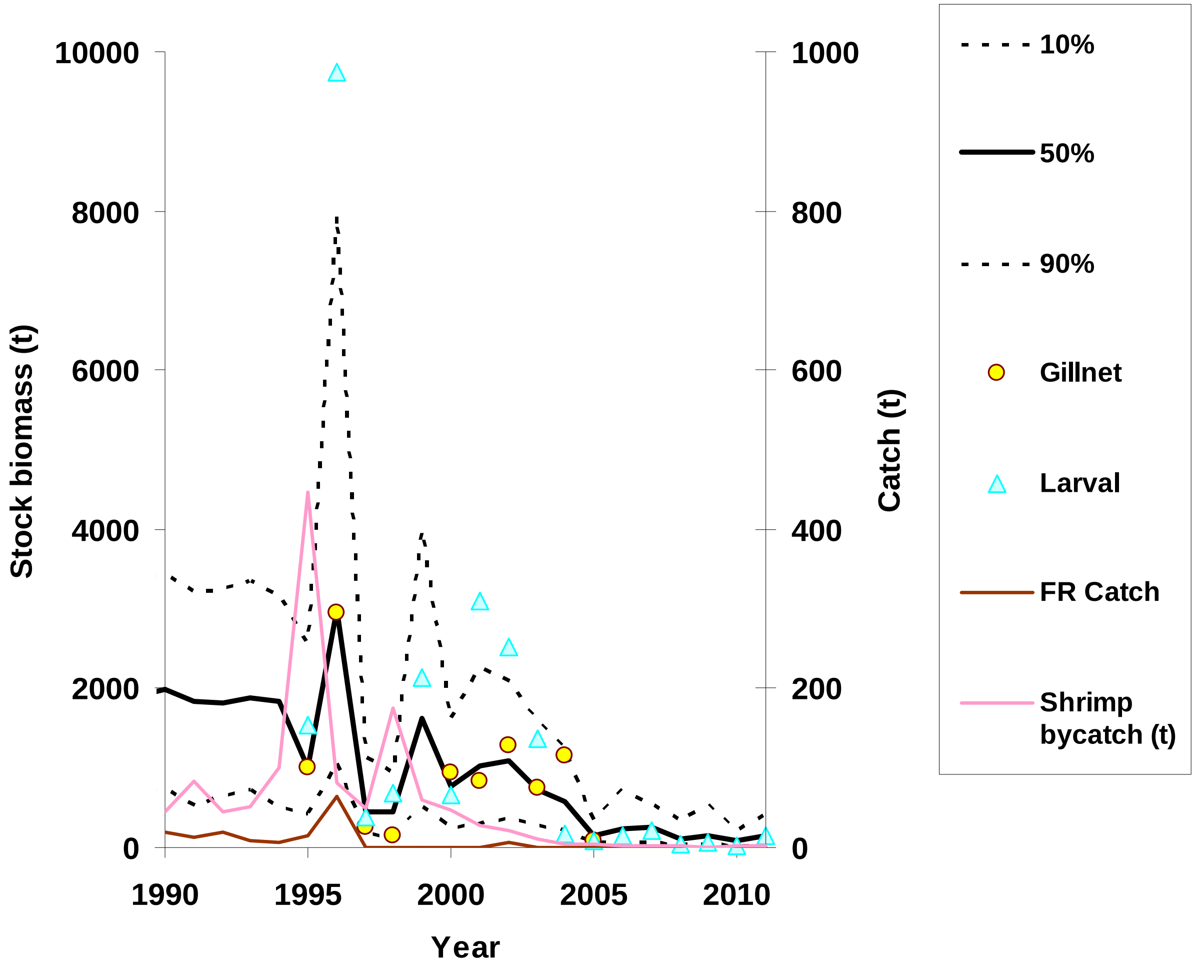


Figure 3. Estimated spawning stock biomass, commercial catch in the Fraser River, shrimp bycatch and the Fraser River gillnet test fishery and larval abundance indices divided by their constants of proportionality for years 1990 to 2010.

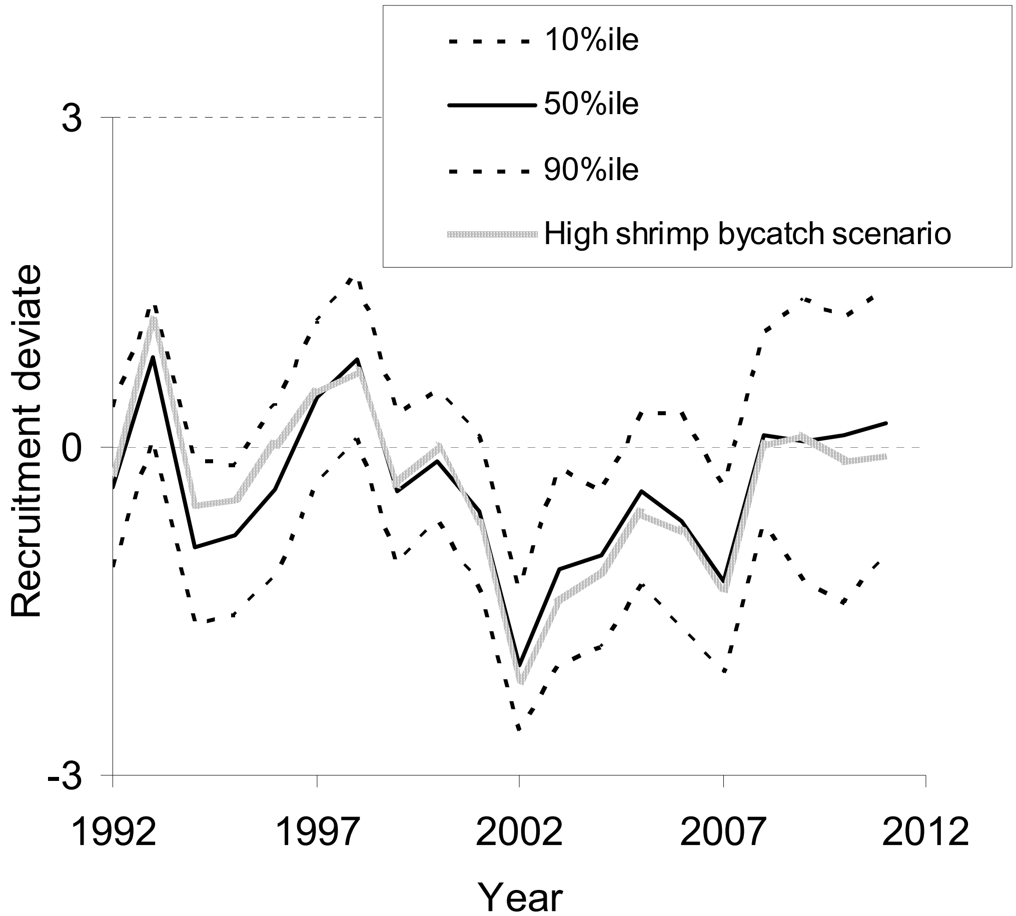


Figure 4. Posterior median recruitment anomalies for Fraser River eulachon for 1992-2011 and 80% probability intervals. The posterior medians from the high shrimp bycatch scenario (4x reference case) are also shown.

