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**A framework for an ecosystem-based
approach to managing the Strait of
Georgia, British Columbia**

**Un cadre de travail pour une approche
écosystémique de la gestion du Déroit
de Géorgie en Colombie-Britannique**

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ABSTRACT

This framework provides strategic direction on an ecosystem-based approach to managing human interactions with the Strait of Georgia marine system. It adopts an ecosystem-based management rather than a narrower ecosystem-based fisheries management approach, although the latter is better developed internationally and so has an important influence on this paper. The framework proposes the overarching goal of ecosystem-based management in the Strait of Georgia as “to protect ecosystems and their components from serious or irreversible harm, but also to allow the use of these ecosystems and components as long as the social-ecological Strait of Georgia system is sustainable”. The framework identifies the essential components of an ecosystem-based approach for the Strait of Georgia as 1) continuing management practices to ensure conservation of individual stocks; 2) preventing by-catch of non-target species; 3) avoiding habitat disruptions; 4) developing a more integrated approach to spatial management; and 5) considering the impacts of anthropogenic stressors to trophic interactions and ecosystem function. These build on existing DFO policies relating to the sustainable fisheries framework, fisheries on forage species, and benthic habitat disruptions, but also represent new directions (e.g. on trophic interactions).

The preliminary findings of the DFO Strait of Georgia Ecosystem Research Initiative are summarised, including contributions to understand the structure and function of the Strait of Georgia ecosystem (identification of important locations for biological activities and important trophic linkages), to develop predictive models to synthesise this understanding and to provide ecosystem-based management tools, and to forecast the future of the Strait of Georgia with climate change and other stressors. These findings are used to identify a set of environmental indicators of the ‘state’ of the ecosystem, including sea surface temperature, near surface stratification, deep-basin dissolved oxygen concentrations, Fraser River flow, spring phytoplankton bloom timing, spring copepod biomass, abundance of juvenile salmon, abundance of herring, abundance of Harbour seals, and wind speed. It is proposed that these be monitored and reported regularly by the Canadian Science Advice Pacific’s Fisheries and Oceanography Working Group, including analyses of the potential impacts of the values of these indicators to the Strait of Georgia ecosystem. These findings are also used to identify the dominant anthropogenic stresses on the Strait of Georgia marine ecosystem, including fishing, introductions of non-native species, fish culture activities, contaminants, and development and land use changes. For each of these stressors it is recommended to follow the DFO precautionary approach to identify critical thresholds beyond which the Strait of Georgia ecosystem would be substantially altered in some way. These thresholds would form the basis for management of these stressors within an ecosystem context.

Significant knowledge gaps remain, for example the diets of pinnipeds in the Strait, the abundance and ecological roles of Pacific hake, and the abundance, interactions, and use of

particular locations within the Strait by juvenile salmon. Critical next steps include continued development of integrated ecosystem models, design and implementation of a targeted ecosystem monitoring program in the Strait of Georgia, reduction of scientific uncertainties concerning these significant knowledge gaps, and a scenario-building activity that would look forward to the potential ecosystem impacts and management issues relating to the expected significant changes due to climate and increasing anthropogenic stresses.

This paper also identifies some governance issues that have been encountered elsewhere in moving towards ecosystem-based management of marine systems, including clarification of the objectives, bridging science and policy, changing public perceptions to consider the Strait as a connected system, and to facilitate community participation.

RÉSUMÉ

Ce cadre de travail fournit une direction stratégique pour une approche écosystémique de la gestion des interactions humaines avec le système marin du Détroit de Géorgie. Il adopte une gestion écosystémique plutôt qu'une gestion écosystémiques plus étroite des pêches, malgré que cette dernière soit plus développée sur le plan international et qu'elle ait donc une influence importante sur ce document. Le cadre de travail de gestion écosystémique proposé a pour l'objectif principal de « protéger les écosystèmes et leurs composantes de dommages sérieux et irréversibles tout en permettant l'utilisation de ces écosystèmes et composantes tant que le système socio-économique du détroit soit durable ». Le cadre de travail identifie les composantes essentielles d'une approche écosystémique pour le détroit de Georgie comme 1) continuer les pratiques de gestions pour conserver les stocks individuels; 2) prévenir la prise accessoire des espèces non ciblées; 3) éviter la destruction de l'habitat; 4) développer une approche plus intégrée pour la gestion spatiale; et 5) considérer l'impact des stress anthropogéniques sur les interactions et fonctions écosystémiques. Ces mesures sont basées sur les politiques existantes du MPO reliées au cadre de travail des pêches durables, des pêches des espèces fourragères et de la destruction de l'habitat des fonds marins, mais représentent aussi de nouvelles orientations (p.ex. sur les interactions trophiques).

Les résultats préliminaires de l'initiative de Recherche écosystémique sur le détroit de Georgie sont présentes, incluant des contributions sur les structures et fonctions de l'écosystème du détroit, sur des modèles de synthèse pour comprendre le système et aider à sa gestion, ainsi que des outils pour prédire le futur du détroit sous l'influence du changement climatique et autres stress. Ces résultats sont utilisés pour établir un ensemble d'indicateurs environnementaux de l'état de l'écosystème, incluant la température de surface de la mer, la stratification près de la surface, la concentration d'oxygène en eau profonde, le flux du fleuve Fraser, la floraison printanière planctonique, la biomasse de copépode au printemps et l'abondance des jeunes saumons, des harengs et des phoques. On propose que ces indicateurs soient mesurés d'une manière régulière et rapportés par groupe de travail sur les pêches et l'océanographie du Pacifique, incluant l'analyse des impacts potentiels sur l'écosystème. Ces résultats permettent aussi d'identifier les stress anthropogéniques principaux sur le détroit, incluant la pêche, les espèces envahissantes, les activités de culture de poisson, les contaminants, et le développement et changement d'utilisation de l'environnement. Pour chacun de ces stress, on recommande de suivre l'approche de précaution du MPO pour identifier des seuils critiques pour lesquels l'écosystème du détroit serait sérieusement

compromis. Ces seuils formeraient la base d'une gestion de ces stress dans un contexte écosystémique.

Il y a toujours certains manques importants de connaissance, par exemple sur la diète des pinnipèdes, l'abondance et le rôle du merlu, et l'abondance, interactions, et usage d'emplacements particuliers pour les jeunes saumons. Les étapes importantes à suivre incluent le développement et intégration des modèles écosystémiques, la conception et implémentation d'un programme de monitoring ciblé dans le détroit, la réduction des incertitudes scientifiques par rapport à ces manques importants de connaissance, et une activité de construction de scénario qui projetterait de l'avant les impacts écosystémiques potentiels et les questions de gestion liées aux changements importants du climat et aux stress anthropogéniques grandissants.

Ce manuscrit identifie également quelques questions de gouvernance qui ont été traitées dans d'autres cas de développement d'une approche écosystémique des systèmes marins, incluant la clarification des objectifs, le lien entre science et politiques, les perceptions changeantes du public sur le détroit, et la participation communautaire.

1. INTRODUCTION

1.1 ECOSYSTEM-BASED MANAGEMENT OF MARINE SYSTEMS

The history of managing human interactions with marine systems has focused on single issues, for example single fish stocks, or single habitat alterations. Increasingly, however, this approach is being seen as insufficient for the stresses and complexities of the demands placed on marine systems today, and a modern approach is now favoured that should take account of the interactions among stressors and among components of marine ecosystems. The term “ecosystem-based management” has come to embody a more holistic and integrative approach to regulating human interactions with marine systems. McLeod et al. (2005) have defined ecosystem-based management as:

“an integrated approach to management that considers the entire ecosystem, including humans. The goal of ecosystem based management is to maintain an ecosystem in a healthy, productive and resilient condition so that it can provide the services humans want and need. Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity or concern; it considers the cumulative impacts of different sectors. Specifically, ecosystem-based management:

- emphasizes the protection of ecosystem structure, functioning, and key processes;
- is place-based in focusing on a specific ecosystem and the range of activities affecting it;
- explicitly accounts for the interconnectedness within systems, recognizing the importance of interactions between many target species or key services and other non-target species;
- acknowledges interconnectedness among systems, such as between air, land and sea; and
- integrates ecological, social, economic, and institutional perspectives, recognizing their strong interdependences.”

The objective of this document is to provide strategic direction towards the development of an ecosystem-based approach to manage human interactions with the Strait of Georgia. The paper outlines the proposed overarching vision and goals for an ecosystem-based approach to managing human interactions with the Strait of Georgia, establishes the design properties for such an approach, recommends indicators of ecosystem state and their needs for observations and monitoring, and identifies some of the governance issues that need to be considered.