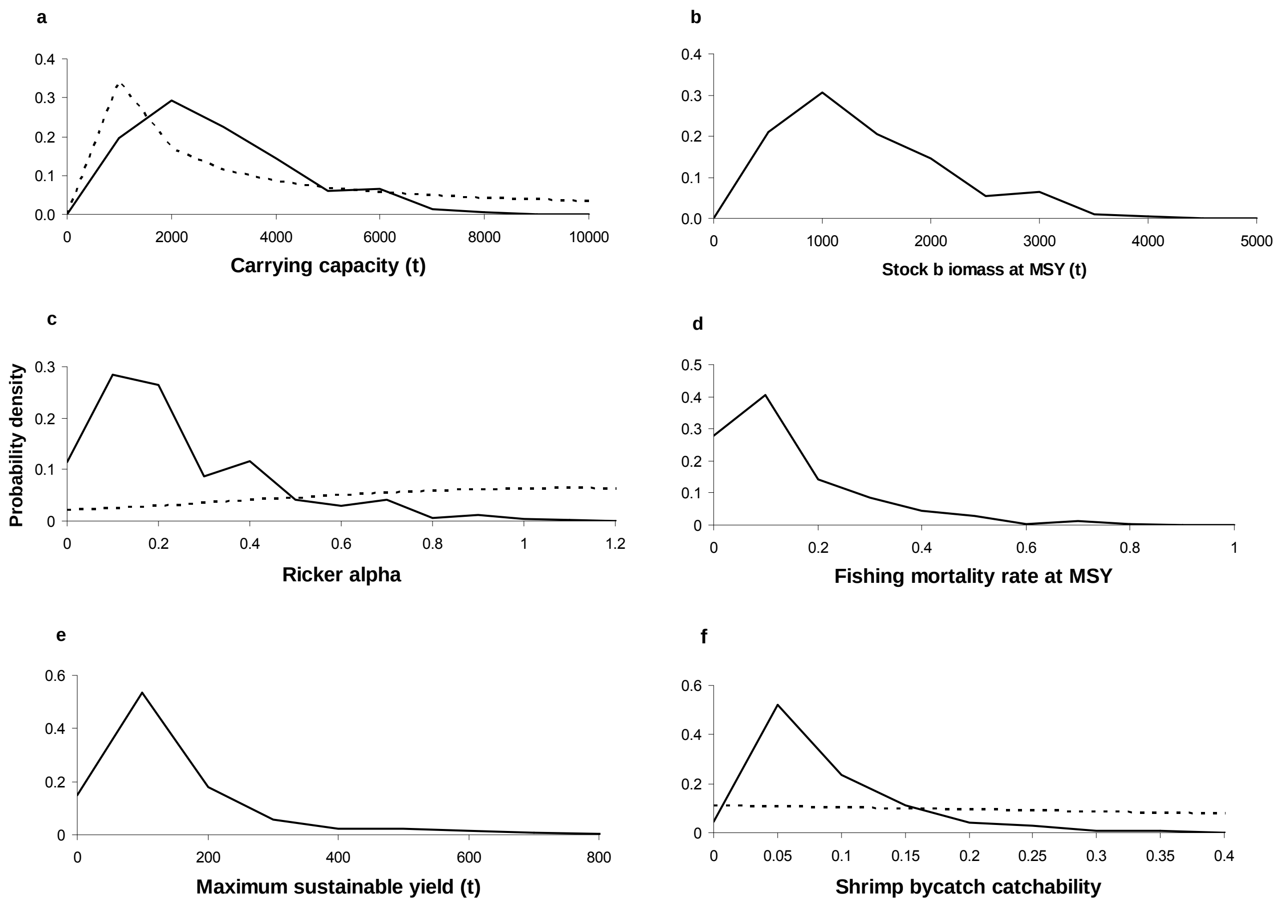


Figure 5. Posterior distributions (solid line) and in some instances, prior distributions (dotted line) also for key model parameters and variables of interest. a) Average unfished stock biomass, b) Stock biomass at MSY, c) Ricker alpha parameter, d) Fishing mortality rate at MSY, e) MSY, f) shrimp fishery catchability coefficient.

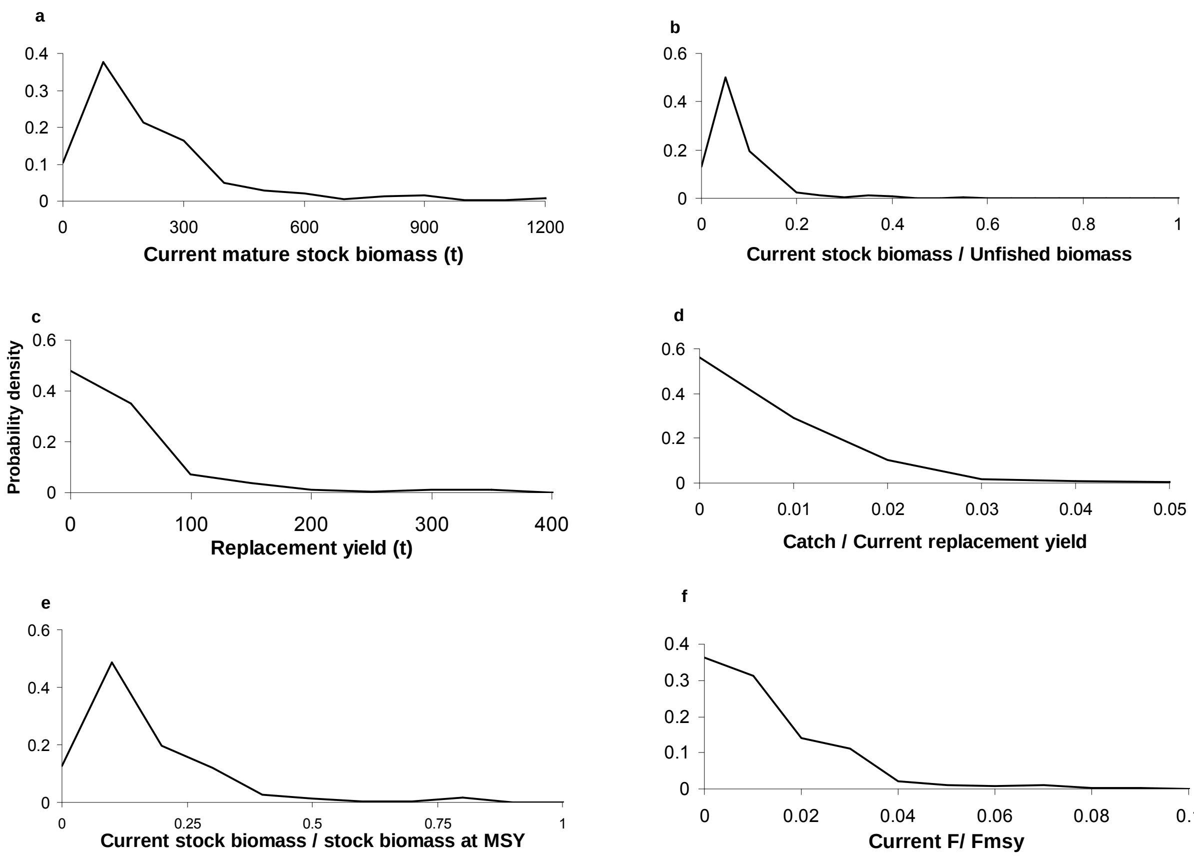


Figure 6. Posterior distributions for key model variables of interest. a) current stock biomass, b) Stock biomass in 2011/ B0, c) Replacement yield in 2011, d) Catch in 2011/ replacement yield, e) Stock biomass in 2011 / stock biomass at MSY, f) fishing mortality rate in 2011/ F_{MSY}*.*

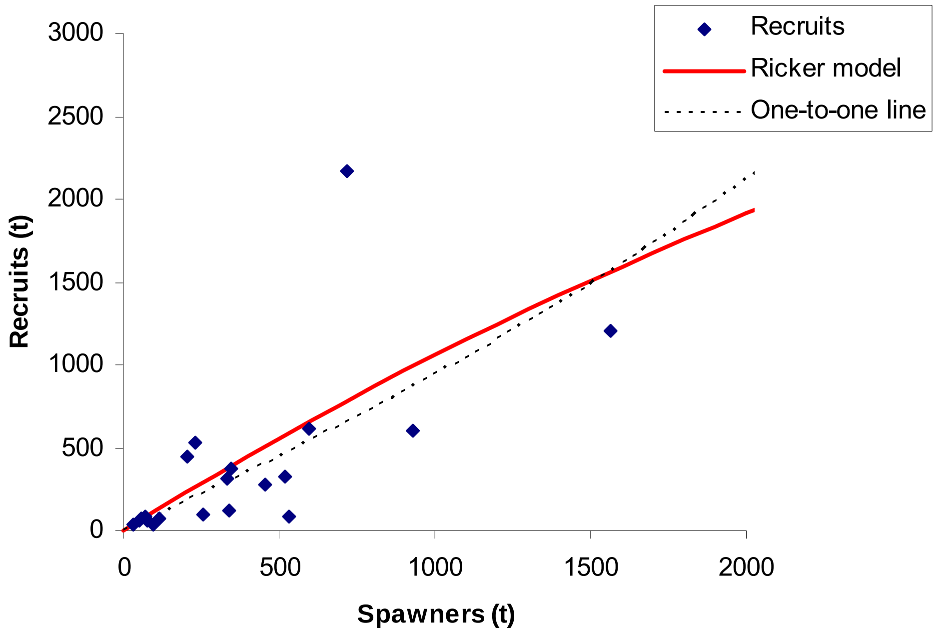


Figure 7. Plot of the posterior mode estimated Ricker stock-recruit function and estimated recruits for years 1993-2008 when data are available to estimate recruitment.

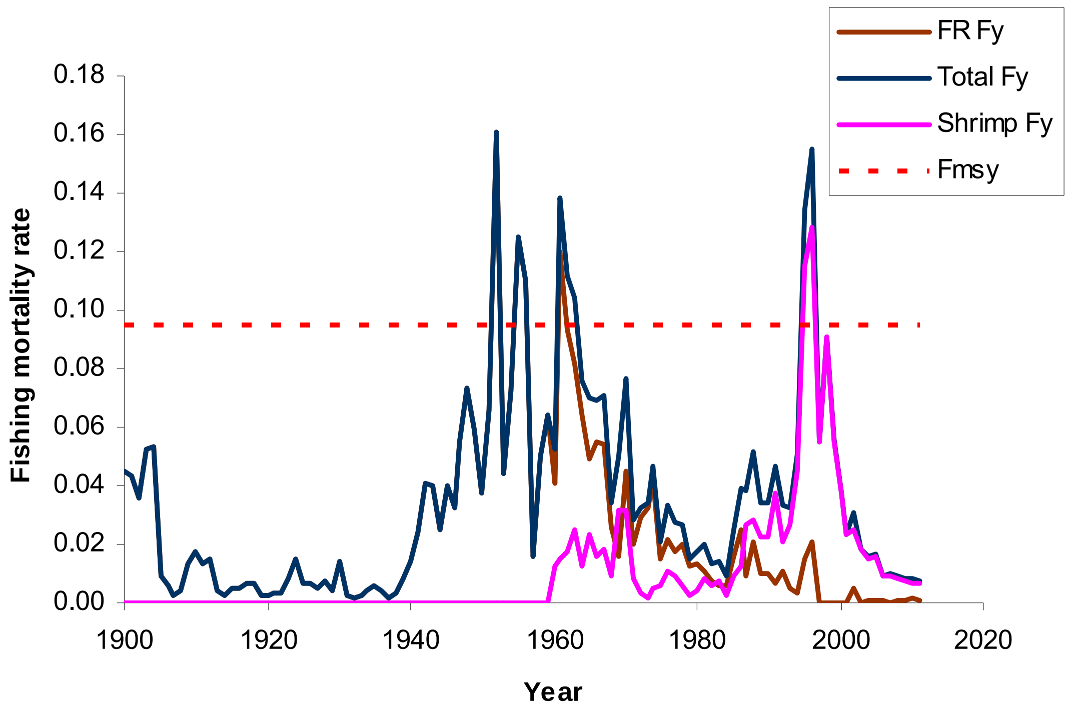


Figure 8. Fraser River Eulachon commercial fishery harvest rates and fraction killed in shrimp fisheries. Mortality rates are measured in yr^{-1}.

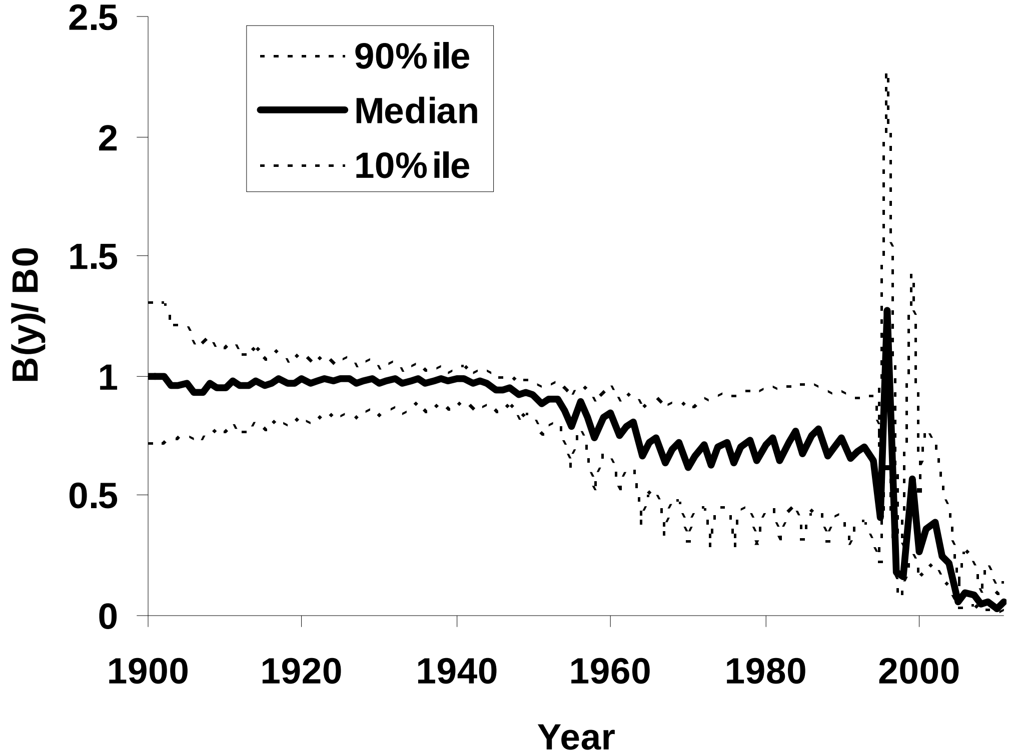


Figure 9. Posterior median ratio of stock biomass to virgin biomass for Fraser River Eulachon and 80% probability intervals.