The paper is organised into five main sections. The remainder of this Introduction briefly reviews the rationale within Fisheries & Oceans Canada (DFO) for moving to an ecosystem-based approach, in particular as described in existing DFO policies, and summarises steps taken in other jurisdictions towards developing similar ecosystem-based management approaches. Section 2 describes the DFO Ecosystem Research Initiative (ERI) pilot project for the Strait of Georgia and its preliminary results. These form the foundation for Section 3, which proposes an ecosystem-based framework for managing human interactions with the Strait of Georgia, B.C. Section 4 discusses critical data and knowledge gaps, and the potential next steps to implementing this framework, while Section 5 provides a brief overview of some of the governance issues to achieve ecosystem-based management for the Strait of Georgia. Although most international efforts to date have focused on ecosystem-based fisheries management (EBFM), the

framework proposed in this paper attempts to go beyond to consider ecosystem-based management (EBM) more generally. A central tenet of this paper is that management is of human interactions with marine ecosystems, and not management of “the ecosystem” itself. The entire complex of the biophysical ecosystem and the human population around the Strait of Georgia is considered as a marine social-ecological system (e.g. Perry et al., 2010).

1.2 WHY THE NEED FOR AN ECOSYSTEM-BASED APPROACH TO THE STRAIT OF GEORGIA?

DFO is being directed to take an ecosystem-based approach to many of its activities, i.e. an approach which recognises the importance and inter-connections among places and processes across an ecosystem. Ecosystem concepts have been included as key points in Canada’s Oceans Act and in several DFO policies, including the sustainable fisheries framework, forage species policy, benthic impacts policy, and the integrated ecosystem science framework.

O’Boyle and Jamieson (2006) and Jamieson (2010) describe how the proclamation of Canada’s Oceans Act in 1997 provided the legislative basis for DFO to adopt a holistic approach to the management of marine systems which would consider the impacts of all human activities on Canada’s marine systems. Within DFO, this has been broadly defined as Integrated Management, being “a commitment to planning and managing human activities in a comprehensive manner while considering all factors necessary for the conservation and sustainable use of marine resources and the shared use of ocean spaces” (DFO, 2002). These publications noted that moving towards a holistic, integrated, ecosystem-based approach to managing Canada’s marine resources will require new concepts and new tools.

Ecosystem concepts and management approaches are also embedded within the DFO Sustainable Fisheries Framework (DFO, 2010a). This framework follows DFO’s conservation and sustainable use policies to incorporate precautionary and ecosystem approaches into fisheries management decisions to ensure the continued health and productivity of Canada’s fisheries and fish stocks, while protecting biodiversity and fish habitat. DFO’s policy on new fisheries for forage species (DFO, 2010b) recognises that forage species play special roles in marine ecosystems and are substantial food sources for many fish, marine mammals, and other aquatic animals. It recognises that these ecological relationships place additional constraints on how the sustainable harvesting of forage species can take place. Further, mid-trophic level forage species are often key components between lower and higher trophic levels of marine ecosystems, and therefore fishing these species risks damage more widely through the ecosystem. This policy provides a framework to enable fisheries on forage species to be conducted in ways which are compatible with conservation of the full ecosystem, based on 10 ecological and fisheries management principles. DFO’s policy for managing the impacts of fishing on sensitive benthic areas (DFO, 2010c) recognises that benthic ecosystems are essential components of Canada’s marine environments, providing habitats to diverse species of plants and animals which support complex ecosystems. This policy describes steps to protect benthic habitats, for example by restricting fishing and limiting or prohibiting the destruction of sensitive benthic habitats and species. It is guided by the principles of an ecosystem approach, conservation of fisheries resources and fish habitat (defined as sustainable use that safeguards ecological processes and genetic diversity for present and future generations), and the precautionary approach, which recognises that a lack of adequate scientific information will not be used as a reason for

failing to take measures for the conservation or protection of fish or fish habitat. Important elements of this policy include assembling and mapping data and information on the extents and locations of such habitats, and developing an ecological risk assessment framework to identify risks that fisheries may pose to ecosystem components.

DFO's Science Management Board identified eight priority areas for science in support of ecosystem-based management (DFO, 2007a):

- 1) setting clear objectives for monitoring and protection
- 2) developing ecosystem indicators and reporting systems
- 3) developing risk-based frameworks
- 4) generating integrated information for fisheries management
- 5) identifying habitats of special importance and sensitivity
- 6) considering impacts on aquatic biodiversity
- 7) understanding pathways of effects that are driving changes
- 8) understanding climate variability and impacts on resources.

In January 2011, DFO announced a new governance structure for the department, focused on four strategic outcomes: economic prosperity, sustainable ecosystems, safety and security, and integrated business management. The economic prosperity theme includes integrated fisheries resources management, and the sustainable ecosystems theme includes integrated oceans management such as marine conservation tools and ecosystem assessments.

Taken together, DFO's commitment to move towards and implement an ecosystem-based approach to managing Canada's marine resources is clear and reflects the diversity of activities in which DFO is involved. However, the difficulties in developing such an approach are also enormous, considering the complexities of marine social-ecological systems. Clear examples of how to implement and manage based on an ecosystem approach for marine systems are currently lacking in Canada. Clear examples are also lacking internationally, although several conceptual approaches have been proposed for different countries and regions.

1.3 ECOSYSTEM-BASED MANAGEMENT CONCEPTS

Ecosystem-based management is currently a "hot topic" of research globally, with a burgeoning number of scholarly papers and books (e.g. McLeod and Leslie, 2009; Diekmann and Möllmann, 2010; Link, 2010). To date, most of these publications have focused on ecosystem-based fisheries management although, as noted above, the issues include much more than fisheries. This section does not attempt a comprehensive review of this topic (of either EBFM or EBM), but describes selected approaches that are deemed relevant to the Strait of Georgia and/or which have NE Pacific examples.

In Canada, considerable conceptual development on the bases of EBM has taken place, in particular under the term "integrated management" (e.g. O'Boyle and Jamieson, 2006). High-level conceptual objectives have been proposed (e.g. Figure 2) and a process for unpacking these conceptual objectives to derive operational objectives, indicators, and reference points have been developed (Table 1). A preliminary set of science-based conservation objectives was proposed for the Pacific North Coast Integrated Marine Area (PNCIMA) following DFO protocols (DFO, 2007b), although these have not been developed further at this time. Gaydos et al. (2008) have proposed

ten principles for the design of healthy coastal ecosystems, using the Strait of Georgia region as an example:

- 1) ecosystems do not conform to political boundaries
- 2) account for ecosystem connectivity
- 3) understand the food web
- 4) avoid fragmentation
- 5) respect ecosystem integrity
- 6) support nature's resilience
- 7) value nature and its services
- 8) watch wildlife health
- 9) plan for extremes rather than focus on mean conditions
- 10) share the knowledge.

Under the Sustainable Fisheries Framework, DFO has been developing a general ecosystem-based approach to fisheries management that considers the impacts of the ecosystem on fish production and fisheries, and the impacts of fishing on the ecosystem, with the latter focused on productivity, biodiversity, and habitat (Figure 3). Under the productivity theme, the objective is to establish clear rules for the management of fisheries that support healthy and productive fish populations. This includes the application of a precautionary approach, consideration of the roles of forage species, and consideration of the roles of top predators. The objective of the biodiversity theme is to manage fisheries in a manner that minimizes the impact of fishing on marine biodiversity. It includes protecting species at risk, the effective management of by-catch, and addressing impacts of lost fishing gear. The objective for the habitat theme is to manage fisheries so as to minimize their impacts on marine habitat, and includes fishing in sensitive benthic areas and developing risk assessment models of fishing activities.

PICES Working Group 19 on "Ecosystem-based management science and its application to the North Pacific" (Jamieson et al., 2010) provides an overview of marine EBM approaches in the North Pacific. It recognises that, to date, management of human activities in marine environments has largely focused on individual sectors, for example commercial fisheries, without explicit consideration of non-commercial species and broader ecosystem impacts. Past practices have typically focused on single species, with progress towards an ecosystem-based approach occurring when more factors and species are taken into account in management decisions. This Working Group developed a typology of ecosystem approaches to the management of marine systems, ranging from traditional single factor management to integrated management in an ecosystem context (Table 2). They concluded that the approaches to EBM by member nations of PICES (Canada, China, Japan, Korea, Russia, and the United States) are diverse, which was interpreted as experimenting with the concept of ecosystem-based management consistent with each country's experiences and circumstances.