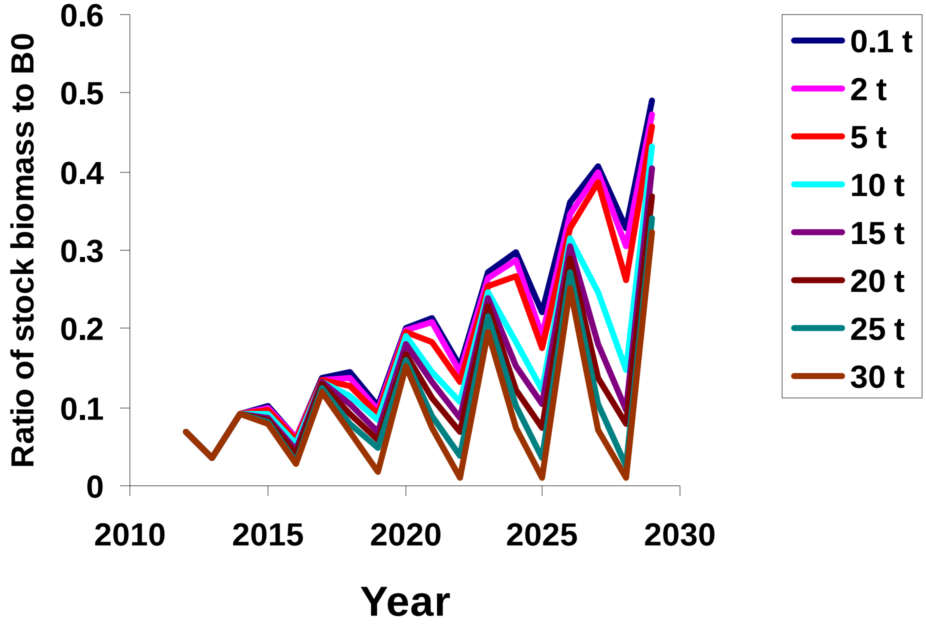
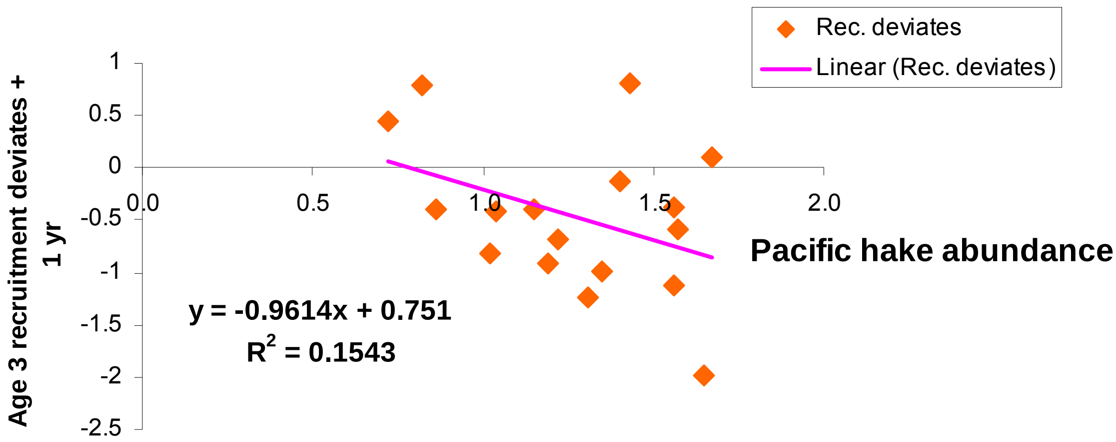


Figure 10. Plots of the ratio of Fraser River eulachon spawning stock biomass to average unfished stock biomass under alternative constant catch removal options.

a. **Plot of Eulachon recruitment deviates versus Pacific hake abundance**



b. **Plot of Eulachon recruitment deviates versus T. spinifera abundance**

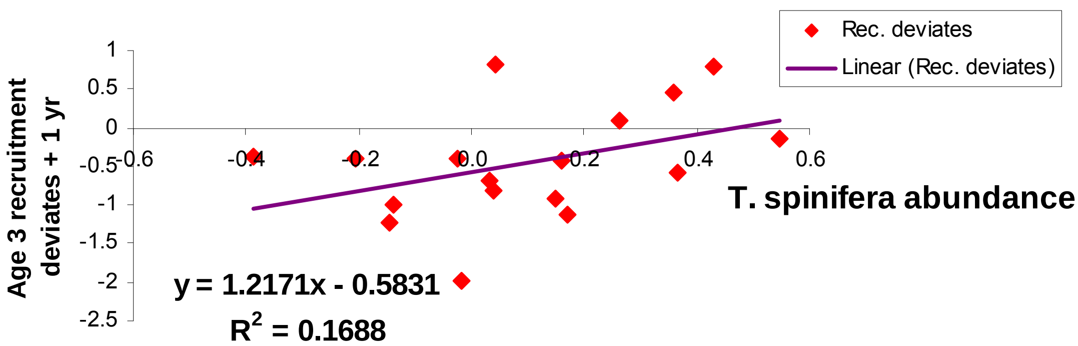


Figure 11. Plots of eulachon recruitment deviates versus a. Pacific hake abundance and b. T. spinifer abundance.

APPENDIX 4 – MARINE MAMMALS

Northern fur seals (*Callorhinus ursinus*)

Northern fur seals are highly migratory and approximately 1/3 of the North Pacific population (~375 000 animals) winters off the coast of North America (DFO 2007). Approximately 1/3 of this overwintering group of animals (~125 000 animals) resides in coastal BC waters for approximately 3 months at some point during December-May, with a peak abundance in May (Olesiuk 2009; DFO 2007). Females comprise the majority of animals and their main wintering area in BC is the La Perouse Bank off of the southwest coast of Vancouver Island (DFO 2007). Northern fur seal abundance in BC waters in 2006 was derived by applying population models to pup counts at rookeries in Alaska and partitioning the population based on the distribution of seals seen on vessel surveys conducted during 1958-74. Female northern fur seal abundance in BC is correlated with the number of pups born on the Pribilof (St. Paul and St. George) and Bogoslof Islands, Alaska (P. Olesiuk, DFO, pers. comm.) so pup production on these two rookeries was used as an index of changes in fur seal predation levels during 1970-2008. Pup counts are not available every year, but pup production can be interpolated between years.

The abundance of northern fur seals in the Pacific has decreased over the last 30 years and is a conservation concern (DFO 2007). This decrease in the North Pacific population has occurred on the Pribilof Islands, Alaska, the cause of which is not known. Abundance on other smaller rookeries has been stable or increasing. Assuming migration patterns have not changed, abundance in BC is probably proportional to pup production, which has decreased overall (Figure A2-1). The distribution of specimens collected during 1958-74 probably reflects the relative distribution of fur seals: 83% were collected in the Fraser DU area, 10% in the Central DU, and 7% in the North DU.

Northern fur seal diet varies by season and region, but stomach samples collected during 1958-74 indicated that overwintering animals in BC waters primarily forage on Pacific herring and squid (DFO 2007, Perez and Bigg 1986). Other important prey items noted in stomach samples at various times and locations during January-June, 1958-1974 included walleye pollock, sablefish, and salmonids (Perez and Bigg 1986). Eulachon occurred in 33 of 1038 (3.0%) of the stomachs containing prey that were collected off BC, and comprised 2.3% of the overall diet based on a volumetric basis. Eulachon can be locally and seasonally important prey when they are spawning. When examined by region, the diets of four northern fur seals sampled in BC inlets were comprised of up to 10% eulachon (Perez and Bigg 1986). However, these estimates were based on small sample sizes and influenced by a few yearling animals collected in Knight Inlet that were feeding on eulachon near the Klinaklini River when eulachon were spawning. Overall, eulachon made up 1.9% of the diet by volume in the Fraser DU, 5.5% in the Central DU, and 1.7% in the North DU. Northern fur seal stomach data collected in earlier years also indicate that eulachon were consumed by northern fur seals off Barkley and Clayoquot Sounds in 1935 (weighted percent of eulachon in Northern fur seal stomachs was estimated as 3%; Clemens et al. 1936).

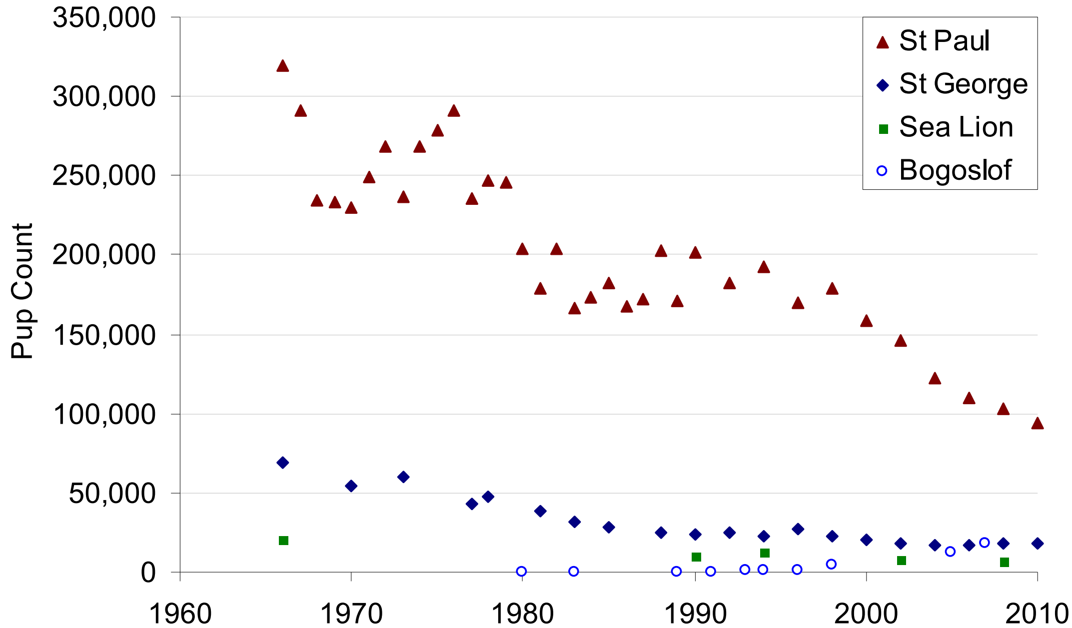


Figure A4-1. Estimated number of northern fur seal pups born at four rookeries in the North Pacific, 1970-2010

<u>California sea lions (*Zalophus californianus*)</u>

Adult and sub-adult male California sea lions began to appear in BC waters in the 1960s. Animals occur during the non-breeding season primarily off southern Vancouver Island (approximately 240 days; Hancock, 1970; Bigg, 1985). Winter survey counts are conducted off southern Vancouver Island to monitor population trends of these animals in BC waters.

California sea lion counts in BC waters increased from a few hundred animals in the 1970s to 1 500 in the 1980s (Bigg 1985; Figure A2-2). Counts peaked at 4 500 animals in 1984 and then stabilized at approximately 3 000 animals (Bigg 1985). Since then, the counts have fluctuated from 1 000 to 3 000 animals (P. Olesiuk,DFO, pers. comm.). Only southern Vancouver Island has been consistently surveyed, as this is where the majority of California sea lions occur. However, the species has extended its range northwards in recent years, and small numbers now occur as far north as the Gulf of Alaska. The only province-wide winter surveys were conducted in 2009-2010 and indicated that relatively few California sea lions occur north of the Fraser DU area (76% of the BC total were counted in the Fraser DU, 19% in the Central DU and 5% in the Northern DU).

California sea lions feed in coastal waters compared with fur seals, but there is considerable overlap in diet (Olesiuk 2009). Scats collected during 1982-1985 indicate California sea lions in BC feed primarily on Pacific herring (35% of their diet), Pacific hake, walleye pollock, dogfish, and some salmon (10% of their diet; Olesiuk and Bigg, 1988). Eulachon were consumed in very small proportions (<0.1% of their diet; Olesiuk and Bigg, 1988; P.Olesiuk, DFO, pers. comm.), with the exception of the mouth of the Fraser River. California sea lions congregate at the Sand Heads Jetty in April-May (Figure A2-3), and eulachon comprise an important prey item (32% of the diet, P.Olesiuk, DFO, pers. comm.).

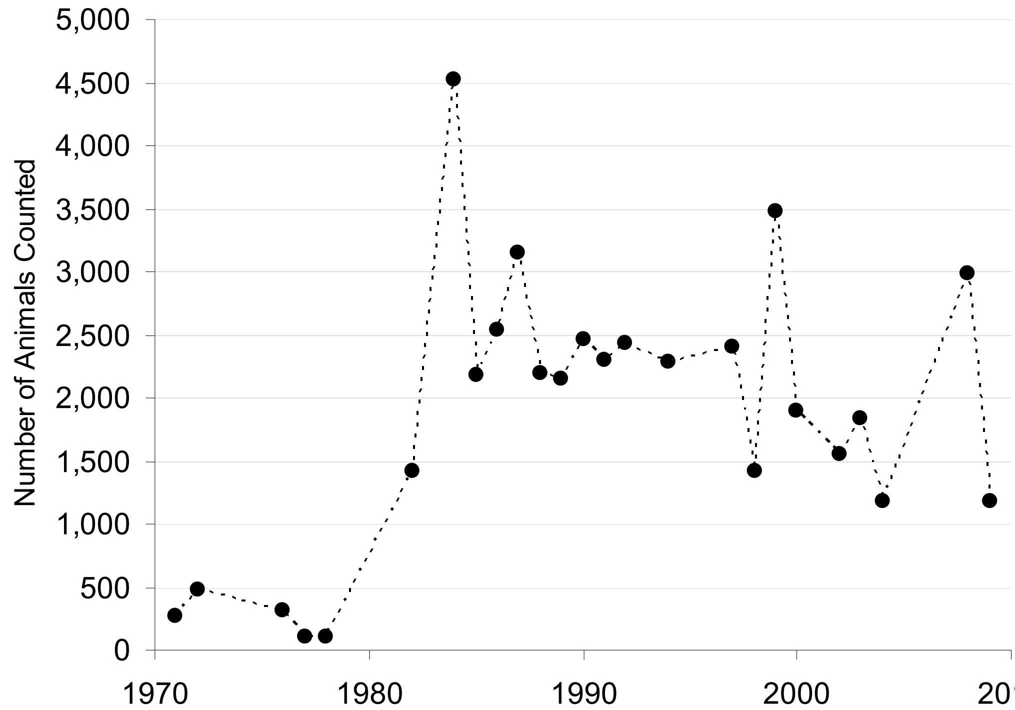


Figure A4-2. Winter counts of California sea lions off southern Vancouver Island, 1971-2009. Counts are averaged where replicates are available (P. Olesiuk, DFO, pers. comm.).