A number of methods and tools have been proposed to aid the development of ecosystem-based fisheries management. These range from qualitative (such as expert judgment) to quantitative (such as based on data and models) approaches, and from fish populations to the entire social-ecological system (Figure 4). The United States is moving ahead with the Integrated Ecosystem Assessment (IEA) concept as their framework for ecosystem-based management (Levin et al., 2009; Tallis et al., 2010). This concept (Figure 5) proposes five steps for ecosystem assessments: 1) **scoping**, in which the ecosystem objectives and threats are identified; 2) development of **indicators** to track ecosystem status and trends relative to the identified objectives; 3) the setting of

thresholds and targets for each set of indicators that represent some ‘desired’ state of the system; 4) a **risk analysis** of how each indicator may be affected by a range of threats and the current position of the indicator in regards to these threats (i.e. the sensitivity of each indicator relative to human or natural disturbance and the likelihood of each disturbance; Tallis et al., 2010, p. 343); 5) **management strategy evaluation** of how proposed management actions may affect the system (and the indicators); 6) **monitoring** the outcomes of management actions via the selected set of indicators (and other outcomes); and 7) **evaluation** of how well the management strategies are performing relative to the objectives. A number of studies have used various elements of this approach to develop integrated ecosystem assessments in the United States and elsewhere (summarised in Levin et al., 2008). Although none of these have as yet completed the full process, the Puget Sound Partnership in Washington State is one of the most advanced, having conducted public discussions on objectives, an analysis of potential indicators, the setting of thresholds for data-poor situations, preliminary risk analyses (including summaries of existing status and threats) and an evaluation to identify priority strategies for Puget Sound (McClure and Ruckelshaus, 2007; Tallis et al., 2010). Their process identified six overarching ecosystem “issues” for Puget Sound: species and food webs; habitats; water quality; water quantity; human health; and human well-being (Tallis et al., 2010).

Hilborn (2011) suggests that there are “core” and “extended” components to ecosystem-based fisheries management. The core components are: a) doing single species fisheries management ‘right’, such as keeping fishing mortality at or below F_{MSY} , and keeping fleet capacity in line with the resource potential; b) preventing by-catch of non-target species, for example by gear modifications, incentives for using by-catch avoidance measures, or by area and seasonal closures; and c) avoiding disruptive habitat fishing practices, for example by closing areas or banning specific fishing methods in sensitive areas. He views the extended components as d) spatial-based management, for example closing areas to protect spawning stocks, juvenile fish or sensitive habitats, designating areas reserved for industrial uses (e.g. aquaculture) or to meet social objectives (such as recreational and native fisheries), reducing by-catch, and so on to more formal Marine Protected Areas; and e) consideration of trophic interactions, which might include modifying single species management to account for ecosystem impacts, protection of mid-trophic level forage species, and identifying ecosystem-based reference points that lead to altering exploitation rates to achieve desired ecosystem states. Hilborn (2011) sees two major impediments to these extended components: high costs of implementation, and uncertain (unclear) objectives.

2. THE STRAIT OF GEORGIA ECOSYSTEM RESEARCH INITIATIVE

The Strait of Georgia is a semi-enclosed marine basin between Vancouver Island and mainland BC (Figure 1). Its waters support an estimated 3000 species of plant and animal life and approximately 75% of the population of BC lives within close proximity. The Strait of Georgia was chosen as the location of the DFO Pacific Ecosystem Research Initiative (ERI) because of its rich and diversified ecosystem as well as of the current and anticipated environmental pressures.

In 2010, a CSAS research document was prepared to summarize existing status and trends for the Strait of Georgia (Johannessen and McCarter, 2010). The authors

describe how the ecosystem has shown resilience in the past, having recovered from numerous stressors and climatic variations and how it is not known how the ecosystem will respond to the cumulative effects of human and climate driven changes in the future. The Strait of Georgia is warming at all depths (1970-2006), while the concentration of oxygen in the deep water is decreasing. The Fraser River's summer temperature has increased (1942-2006), while its summer flow has decreased, resulting in increased pre-spawning mortality of Pacific salmon. Zooplankton abundance is decreasing in the Strait of Georgia, and the maximum biomass is peaking as much as 50 days earlier now than in the 1970s. These changes threaten the survival of some marine birds, and may threaten late-migrating juvenile salmon, but a directly attributable effect on planktivorous fishes has not been demonstrated. The populations of several piscivorous fishes (coho and Chinook salmon, ling cod, Pacific cod and inshore rockfish) have declined (1986-2006), while those of predominantly planktivorous fishes (chum and sockeye salmon, Pacific hake, spiny dogfish, walleye pollock) are relatively stable or within the normal range of historical variability (1981-2006). Resident killer whales are threatened because of contaminants, traffic and declining availability of prey (primarily Chinook salmon). The populations of all the pods were stable or increasing locally until the mid-1990s, when they all began to decline simultaneously, closely correlated with a coast-wide decline in the population of Chinook salmon. Since 2001 the killer whale population has increased again, though more gradually than it declined.

The overall objective of the Strait of Georgia ERI project is to establish the basis for the management of ecosystem and human interactions in an integrative ecosystem framework. More specifically, it addresses the following departmental priorities:

- 1) Understanding how this system works (What controls the **productivity**?)
- 2) Identifying the drivers of change acting on the Strait and how these drivers might change in the future (What controls the **resilience**?)
- 3) Developing science-based management and decision-making tools to support healthy and sustainable marine resources

Within this initiative, a series of projects have been conducted to address the impacts of climate variability and human impacts on ecological processes in the strait. In addition to decadal-scale influences of climate forcing on the ecosystem components, there are strong interannual variations in, for example, the timing of the Fraser River freshet, frequency and intensity of the spring phytoplankton bloom. In particular, the various projects have been conducted to assess the current ecosystem state in relation to climate record by examining the influence of different forcing acting, at different scales, on ecological processes, and by identifying the specific mechanisms leading to changes in the ecosystem state or to resilience to such changes. A variety of approaches have been adopted, including process-oriented studies and modeling work, to evaluate the role of specific mechanisms in governing the observed and future variability of the physical-chemical environment, marine populations, and biogeochemical fluxes.

2.1 SYNTHESIS OF ERI PROJECT ACTIVITIES

In this section, a brief summary of each the projects of the Strait of Georgia ERI is presented, grouped under common themes. In addition, more detailed reports are included in the Appendix.

2.1.1 Ecosystem structure and function

a) Temporal variability

Short term variability [Appendix A1]

Short-term variability, including rainstorms, windstorms and variability in river discharge, is expected to increase with climate change. The purpose of this study was to determine the contribution of short-term events to the productivity and carbon cycle of the Strait of Georgia. To that end, we deployed moorings in June 2008 in the northern and south-central Strait that comprised sediment traps and instruments to measure water properties at 50 m depth, together with a shorter deployment of instruments to measure oxygen and pH at depth. We also collected water samples at the mooring sites and along a transect across the Fraser River plume and sampled eight rivers that discharge into the Strait of Georgia. Preliminary interpretation indicates that windstorms can precipitate abrupt and long-lasting change in mid-depth water properties, particularly in the northern Strait, where the influence of the Fraser River is less than in the south. Rainstorms are significant to particle flux in the northern Strait, where most of the direct freshwater input comes from rain fed rivers. The comparison between the two sites implies that coastal seas that receive significant freshwater input are likely more resilient to changes caused by wind and rainstorms than are those margins that do not receive much fresh water.

Contaminants: Persistent Organic pollutants (POPs) in seals [Appendix A7]

The approximately 35,000 harbour seals in the Strait of Georgia are omnivorous but have a preference for small, lipid-rich prey including Pacific hake, Pacific herring and Pacific tomcod. The harbour seal has become a useful 'sentinel' of marine food web contamination because of its abundance, distribution, high trophic level, non-migratory nature, and relative ease of handling. Our objectives with this study were: collect biopsies from free-ranging harbour seals to characterize the concentrations of two priority POPs (PCBs and PBDEs); develop a new health 'toolbox' in collaboration with the University of Victoria using a harbour seal-specific genomics approach, and apply this to biopsies; interpret contaminant and/or health findings through to the year 2030 in the context of effects thresholds. Harbour seals in the Strait of Georgia are still at risk for health risks associated with exposure to legacy PCBs, but regulations enacted in 1977 will reduce these risks substantially by the year 2030. Predictions for the structurally-related PBDEs are more difficult, as regulations enacted today have yet to result in a clearly detectable temporal trend in environmental matrices. In the absence of any regulations, the current doubling time of 3.1 years in Puget Sound harbour seals would lead to a Strait of Georgia population at risk for health effects in 2030 (0% below TRV). However, if PBDE concentrations decline in seals with a half-life of 10 years beginning in 2006, 96% of seals are predicted to fall below the TRV by the year 2030. Initial indications suggest that PBDE levels have begun to respond to regulations and source control, increasing the likelihood that our second scenario may bear out. The main value of these scenarios is to illustrate that PBDE concentrations in harbour seals are likely to be similar to PCBs in 2030. In these scenarios, we assume a similar environmental response of PBDEs to the PCBs, and a similar health effects threshold. Further research is needed to clarify these assumptions.

Contaminants: unexplored major stressors, eEDCs and PPCPs [Appendix A29]

Major current sources of coastal and freshwater pollution in BC are effluents from sewage treatment plants, effluents from pulp mills and agricultural runoff all of which are major sources of estrogenic endocrine disrupting chemicals (eEDCs). The continuously increasing urbanization of coastal areas and an aging population are expected to cause increases in the emissions of eEDCs, pharmaceuticals and personal care products (PPCPs) from sewage treatment plant effluents into the Strait of Georgia. Our aim is to obtain an understanding of the impacts of eEDCs and PPCPs on the marine ecosystem in order to (i) assess the current state of the ecosystem in terms of environmental loadings, (ii) develop bio-indicators for continual assessment of the impacted areas and (iii) develop models that will explore the fate of these emerging contaminants.

This study contains 2 components: a) make measurements of selected EDCs and PPCPs in abiotic media (sediments) and some biota samples (invertebrates and representative ground fish) collected near potentially impacted areas, such as the Iona GVRD municipal outfall, Ladysmith harbor, and at reference sites; and b) assess and apply computer simulation models to investigate the fate and environmental behaviour of these emerging contaminants in the ecosystem. An assessment of the current conditions in terms of environmental levels and linkage to what these mean in terms of biological impacts will be performed.

Zooplankton Data Recovery and Analysis [Appendix A4] [Appendix A30]

The initial activities of our project have been to: consolidate recoverable zooplankton data into a single and secure digital archive; do quality control assessment for individual samples, and either hide or adjust records with large errors in reported flowmeter readings or extent of subsampling; document meta-data characteristics for the remaining “good” data (sampling gear, depth range, horizontal location, date and time of sampling, laboratory processing methods, and detail and breadth of taxonomic resolution), to help decide which subsets of samples, and aggregations of variables, are best intercomparable, and in what “currency” (in increasing information content: total biomass, biomass within major taxa, biomass within species); and classify the intercomparable samples into statistical categories based on season (month of sampling), depth, horizontal location, and taxonomic resolution. The following effort was made in two major steps: calculate climatologies (monthly geometric averages across years of available monthly data within a region) for the above spatial classifications and taxa; calculate “anomaly time series” that quantify log-scale deviations of the data from their respective climatologies. Both approaches suggest a large change in the Strait of Georgia zooplankton community before and after 1998-2000. This change involves both decreases in total biomass of copepods and other crustaceans, and changes in species composition within the major taxonomic categories such that the decade from 2000-2009 may have provided a “lean cuisine” diet for plantivorous predators.

Plankton samples were collected by the Strait of Georgia program on numerous occasions between 1990 and 2010. The collections are from a variety of projects, time, and areas and were collected from different vessels and with different crew. In general, samples were collected from 50m and 200m+. There were 13 stations in the Strait of Georgia that were sampled from bi-weekly to occasionally depending on location and year. Only a portion of the collected samples have been analyzed and the data from this have been collated into an Access database. Analysis of these data is ongoing. Our database identifies the different levels of taxonomic information. The details of analysis level and specifics of Access database parameters are currently being documented. When this is completed the database will be transferred to IOS to be included in the DFO plankton database. A second and valuable source of information is in samples that

were collected but have not been analyzed. These samples were collected throughout the Strait of Georgia, at 50m and 200m+ and across multiple years. We now have a set of data that can be used to test the hypothesis that there has been a major change in the relative abundance of *Neocalanus plumchrus* from the early 1970s to the late 1990s.

Groundfish [Appendix A27]

This project examines groundfish variability in the Strait of Georgia from commercial catch data. At present groundfish stocks tend to be highly localized and relatively small (with two exceptions) compared to more productive areas like the Queen Charlotte Basin. Most species are distributed between 50 and 100 m. Species include various flatfishes and rockfish species along with Pacific cod, hake, pollock, dogfish and lingcod. There are three gear types employed in commercial fisheries, bottom trawl, midwater trawl, and hook and line. There is presently no commercial fishery for Halibut in the strait, likewise the Strait has been closed to commercial lingcod fishing since 1991 and the inshore rockfish fishery was drastically reduced in 2000. At present the only significant commercial hook and line fishery is for Spiny dogfish. In recent years the fishery has focused on small landings of flatfish and cottids to local live markets. Most of the trawl fishery has taken place in the mid-southern portion of the Strait. Midwater trawl has been used to target Pacific Hake and Walleye Pollock. Total all species landings have declined from around 2000 t in the early 1950s to around 500t at present. Total landings for flatfish species declined from 205 t to 100 t over the same period. Pacific cod landings declined from 1300t in 1954 to zero by 1995. By far the largest fishery in terms of biomass removals has been mid-water trawl and this fishery targets Pacific Hake and Walleye Pollock. It peaked at 20,000 mt in 1995 and fluctuates based on market conditions and size of available Hake. Hake and dogfish probably make up most of the resident fish biomass. Lingcod biomass declined from 14000t in the 1920s to under 2000t by the early 1990 at which time the commercial fishery was closed. The recreational fishery was closed in 2002 and reopened in 2005 after the stock had shown some recovery. It has continued to recover since that time. A decline is apparent for all species. It is greatest for Dover sole and Pacific cod and least apparent for Rock sole and English sole. Environmental factors have been shown to be important for a number of species in areas outside the strait and may be important for the strait as well. Most notable are temperature and transport at the time of egg and larval stages. The overall range of species is considered to be a general indicator of how species will respond to environmental forcing. A number of species are near the limit of their geographic range and significant changes in the environment may affect their abundance. A temperature increase may favour Dover sole, English sole and Petrale sole while it could negatively impact Pacific cod and rock sole.

b) Spatial variability

Dynamic bathymetry [Appendix A15]

High resolution (10 m) bathymetry tiles have been added or updated for the greater part of the strait, from Juan de Fuca Strait and the southern Gulf Islands to the Bute and Toba inlets area. Eight existing tiles were updated and one new tile was created with 2010 data. Low resolution bathymetry and bottom type data sets have also been enhanced through the digitizing of three FS in the Okisollo Channel – Bute Inlet area.

Localised bathymetry changes are happening in the strait – both natural and man made. These changes occur at various time and spatial scales but, for most of the area, the changes are generally undetectable within the time frame of the measurements. An

exception is sea level change, which in the strait is an increase of the order of +10 cm/century. However, the next Cascadia Subduction Zone earthquake will drop the land in the SoG area by an amount that is likely to be < 1 m.

Resuspension and transport of sediments [Appendix A19]

Resuspension fluxes of nutrients and trace-metals were characterized in the shallow-water environments using the Sea Carousel. Particulate material was analyzed for C:N ratios, stable carbon/nitrogen isotopes, and a suite of trace-elements. Since benthic microbial biofilms play a major role in sequestering contaminants (trace-elements), altering the erosion criteria of sediments, and providing a food source for primary and secondary consumers, groundfish, and shorebirds, benthic grab samples were also collected to measure biofilm and geotechnical properties. Erosion thresholds were determined by examining the relationship between suspended particulate matter and current velocity. Sediment stability coefficients and resuspension fluxes will be available as model inputs for particle transport models, deep-water renewal, and nutrient-contaminant budgets.

Water column profiles were carried out along a canyon-axis within the Georgia Basin using both a CTD and a LISST profiler. These profiles took place under neap-tide conditions which favour deepwater renewal events. We observed a sharp increase in oxygen and turbidity levels along with a decrease in water temperature at depth, suggesting an association between benthic resuspension and deep-water renewal within the basin. Work has been ongoing to quantify shallow-water and deep-water resuspension fluxes and develop tracers to help characterize transport pathways of nutrients and trace-metals.

Nearshore classification [Appendix A5]

The nearshore region (0 – 50 m depth) is a highly productive environment, providing both permanent (e.g., for shellfish) and transitory (e.g., for fish) habitat for many commercial species. We are developing Habitat Patches (HaPs) to provide a physical context with which to represent our understanding of ecological processes in the nearshore. The HaPs provide the first, high resolution representation of the nearshore in the strait. Preliminary analyses have been performed to determine how well the current version of the HaPs corresponds to existing biological data sets. Using fishing information provided by red sea urchin harvesters (not used as a data source), 65% and 21% of fished areas were overlaid HaP with hard and mixed substrate, respectively. Conversely, 73% of surveyed points from stock assessment surveys where geoduck were present overlaid HaP with soft substrate. These results show how that the HaPs already give a suitable representation of nearshore substrate. These results are expected to improve as additional physical attributes are added.

Spring bloom spatial pattern and timing [Appendix A2]

We used MERIS and MODIS satellite imagery and in-situ recording fluorometers to monitor the pattern and timing of the Strait of Georgia spring bloom in 2001 to 2010. The imagery shows a previously unreported bloom pattern in February and March which suggests seeding of the early spring bloom from deep, glacial inlets to the north in five of the ten years. The images give the first observations of “seeding from inlets” into the Strait of Georgia. This seeding has been suggested as a mechanism for triggering the

main spring bloom in the Strait, but has not been previously observed. Our results suggest that the bloom occurs earlier in years with seeding.