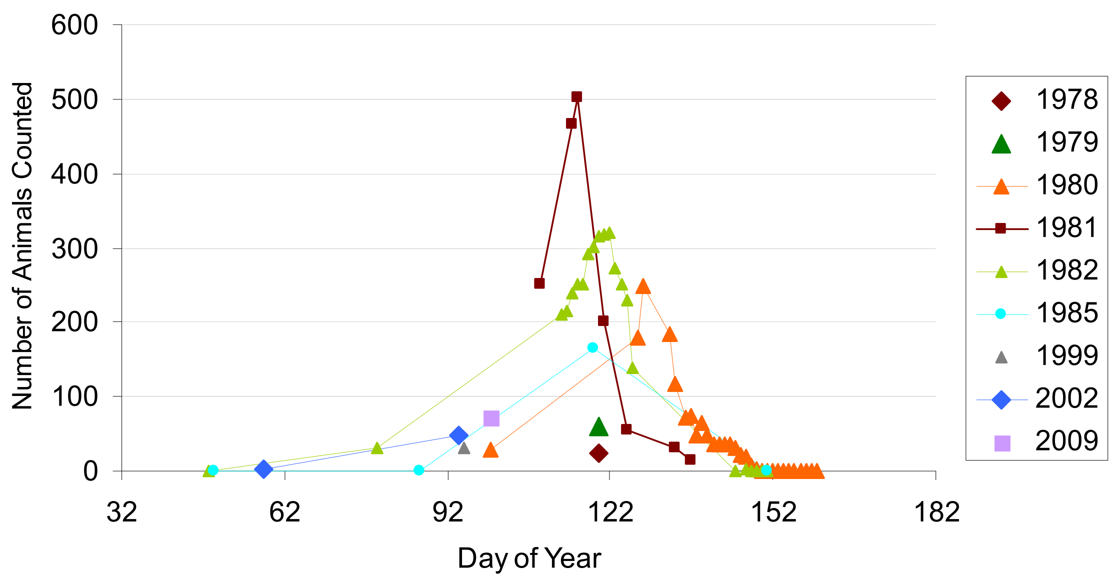


Figure A4-3. Seasonal trends in the numbers of California sea lions at Sand Heads Jetty at the mouth of the Fraser River in select years (P. Olesiuk, DFO, pers. comm.).

Steller sea lions (*Eumetopias jubatus*)

Steller sea lions are year-round residents of BC waters. Breeding animals spend the spring and summer on breeding sites (DFO 2010a; Olesiuk 2008). Territorial males fast during breeding season and females spend a week with newborn pups before making foraging trips. In August-September, breeding animals disperse from rookeries and occupy winter haul-out sites in protected waters and intermingle with California sea lions (DFO 2010a). Non-breeding animals are found at year-round haul-out sites on the outer, exposed coast (DFO 2010a). Province-wide aerial surveys are conducted approximately every four years at the end of breeding season to provide an estimate of pup production and counts of juveniles and adults (DFO 2008).

Survey counts provide minimum estimates of juvenile and adult abundances and an indicator of population trends, during 1971-2010. Survey counts indicate that local breeding populations of Steller sea lions in BC and SE Alaska have been increasing at a rate of 3-4% per year (DFO 2010a) since the mid- 1960s (Figure A2-4). Pup counts also have increased since the mid-1960s (DFO 2008). Applying corrections to account for animals at sea and missed during surveys, abundance of Steller sea lions in BC waters during the summer breeding season in 2010 was estimated as 31 900 animals, with 22% in the Fraser DU, 46% in the Central DU, and 32% in the North DU. Based on winter surveys, abundance outside the breeding season in 2010 was estimated as 48000 animals, with 30% in the Fraser DU, 29% in the Central DU, and 41% in the North DU (DFO 2010a). The seasonal increase during winter is due to the influx of animals from neighbouring rookeries in SE Alaska and Oregon. The increase in Steller sea lion abundance is partly attributable to recovery from hunting and predator-control programs, but in recent years populations have exceeded peak historic levels.

During the summer breeding season, the Steller sea lions prey on forage fish (mainly herring, sand lance and sardine), gadids (mainly hake), salmon, rockfish, flatfish and other prey (Trites, A. and Olesiuk, P.F., unpubl. data). Based on SSFO, eulachon comprised less than 0.1% of the summer diet in BC and SE Alaska. During the non-breeding season, primary prey includes forage fish (mainly Pacific herring and sardine), gadids (mainly Pacific hake and walleye pollock), dogfish, salmon, squid and octopus, eulachon, sandlance, and lingcod (Olesiuk and Bigg 1988). With the exception of Sand Heads, where both California and Steller sea lions congregate when eulachon are spawning, eulachon otherwise constitute <0.1% of the winter diet.

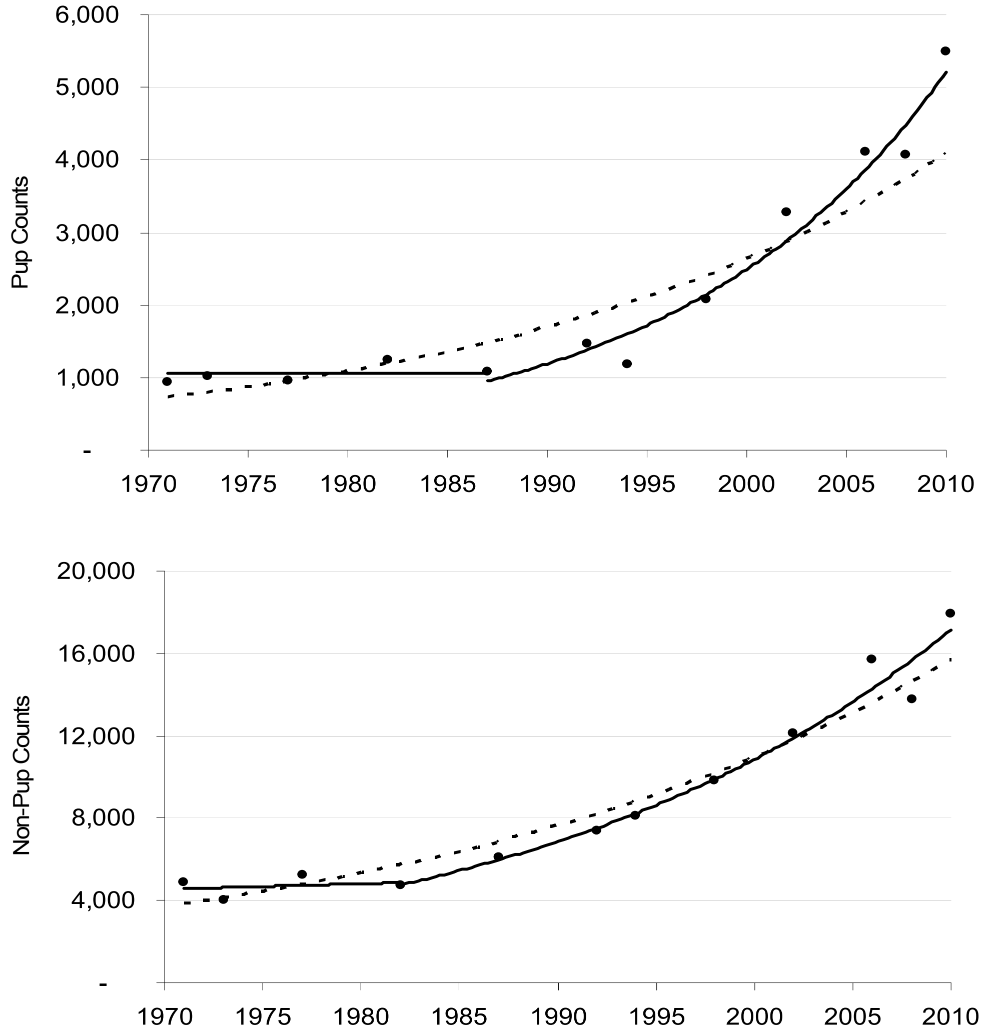


Figure A4-4. Number of non-pup (top panel) and pup (bottom panel) Steller sea lions counted during aerial surveys in BC during 1971-2010. Dashed lines show population trends over the entire study period, and solid lines show changes in population trends during the study period. Figure from DFO (2010a).