Hot spots: Pelagic species [Appendix A18]

Pelagic species are an important linkage between lower and upper trophic levels in the Strait of Georgia. This project focused on identifying hotspots using acoustic data collected in Feb-Mar 2009 and Oct 2009 and characterizing these hotspots based on fish and zooplankton backscatter. Sampling with trawls and Bioness provided information on fish and zooplankton species assemblages and key species at each trophic level. Malaspina Strait and the west side of Texada Island were assessed in more detail in Feb 2009. During the day, positive fish anomalies occurred in the mouth of Jervis Inlet and along the Lasqueti Ridge, west of Texada island. These hotspots differ in terms of key species and layering. The Jervis hotspot is primarily related to hake, which accounted for 73% of the catch weight and occupied a depth range of 160-420 m. Spiny dogfish, pollock, and brown cat shark were of secondary importance in Malaspina Strait. In contrast, hotspots on the west side of Texada Island were dominated by herring which accounted for 55% of the catch weight and occupied a depth range of 60-160 m. Hake, spiny dogfish, rattfish and pollock were secondarily important and occupied a depth range of 200-400 m in the Quadra Basin. Two plankton hotspots were observed in Malaspina Strait adjacent to Northeast Bay during the day and one positive fish anomaly occurred at night, off the tip of Sinclair Bank in Malaspina Strait. Plankton hotspots were dominated by euphausiids, chaetognaths, and glass shrimp.

A brief survey of Malaspina Strait in fall 2009 revealed higher fish productivity than in the winter and a more consistent pattern of positive biomass anomalies, primarily in the main trough. These anomalies are dominated by spiny dogfish and hake at depths below 200 m and accounted for 85% of trawl samples by weight, and secondarily by schoolmaster squid and brown cat shark. Herring were not detected acoustically nor in trawl samples. However, in contrast to the winter results, young-of-the-year hake were found sympatrically with older hake in the fall. Positive plankton biomass anomalies occurred on the east side of Malaspina Strait, over relatively shallow bottom depths and consistent with persistent northwesterly winds at the time of the survey.

Hot Spots: Forage species [Appendix A8]

Forage species are a critical component of most ecosystems providing the glue that links lower trophic levels to upper trophic levels in most marine and freshwater ecosystems. The focus of the forage species project has been to collate and synthesize available information and data on the distribution and relative abundance of forage species within the Strait of Georgia. Unfortunately, data for non-commercially harvested species was very limited and even for relatively abundant species such as sand lance and eulachon very little information exists. As such, most of our effort focused on continuing to monitor the abundance of juvenile and adult Pacific herring within the Strait of Georgia and conducting analysis of the relationship of young herring survival to environmental conditions within the area during their first year of life. During the course of the study we witnessed very strong and very weak herring survival years that appear to be linked in part to the condition of the fish at the end of their first summer and this in turn may be a function of the match-mismatch of herring spawning and the timing of the spring plankton bloom. In addition, we conducted investigative field work to define and map

Pacific sandlance spawning and rearing areas through grab sampling in areas identified by habitat mapping as potentially suitable substrate.

Salmon DNA [Appendix A22]

DNA analysis is a critical tool in understanding the early marine survival and distribution of juvenile Pacific salmon. Through DNA analysis we are improving our understanding of the changes in the juvenile Chinook and sockeye salmon population in the Strait of Georgia during their early marine life. This has provided information on important changes in the stock structure of both species between July and September. We analyzed approximately 1000 Chinook salmon collected in the Gulf Islands purse seine survey and in the Strait of Georgia in Feb 2010, July 2010 and September 2010. We have an additional 3000 Chinook DNA samples that were collected during surveys in the Strait of Georgia and Gulf Islands in 2010 that have not been analyzed. DNA analysis is completed from approximately 1500 Chinook salmon submitted in 2010. In 2010, Cowichan River Chinook salmon continue to be the dominant stock in the Gulf Islands in June and July. The residence of this stock in the Gulf Islands through the summer months has been a consistent observation for the past three years supporting our hypothesis that the Gulf Islands is a critical rearing habitat for this stock and that they remain and rear in this area for an extended period of time. In general, there were 69 distinct stocks identified between July and September with the majority of these (44) originating from the Fraser River. Other stocks identified included eight from the east coast of Vancouver Island, five from south coast mainland and eight from Washington State.

In the past two years the analysis indicated that Harrison River sockeye salmon appear in the Strait in July and are the dominant sockeye stock in the Strait of Georgia in September. This is important information as the Harrison River stock had increased marine survival in recent years whereas the marine survival of other (lake-type) Fraser River sockeye salmon stocks declined. To understand the mechanisms that may be regulating the marine survival of sockeye salmon in general, and this stock in particular, it is important that we understand the marine distribution patterns and if there are specific rearing areas within the strait for various stocks or if the distribution between years varies.

c) Food webs – drivers of productive capacity and species linkages

Prey quality [Appendix A9]

The goals are to determine the spatial variability in stable isotopes of carbon and nitrogen at the base of the food chain, to compare prey quality at the base of the food chain and to quantify food web interactions in two contrasting pelagic ecosystems (the Strait of Georgia and the west coast of Vancouver Island). To date, a total of 537 zooplankton samples have been analyzed for stable isotopes and C:N ratios. Overall, the carbon and nitrogen isotopic signatures are higher by 0.7‰ and 0.5‰, respectively, in medium size zooplankton compared to small size zooplankton. This suggests that larger zooplankton occupy a slightly higher trophic level. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ increased in small and medium size zooplankton from winter to fall. This may reflect a shift from autochthonous carbon to alloctonous carbon (i.e. Fraser River Plume). The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signature varied among species, with lower values for juvenile sockeye salmon and higher values for juvenile coho salmon, consistent with the expected diet of these fish: juvenile sockeye salmon are generally planktivorous, whereas juvenile coho salmon and Chinook salmon feed on a mixture of forage fish and zooplankton.

Smolt release [Appendix A3]

Altering the release timing and/or size of coho salmon hatchery smolts will not reverse their precipitous survival declines of the last three decades. We evaluated the effects on survival of varying sizes and timings for smolts released during 1979-2006 into the Strait of Georgia and whether these effects changed over the time. During this period, smolt to adult survivals declined similarly for coho salmon from five hatcheries and a population of wild coho salmon used for comparison. Separate multiple regression models using logit transformed survival data for each hatchery had three explanatory variables; mean fish size (weight), release day, and ocean entry year. At four of five hatcheries, larger smolts survived significantly better than smaller smolts. At one hatchery, a significant interaction between ocean entry year and weight reflected an increased positive effect of weight later in the time series. At two Vancouver Island hatcheries, early release groups survived better than later releases in early years, while later release groups survived better than early release groups in recent years. Best models varied among hatcheries, implying differences in the optimal timing and size of smolt release, but these differences are extremely difficult to detect with current low survivals and uncertainty in their estimation. Given our limited ability to document benefits of altered release timing and size, we do not recommend further experiments with smolt release size and timing. We suggest that a better use for Strait of Georgia hatcheries would be to evaluate interactions between hatchery and wild coho salmon, through pulsed releases of large and small numbers of hatchery origin smolts.

Pink/Coho salmon mortality [Appendix A21]

In even numbered years, large numbers of juvenile pink salmon enter the Strait of Georgia from the Fraser River. This results in juvenile pink salmon being one of the dominant juvenile salmon species in the Strait of Georgia in late spring/early summer. However, possible interactions or competition between this species and other species of Pacific salmon has largely been ignored. This project examined possible interactions between juvenile pink salmon and coho salmon including overlap in distribution and diet and variation in coho survival and growth in years with (even years) and without (odd years) pink salmon. Juvenile salmon were collected from the Strait of Georgia in years with and without large abundances of juvenile pink salmon. This provided a natural control to examine the interaction between pink and coho salmon. Surveys of juvenile salmon in July and September indicate that in even numbered years the CPUE of pink salmon ranges from approximately 75-750 fish/hour in July and 26-80 fish/hour in September. In 2010 the CPUE in July was 753 fish per hour and was the highest recorded since the surveys began in 1998. In general, 80% of the juvenile pink salmon diet was amphipods, decapods and euphausiids although the ratio of these three prey group changed over the years of the surveys. These diet items were also common in the diet of coho representing approximately 60-65% of their diet. When pink salmon were present in the strait there was an increase in the percentage of empty stomachs observed in coho in September. This relationship was not apparent in July. In years when pink salmon were in the Strait, there was also a decrease in both the abundance and percentage of hatchery coho salmon in September. In addition, there has been a steady decline in the early marine survival of coho salmon over the past 15 years. This decline has been greater in years when pink salmon were in the Strait of Georgia. In general, our study demonstrates that there is a interaction between juvenile pink and coho salmon during their early marine period in the Strait of Georgia and that this interaction may impact the resulting marine survival of coho salmon. The impact on

hatchery and wild salmon is not consistent and appears greater for hatchery fish and should therefore be of concern to hatchery managers.

Coho salmon in SoG and Puget Sound [Appendix A23]

The early marine mortality of juvenile coho salmon is greater in the Strait of Georgia than in Puget Sound. The objectives of this project were to compare the physical and biological differences between coho salmon from these two adjacent basins between May and September. Over the period of declining marine survival, the sea surface temperature in both regions has increased. The preferred temperature range of coho salmon is between 12 and 14°C. The average SST in the Strait of Georgia during May to September 1980 to 2007 15.6°C compared to 13.2°C in Puget Sound. Thus, coho salmon in the Strait of Georgia over the past three decades have been rearing slightly outside of their preferred temperature range whereas those in Puget Sound have seen optimal temperatures. This variation in temperature between the regions is critical as higher temperatures can have great impacts on the bioenergetics of juvenile Pacific salmon, and these responses are more pronounced when fish are at or near the marginal temperatures for optimal growth. Historical studies on optimal size and time of release indicated that juvenile salmon that entered the ocean at a larger size had better survival rates than smaller fish and provided the basis for the management practices in the hatchery system. However, changes in the aquatic environment may change the optimal migration time and even optimal size of fish, suggesting that historical release strategies may not be appropriate. The release time of coho salmon smolts into the Strait of Georgia has varied very little in the past three decades with releases occurring in mid-May. The average release timing of coho into Puget Sound is similar however, there is more variability in the range of release dates. Releasing over a longer window of time allows for a greater chance that the coho will enter the ocean when feeding and growth conditions are favorable. The average size of coho entering the ocean from hatcheries in the Strait of Georgia has also remained consistent over the past three decades. In Puget Sound the average size at release is larger and has greater variation or range in any brood year cohort. These larger fish may be more equipped to feed, avoid predation and grow to the critical size required for increased survival over the first winter. Changes in climate may be responsible for declines in the early marine survival of juvenile coho salmon in the Strait of Georgia and Puget Sound, but survival may be able to be improved through optimal enhancement strategies. Coho salmon currently reared in hatcheries may not be physiologically able to adapt to the changes in the marine conditions although it is clear that marine survival of coho from Puget Sound is greater than the Strait of Georgia.

Acoustic tagging [Appendix A24]

The study examines the mortality associated with implanting acoustic tags in juvenile Chinook salmon in the marine environment. Tagged Chinook salmon were maintained in net pens in 2010 to determine tag loss and tagging mortality for juvenile Chinook salmon. The studies were a replicate of a study that was conducted in Cowichan Bay in 2008. In 2010, three sites were used; Campbell River (Hidden Harbour net pens), Nanaimo (PBS net pens) and Cowichan Bay. In each study there were 4 groups of fish. Group A consisted of 30 fish were tagged with dummy acoustic tags that matched the size and weight of the VEMCO V7-2L tags used in our telemetry studies. Group B consisted of 30 fish and were treated identical to group A except that they were sutured up without placing a tag in their abdominal cavity. Group C was a group of 30 fish that were the first control group. They were treated with anaesthetic and had their adipose

fin removed but had no surgical procedure. Group D was the second control of 30 fish. They were transferred directly to study tank without any anaesthetic treatment and were not measured prior to study. In all studies, fish were held post surgery in the net pens for two weeks. The 2008 study in Cowichan Bay was similar except there was no group that underwent surgery without having a dummy tag implanted into their abdominal cavity. There was no mortality or tag loss of the 30 fish at the Campbell River site in 2010. At the Nanaimo location in 2010, one fish lost its tag through the incision location and none died. The Cowichan net pen study in 2010 was lost due to a large tear in the net pen during a major wind storm in the estuary. This work provided some baseline information on the effect of acoustic tags on the survival of juvenile Chinook salmon.

Predator/prey: Harbour seals, hake and herring [Appendix A11]

The two main objectives of the study are to synthesize and model information on the abundance, population dynamics, bioenergetics and diet of harbour seals and to update abundance and activity levels with telemetry. The behavioural data will be used to update bioenergetics models and survey correction factors both of which had been developed in the 1990s when the seal population was still increasing. Preliminary analysis of data from recent instrument deployments indicate that seals are now making more extensive movements and spending more time foraging than they were in the 1990s. We also continued to explore the interactions between seals and their prey. Based on harbour seal population trends and bioenergetics models, it is estimated that seals in the Strait of Georgia currently consume about 8,100 tonnes of prey annually, compared with about 500 tonnes in 1970. Based on the proportion of herring in the diet and herring stock assessment models, it is estimated that seals consumed 1.3% to 19.3% of the herring spawning biomass annually. Predation levels increased during the 1970s, 1980s and early 1990s as seal populations grew, but predation levels also fluctuated due to changes in herring abundance levels. There appears to be an inverse relation between herring survival rates and seal predation levels, especially for older age-classes of herring. This suggests that seals have a greater impact on older age-classes, presumably because they are targeting larger fish. Selective predation on larger fish may also be contributing to an observed decline in the mean weight at age of herring over time. Based on the proportion of hake in the diet and the hake biomass surveys, it is estimated that seals consumed 3% to 31% of the hake biomass annually. Predation levels appear to have increased sharply over this period due to the rapid growth of seal populations as well as a slight decline in hake biomass. There has also been a decline in the size-at-age of hake over time similar to that observed in herring, again suggesting that seals might be selectively targeting larger hake. Hake less than 40cm feed primarily on euphasids, whereas hake larger than 40cm include fish in their diet. As a result of the decline in size of Strait of Georgia hake, there has also been a shift in their diet from fish to euphasids. The reduced predation of hake on juvenile hake and herring appears to have resulted in improved recruitment levels to these stocks, which to some degree offsets the increased predation on larger hake and herring by seals. These interactions are being modelled to assess the extent to which seals have displaced hake as the main fish predator in the Strait of Georgia, and the consequences of reduced predation on smaller fish by hake and increased predation on larger fish by seals.

Apex predators [Appendix A13]

Killer whales are a high profile, iconic species in the waters of the Strait of Georgia. The three ecotypes found in the area have distinct diets based on fixed behavioural traditions

that are highly resistant to change. Resident killer whales are salmonid specialists, with a strong preference for Chinook salmon and, secondarily, chum salmon. Offshore killer whales are a poorly known population of at least 300 whales found primarily in outer coast waters and appear to be fish feeders and may specialize on sharks. Transient killer whales are mammal-hunting specialists that feed on pinnipeds and small cetacean species found in their coastal range. By far the most important prey species, however, is the harbour seal, which comprises over one-half of their kills. The abundance of harbour seals in the Strait of Georgia has fluctuated widely over the past century and this likely had a major impact on the abundance and distribution of transient killer whales. The occurrence and survival of each ecotype in the Strait is thus influenced by different ecological factors, and these should be taken into consideration in conservation and management decisions to promote recovery of these species at risk.

2.1.2 Putting it all together – modelling and synthesis

Ocean circulation model [Appendix A26]

An application of the Regional Ocean Modeling System (ROMS) has been developed for the Strait of Georgia. This model is the ocean dynamics component of an end-to-end modeling system. The model is forced by freshwater inflow from major rivers, tidal forcing and seasonal climatology at open boundaries, as well as wind stress and heat flux at the ocean surface. The model is being developed to reproduce realistic circulation features and water properties (temperature and salinity) for the Straits of Georgia and Juan Fuca over a typical seasonal cycle as well as to capture year to year variability. Because the model output is used to force a lower trophic model, simulating a realistic near surface stratification is a primary concern. As such, one needs to force the model with a realistic wind stress and new wind stress field were prepared using hourly data for 30 local wind observation stations. The measured wind stress vectors were interpolated onto the model grid using a thin plate radial basis function. Using the improved hourly wind stress, a yearly simulation was successfully completed for 2007. At the surface, the modeled temperature closely follows the observations, from a winter low of about 6°C to a summer maximum of about 17°C. At depth, the much smaller seasonal temperature variations are well captured by the model, with a winter maximum and a summer minimum, although the modeled temperature are generally too high by about 0.5°C. At mid-depth, the model appears to also capture the seasonal signature of the sill depth intrusions, relatively cold in the spring and warm in the fall.

Plankton model [Appendix A16]

The Strait of Georgia is a highly productive, semi-enclosed sea with strong estuarine circulation connected to the North Pacific by the Juan de Fuca Strait. In order to better understand the key links between physical and biological processes determining lower trophic level and to predict plausible ecosystem changes, a coupled plankton/circulation models (ROMS-Regional Ocean Modeling System) has been developed. The biological model includes two size classes of phytoplankton and zooplankton, nitrate, ammonia and silicate. Model results from simulations of the mean annual cycle shows that in the Strait of Georgia, modeled phytoplankton biomass is higher and more variable than in the Juan de Fuca Strait and show pronounced seasonal variability consistent with observations. In the model, physical variability plays an important role in maintaining the high spatio-temporal variability of plankton abundance. In particular, the influence of tidal mixing on phytoplankton production and biogeochemical cycles is dominant.