<u>Harbour seals (*Phoca vitulina*)</u>

Harbour seals are year-round residents of coastal BC waters (DFO 2010b). They are primarily distributed within 20 km of shore and enter some rivers, such as the Skeena and Fraser Rivers (DFO 2010b). They typically forage within 10-20 km of haul-out sites and demonstrate high site-fidelity (DFO 2010b). Estimates of abundance of the harbour seal population in BC is estimated using standardized counts of animals at haul-out sites. Surveys to determine trends have been conducted in the Strait of Georgia (Figure A2-5, top panel) and in representative areas (index areas) distributed throughout B.C. (Figure A2-5, bottom panel). Corrections are applied to account for animals at sea and missed during surveys.

Surveys of the SOG, harbour seal populations increased exponentially during the 1970s and 1980s and stabilized in the 1990s at approximately 40 000 animals (DFO 2010b; Figure A2-5). In British Columbia waters outside of the Strait of Georgia, trends were similar with counts in index areas (DFO 2010b). Overall, harbour seals in BC have increased ten-fold since the

1970s, with an estimated total of 105 000 animals currently inhabiting coastal waters (DFO 2010b). The harbour seal population increase is due to the recovery of the population, which had been severely depleted by over-hunting prior to their protection in 1970 (DFO 2010b). The population growth rate appears to have stabilized suggesting the population has reached carrying capacity at near-historic levels (DFO 2010b).

Harbour seal diet information is available primarily for the Strait of Georgia (SOG) (Olesiuk et al. 1990, Olesiuk 1993). In the SOG and its estuaries, harbour seal diet varies seasonally but is generally comprised of small- to medium-sized schooling fish, such as hake and herring (Olesiuk et al. 1990, DFO 2010b). Smelts (mainly eulachon) were found to be consumed incidentally and in small quantities (Olesiuk et al. 1990). Eulachon represented about 0.4% (range 0.3 % and 1.8% of seal diets in 1988, which, given certain assumptions of harbour seal energetic requirements, suggests harbour seals in the SOG consumed between 23 and 149 t of eulachon annually in 1988 (Olesiuk 1993). Most of the eulachon occurred in samples collected in the southern Strait of Georgia, with few in the central and northern Strait. Current estimates of harbour seal consumption are unknown, but the seal population has doubled since 1988. Although, harbour seal abundance is currently higher than it was in 1988, the foraging success of seals may be affected by the lower abundance and availability of eulachon in recent years relative to 1988. Scat samples collected in the San Juan Islands indicate that eulachon occurred in 1.8% of the samples (Lance and Jeffries 2007). Little diet data is available for other areas of B.C., but eulachon were an important prey (13% of diet by SSFO) in the few samples (3 collections of 49 samples) collected in Queen Charlotte Strait in summer-fall.

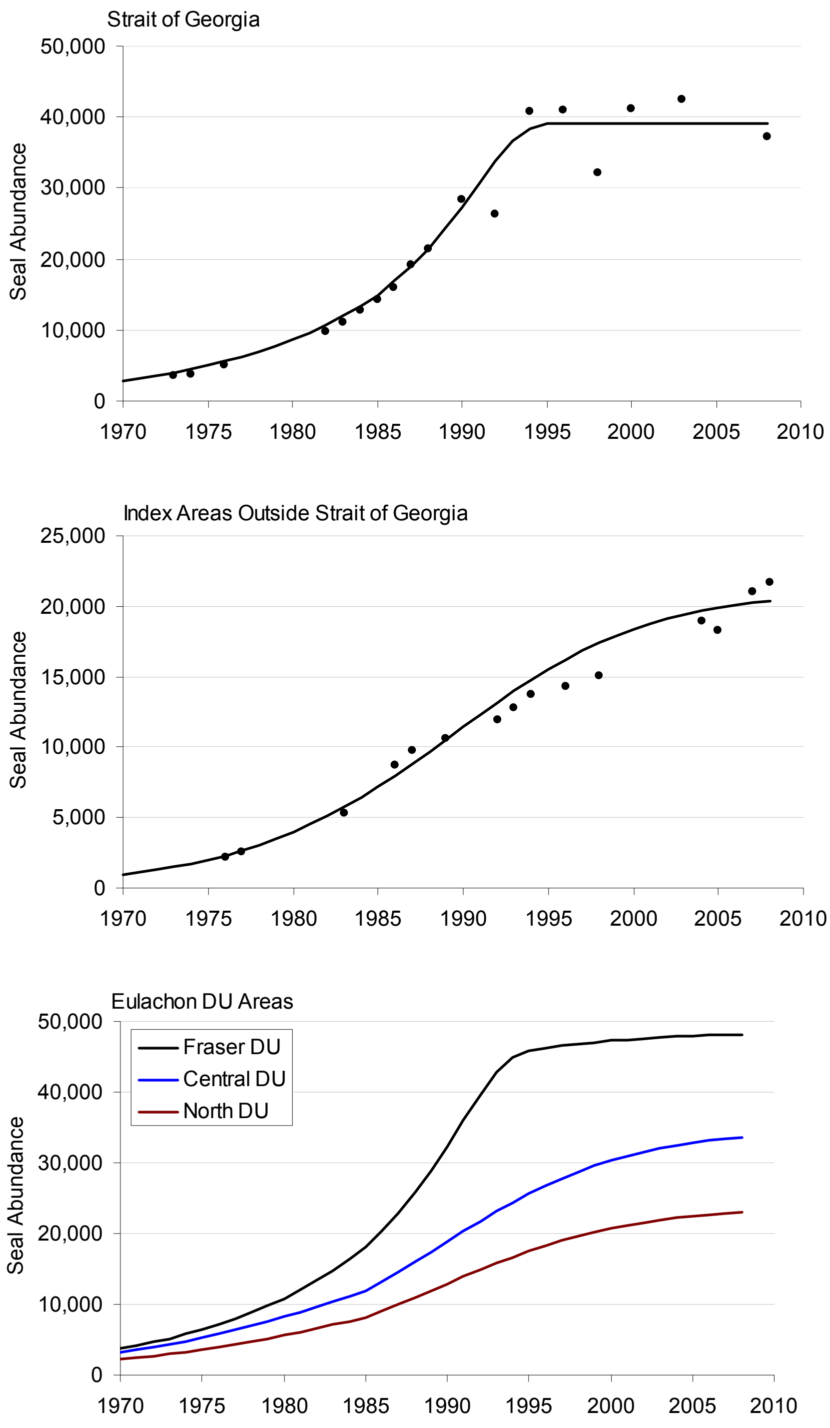


Figure A4-5. Recent trends in harbour seal abundance in the Strait of Georgia (top panel) and in Index Areas outside the Strait of Georgia (middle panel) and in the eulachon DUs (bottom panel). The Index Areas are widely distributed throughout B.C. and include the lower Skeena River, most of the Queen Charlotte Islands, Queen Charlotte Strait and Broughton Archipelago, and the west coast of Vancouver Island. The trend lines represent generalized logistic curves fitted using maximum likelihood methods. Figures adapted from DFO (2010b).