Ecosim [Appendix A20]

This program has developed a dynamic model to examine mechanisms governing changes in managed species of the Strait of Georgia ecosystem from 1950 to the present, with particular reference to salmon populations. The model is capable of emulating the timing, direction and magnitude of changes in significant species like herring, seals, orcas, marine birds, lingcod and salmonids. The basis for this work is an Ecopath with Ecosim model that incorporates influences such as: the effects of long-term physical/oceanographic processes (climate variation), lower trophic level production changes (phytoplankton and zooplankton), known changes in fishing policy (gear types and effort) and changes in predation and competition. At present the Strait of Georgia model contains 39 groups. The next stage of work will include fine-tuning historic simulations, adding a few new species groups and developing scenarios of likely future Strait of Georgia ecosystem configurations given conditions derived from oceanographic models developed by colleagues at the Institute of Ocean Sciences.

OSMOSE [Appendix A14]

An individual-based ecosystem model OSMOSE has been applied to the Strait of Georgia ecosystem and has been extensively upgraded to address various ecosystem research issues related to impacts of fishing and climate change, ecosystem indicators, and fisheries management. Through various simulations, we have reached a number of conclusions. Ecosystem research should consider the pathways through which environmental disturbances enter the ecosystem and interact with predator-prey dynamics and species life history in order to understand species' responses to environmental changes and management actions. It is important to use a model such as OSMOSE to explore scenarios which combine species interactions, fisheries management, and climate change. Comparing among the different ecological indicators across all fishing scenarios and climate regimes enables us to identify ecological indicators that help indicate fish community changes in response to fishing and climate regimes. Through further modification of the OSMOSE model, we are to undertake a number of potential research projects in the near future.

Bayesian Belief Network [Appendix A17]

Marine survival of coho salmon in the Strait of Georgia has declined 10-fold over the past 25 years to a critical low level (<2% in 2010). Recent studies have linked early marine survival with changing ocean and atmospheric conditions, and inter- and intra-specific interactions. In question are the benefits of hatchery supplementation, a program designed to increase adult returns by improving freshwater survival. Evidence suggests that fish from hatchery origin tend to have lower marine survival than fish originating in the wild, and high densities of hatchery-origin fish may reduce the ability of wild fish to compete for the same prey resources. These and other related findings have generated controversy among researchers questioning the long-term benefits of supplementation. We developed a Bayesian belief network to evaluate the combined effects of climate change and variability and hatchery production on the early marine survival of coho salmon. The Bayesian belief network allows us to integrate physical and ecological data from various sources in a coherent structure and evaluate relative degrees of support for alternative hypotheses about drivers of population dynamics. Findings imply that worsening of the current climatic conditions will likely result in further declines in early marine survival while potential benefits of hatchery supplementation are perhaps limited to periods of favorable ocean conditions.

2.1.3 Into the future – climate change and other stressors

a) Environmental variability

Mid-term temperature variability [Appendix A6]

A key objective of the Strait of Georgia ERI is the construction of plausible scenarios for the Strait and the ecosystems it supports over the middle term. Here 'middle term' refers to the next two decades, the period out to 2030. Based on data from the Nanoose Station in the central Strait, a statistically significant warming trend of about 2-3°C/century has been found through the entire 400 meter depth of the water column for the period 1970-2005. The salient question is whether this warming trend can be expected to continue over the middle term. This question is considered in terms of some of the longest sea surface temperature records available from coastal British Columbia lighthouses. Data from four representative stations were selected, each of which displays a statistically significant long-term warming trend. For each record, running temperature trends were computed based on least-squares fits of 20-, 30- and 40-year data windows. Averaged probability distributions were then constructed. It is found that all these distributions are skewed such that warming trends dominate. However, the results suggest that over periods of 20-30 years there is a significant chance (40-45%) of the occurrence of a period with zero or negative temperature trend (cooling). Over periods of 40 years, the probability of such an occurrence decreases substantially to 20%, but is still not negligible. These results are indicative of the dominant influence of low frequency variability on conditions in coastal British Columbia. Over periods of 20-30 years, the long-term secular trend associated with global warming can easily be overwhelmed by such variability. Our conclusion is that it can not be taken for granted that the strait will see continued warming over the middle term.

Coastal upwelling/downwelling [Appendix A10]

Fifty-year time series of winds at six buoys near the British Columbia shelf break were examined for trends in the timing and cumulative intensity of upwelling and downwelling. Unlike a similar analysis to the south, the onset of upwelling was not found to be progressing later in the year. However, the cumulative upwelling and downwelling intensities were both found to increase over their respective seasons and this is related to previous findings of trends in atmospheric pressure in the Northeast Pacific. Analyses of global and regional climate model forecasts that seek to determine if these trends persist in the future are continuing.

River runoff [Appendix A12]

River runoff is an important influence for many oceanic processes on the coast of British Columbia but, as in most places in the world, much of the flow is in ungauged rivers (40% for this study area). The model developed in this study uses the historical relationship between precipitation and runoff and applies it to the ungauged areas to estimate their associated ungauged flow. The combination of gauged and ungauged flow produces a total coastal freshwater flux into the coastal waters off British Columbia. Distinction is made between pluvial and nival-glacial watersheds to accommodate the widely different precipitation regimes within the study area. Calendar year and water year variants of the model are tested with the water year version proving to be superior

for short time span evaluations. Total runoff for the study area was found to be 747 km³/yr. Runoff from a subset of the study area matched an earlier study that used area scaling rather than precipitation scaling. The freshwater flux estimated by this method is twice the flux predicted for this region in a global runoff model, however the global model also reported a suspected under representation of precipitation.

b) Human population growth and economic changes: increased marine traffic, habitat disruption/destruction, contaminants, invasive species and fishing effort

Development of generalized indicators [Appendix A25])

The Strait of Georgia is arguably the most human dominated marine ecosystem in Canada. It is surrounded by the 3rd, 15th, and 38th largest cities in Canada, is the location for active fishing, aquaculture, marine transport and recreation, and is influenced by local and remote land use and climatic changes. It has also experienced recent high profile fish stock changes. This pilot program aims to develop an ecosystem-based approach to managing marine ecosystems. It focuses on the development of marine ecosystem indicators for the region, using a Driver-Pressure-State-Response framework. The use of a Bayesian Network model is demonstrated for integrating ecosystem indicators into a probabilistic prediction system for the region. 'End-of-chain' nodes such as seals or transient killer whales can serve as indicators of the entire ecosystem, as they integrate the productivity conditions that support them. However, their response times to perturbations may be relatively slow, because of their longer life spans. For indicators of conditions and specific pathways within the ecosystem, 'central' nodes with multiple connections, for example the timing of the spring chlorophyll bloom or herring spawning biomass, will be useful. Overall, Bayesian Network models show promise as tools to integrate ecosystem observations and to predict outcomes (with probabilities) that can be useful to resource managers.

2.2 RELATED ACTIVITIES

- VENUS, the coastal network of the Ocean Networks Canada Observatory, is a cabled undersea laboratory for ocean researchers and explorers. VENUS delivers real time information from seafloor instruments via fibre optic cables to the University of Victoria, BC (<http://venus.uvic.ca>)
- UBC Peter Wall Institute Major Thematic Grant proposal (T. Pitcher, M. Lam, et al.)

3. AN ECOSYSTEM-BASED MANAGEMENT FRAMEWORK FOR THE STRAIT OF GEORGIA

3.1 ECOSYSTEM OBJECTIVES

The framework proposed here adopts the general concepts of the Integrated Ecosystem Analysis approach, with an initial focus on the first 3-4 steps (scoping, indicators, thresholds, and risk analyses; Figure 5). To date, no comprehensive scoping activity has been conducted to elaborate on the specific ecosystem objectives for the Strait of Georgia. We therefore start with the high-level objectives outlined by Jamieson et al. (2001), i.e., sustainability of human use, and conservation of species and habitats

(Figure 2). We generalise these, and propose a high-level ecosystem objective for the Strait of Georgia to *protect ecosystems and their components from serious or irreversible harm, but also to allow the use (e.g. for economic and/or socio-cultural purposes) of these ecosystems and components as long as the social-ecological Strait of Georgia system is sustainable*. This objective includes the (still rather general) objectives of the DFO sustainable fisheries framework and policies described in Section 1, above. Achieving this goal requires recognising and assessing how human activities alter the ability of the Strait of Georgia ecosystem to produce these services in interaction with natural environmental variability and change.