Humpback whales (*Megaptera novaeangliae*)

Humpback whales migrate to BC waters to forage during the spring and fall. Capture-recapture techniques, combined with a photo-identification program to identify individual whales, were utilized to estimate the abundance of humpback whales. Ford et al. (2009) estimated a bias-reduced abundance of humpback whales in BC waters during 1992-2005 using photograph records from May to October, 1984-2006. Ford et al. (2009) estimated that the humpback whale population in BC waters increased at a rate of 4.1% annually since 1992 (Ford et al. 2009; Figure A2-6). In 2006, it was estimated 2 145 humpback whales occupied BC waters in the spring and fall, which is lower than the estimated 4 000 animals thought to occupy BC waters in the early 1900s, prior to large-scale commercial whaling (Ford et al. 2009). The increase in humpback whale abundance is likely due to the recovery from whaling; legal whaling ended in 1966 (Ford et al. 2009).

Humpback whales consume large zooplankton and schooling fish. Euphausiids comprise the majority of prey items consumed by humpback whales (Ford et al. 2009) but proportions of their prey types likely vary spatially and temporally, depending upon availability. Fish prey includes Pacific herring, mackerel, sand lance, Pacific sardines, anchovies, and capelin (Ford et al. 2009). Witteveen et al. (2006) suggested that humpback whales consumed fish in proportion to those available in the water column, as sampled with a midwater trawl, where whales were actively feeding. The majority (>90%) of the pelagic fish biomass sampled by a pelagic trawl off the WCVI includes Pacific herring, Pacific hake, Pacific sardine, chinook salmon, and spiny dogfish (Tanasichuk et al. 1991; Ware and McFarlane 1995; Robinson 1994; McFarlane and Beamish 2001). There is no direct evidence that humpback whales consume eulachon, but if they co-occur with eulachon, it is likely they could consume some.

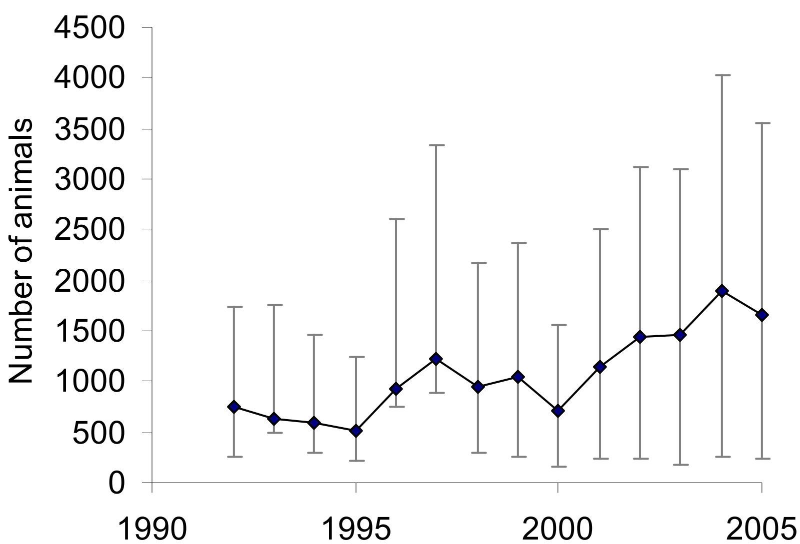


Figure A4-6. Bootstrap-corrected Chapman-modified Lincoln-Petersen abundance estimates (with 95% confidence intervals) for humpback whales in BC waters, 1992-2005. Figure from Ford et al. 2009.

Harbor porpoise (*Phocoena phocoena*)

Harbor porpoises occur year round in inland waters (<200 m depth); they are not considered migratory, but may move to deeper offshore waters during late winter (Dohl et al. 1983, Barlow 1988; DFO 2009; Hall 2004; Heise et al. 2007). More dense aggregations have been observed in the southern SOG and in Juan de Fuca Strait (DFO 2009). Reliable long-term data time series of harbour porpoise population abundance in BC are lacking. Aerial surveys of inside waters of Washington and British Columbia were conducted in 1996 (Calambokidis et al. 1997), 2002-2003 (did not include BC waters; NMFS 2006) and 2005-2006 (Williams and Thomas 2007).

The 2006 U.S. harbour porpoise status report (NMFS 2006) indicates that there may be an increasing trend in the population occupying Washington inland waters; however, there have been few sightings in Puget Sound, Washington, and southern BC where they were commonly observed in the past. Harbour porpoises were commonly observed in Puget Sound in 1942 (Scheffer and Slipp 1948) and commonly sighted from shore in the Juan de Fuca Strait, near Victoria, but sightings are now considered rare (DFO 2009). The harbour porpoise was listed as a species of special concern under SARA in 2003 (DFO 2009).

Opportunistically collected porpoises from individual strandings or incidental captures during 1990-1997 primarily off eastern Vancouver Island were sampled and their stomach contents were examined (Walker et al. 1998). Fish and squid were the primary prey of harbour porpoises (Walker et al. 1998). The dominant fish species consumed was blackbelly eelpout (49.6% of prey consumed); minor amounts of Pacific herring, walleye pollock, Pacific hake, eulachon, and Pacific sanddab were also consumed (collectively representing 2.4% of the prey consumed; Walker et al. 1998). Three species of squid were consumed (46.5% of the diet), and the dominant species was *Loligo opalescens* (Walker et al. 1998). Pacific herring and cod were identified as important prey items in other studies (Gaskin 1984, Hall 2004)

Dall's porpoise (*Phocoenoides dalli*)

Dall's porpoise is widely distributed and commonly observed in deep coastal waters of BC (Williams and Thomas 2007). There are over 1 000 000 Dall's porpoises in the North Pacific; however, the abundance in BC waters is not known (Ford and Olesiuk 2010). In 2004 and 2005, surveys conducted in inside BC waters resulted in estimates of 4 910 (95% confidence interval: 2 700-8 940) Dall's porpoises (Willams and Thomas 2007).

Information on the diet of Dall's porpoises is based on stomach content collection and opportunistically collected carcasses from strandings or bycatch. Opportunistically collected porpoises from individual strandings or incidental captures during 1990-1997 primarily off eastern Vancouver Island were sampled and their stomach contents were examined (Walker et al. 1998). In these samples, fish comprised 99% of the number of prey consumed by Dall's porpoises. The primary fish prey consumed was blackbelly eelpout, representing 96.2% of all prey consumed. Other fish species included Pacific herring, eulachon, walleye pollock, Pacific hake, and Pacific sand lance (Walker et al. 1998). Prey species found in stranded Dall's porpoises in southern BC contained primarily squid, Pacific herring, walleye Pollock, sculpins, myctophids, Pacific hake, polychaetes and bathylagidae (Ford and Olesiuk 2010).

Pacific white-sided dolphin (*Lagernorhynchus obliquidens*)

Very little information exists on the abundance trends of Pacific white-sided dolphins in BC waters. Pacific white-sided dolphins were rarely seen in nearshore BC waters, until the mid-1980s. They returned to BC waters after an unknown period of absence (Morton 2000). Aerial surveys were conducted in 2004 and 2005 and counts adjusted to account for detection errors. Their abundance in BC waters in 2004-2005 was estimated as 25 906 animals (95% confidence interval: 12 872-52 138; Williams and Thomas 2007).

Heise (1997) found Pacific white-sided dolphins feeding on Pacific herring, salmon (pink, sockeye, and chum), Pacific cod, shrimp, and capelin. Morton (2000) found Pacific white-sided dolphins in the Broughton Archipelago feeding on Pacific herring and capelin, with indications that they may have fed on Pacific sardine and eulachon, during 1989-1998.