Key processes and components of the structure and functioning of the Strait of Georgia ecosystem have been identified from the Ecosystem Research Initiative and other programs (Section 2, above). These include physical properties such as water temperature, seasonal wind patterns, freshwater inflow to the Strait, and lower trophic level biological properties such as seasonal phytoplankton species composition and productivity, and species composition and timing of zooplankton populations. Key upper trophic level components comprise the Ecologically Significant Species and Community Properties and Ecologically and Biologically Significant Areas (EBSAs) (e.g. DFO, 2007b). Ecologically significant species in the Strait of Georgia include Pacific herring, Pacific hake, spiny dogfish, salmon (in particular the timing and numbers of juvenile salmon entering the Strait), and the abundances of pinnipeds. Significant areas are beginning to be identified, e.g. through the EBSA process (Jamieson and Levesque, In preparation; Figure 6), within the projects of the Ecosystem Research Initiative, and other studies.

3.2 “STATUS” INDICATORS

Implicit in this goal are two classes of stressors or pressures impacting the Strait of Georgia: ‘natural’ environmental variability and change, and direct anthropogenic pressures. Many of the key components of the functioning of the Strait of Georgia ecosystem are environmental properties, over which no direct management control is possible. However, they form the foundation on which human actions take place and are sufficiently important to the ecosystem that they should be monitored, regularly reported, and considered when taking management actions.

For the Strait of Georgia, we recommend the following as indicators of the state (or “status”) of the Strait of Georgia ecosystem:

- sea surface temperature
- near surface stratification
- dissolved oxygen in deep basin
- date to reach 50% of the Fraser River flow
- timing of the start of the spring phytoplankton bloom
- spring (April, May, June) copepod biomass in the central Strait of Georgia
- abundance of juvenile salmon in the Strait of Georgia during May
- Strait of Georgia herring population abundance as a mid-trophic level indicator (this is under management influence, but other mid-trophic level species such as sandlance or smelts are too difficult to sample at present)
- abundance of harbour seals in the Strait
- wind speed in the spring (April – June), expressed as wind speed cubed (as a surrogate for wind stress)

Reporting on each of these “status” indicators every year should be one of the tasks of the CSAP Fisheries and Oceanography Working Group (FOWG). It should report the most recent value in relation to a baseline, in an easy-to-understand plot such as a ‘radar’ (or spider) plot (e.g. Figure 7 and Table 3; see also Rockström et al., 2009). Identifying an appropriate baseline is rather subjective, but has important implications for interpreting how much these indicators may be changing. We recommend following the oceanographic convention, which defines the baseline to be the most recent 30 years starting in the year ending with a “1”. This would mean the baseline for reporting should be the average over the period 1981 – 2010.

To identify the potential implications of the present values of these indicators, we recommend they be run through a Bayesian Network model to obtain probabilities of their impacts. This could be done annually for the FOWG State of the Ocean report, but it could also be done immediately and regularly during the year once the appropriate status indicator values are available, for example by giving the Bayesian model to interested groups such as hatcheries, who might be interested in the timing of the spring bloom and its implications for salmon survival. Once constructed, these Bayesian Network models are easy and fast to run, and use freely-available software. However, since these Bayesian networks are parameterised based on historical data and relationships (i.e. correlations and expert knowledge), these annual indicator values also need to be run through more complex coupled biophysical models, which are based on fundamental processes rather than correlations. This would, to some extent, identify when conditions are changing beyond those used to parameterise the Bayesian Network model, and provide warnings as to when the Bayesian Network model forecasts may not be appropriate. In all circumstances, the FOWG should regularly assess the predictive skill of these methods by comparing forecasts with observed outcomes once these observations are available (i.e. a learning and updating activity).

3.3 PRESSURES (STRESSORS) ON THE STRAIT OF GEORGIA

In developing a framework for ecosystem-based management of the Strait of Georgia, it is important to identify the potential ‘threats’ (pressures, stressors) that could prevent the above overarching goal from being reached. As noted above, there are two obvious classes of threats, i.e. from ‘natural’ and anthropogenic, sources. The ‘natural’ stressors include environmental variability, from shorter (inter annual) to longer (e.g. multi decadal) time scales, as well as secular environmental change (e.g. climate change, ocean acidification). The anthropogenic stressors include a range of pressures affecting habitats and living marine resources directly and indirectly, including fishing, invasive species, fish culture activities, contaminants, and development and land use changes within the Strait of Georgia watershed (Table 4). In identifying and considering the impacts of these stressors, it is important to highlight the response time scales of the ecosystem and its components compared with the time scales of the stressor(s). For example, physical properties of the Strait of Georgia can be characterised as displaying a small long term trend due to a changing climate which is overwhelmed by medium term (decadal) variability (such as due to the Pacific Decadal Oscillation). It is this strong medium term variability, however, which is more closely matched with the response time scales of the ecosystem. In addition, one has to take into account the significant trend imposed by direct anthropogenic stresses (for example relating to the increasing human population around the Strait), the time scales for management actions to be implemented and to take effect, and the inertia of management actions due to the needs for adequate data to be collected and decisions made to change past practices.

3.4 PROPOSED MANAGEMENT FRAMEWORK IN AN ECOSYSTEM-CONTEXT

The issues that are the most significant for management of the Strait of Georgia in an ecosystem-context are the 'direct anthropogenic' stressors identified above as they are the ones that can directly be acted upon. We recommend building on the DFO policies already in place (Section 1) and developing this framework around the 'core' and 'extended' aspects of ecosystem-based management (e.g. Hilborn, 2011). These are" 1) continuing management practices to ensure conservation of individual stocks; 2) preventing by-catch of non-target species; 3) avoiding habitat disruptions; 4) developing a more robust and integrated approach to spatial management; and 5) considering the impacts of anthropogenic stressors to trophic interactions and ecosystem function. These five aspects, along with monitoring and evaluating the environmental 'status' indicators proposed above (Section 3.2), would form the central components of an ecosystem-based management approach to the Strait of Georgia. The first three (and some of the fourth) are already included in DFO policies, however, while they are necessary components of an ecosystem approach, they are not sufficient. What is also needed is an assessment of how these stressors may affect the entire ecosystem, and what are their limits before significant impacts and changes occur in the system.

The proposed approach implies two key aspects: whole ecosystem impacts, and the thresholds (for each stressor) that will cause the ecosystem to change in some significant way. It must also be recognised that changes due to anthropogenic stresses co-occur and interact with natural changes due to the environment, and on a variety of time scales, some of which may resonate with the time scales of ecosystem processes to amplify changes, whereas other may dampen changes. We suggest a focus on the concept of "critical thresholds", and recommend adopting an approach similar to the precautionary approach used in Canadian fisheries management (DFO, 2006; Figure 8). Rice (2009) has proposed a generalization of this concept which is applicable to ecosystem properties and stressors. His approach assumes that 1) for any ecosystem property there are healthy states in which some level of human impact can be sustained; 2) that for any ecosystem property there is a maximum level of disturbance that can be sustained; 3) that most ecosystem properties have some levels which can be considered to be seriously degraded or which represent irreversible harm (interpreted as having a low likelihood of recovery within biologically measureable time scales); and that 4) by the time this degraded state is reached the human activities causing the impacts should be reduced as much as possible (Rice, 2009). Broadly stated, for each ecosystem stressor over which there is some degree of management influence, the threshold would be identified beyond which continued human actions are likely to have significant impacts to the Strait of Georgia ecosystem. Periodic evaluations would be conducted of current conditions in relation to these thresholds and how management actions may change this relative position.

3.4.1 Marine zoning and spatial management

As noted above, spatial management (marine zoning) is one of the key components of ecosystem-based management. Spatial management includes permitting or prohibiting certain activities in specific places, identification of locations critical to the healthy functioning of the Strait of Georgia ecosystem (such as EBSAs and biological "hotspots"), and spatial modeling of the ecosystem impacts of disturbances in these locations. Industrial activities that often have some element of spatial zoning in their

management plans include fisheries, aquaculture sites, marine dumping, log booming grounds, and other marine industrial operations. The Strait of Georgia already has some degree of spatial management, although the locations have usually been assigned because of single issues (i.e. generally not for their significance to the entire ecosystem) and are rarely evaluated in a network context. Protected areas are important tools for managing human impacts in the Strait of Georgia. Several different types of protected areas have been designated in this region, each with somewhat different degrees of protection. These include national wildlife areas, migratory bird sanctuaries, provincial parks, ecological reserves, wildlife management areas, wildlife reserves, and municipal parks. In the Strait of Georgia (as of 1997), 62 such areas have been designated comprising a total marine area of 35,214 ha (Jamieson and Lessard, 2000) representing 5.2% of the total surface area of the Strait of Georgia. Over half of these sites are provincial parks, although wildlife management areas make up the largest area (almost 40% of the total protected area). In addition, there are over 300 locations with persistent (although not necessarily year-round) fishery closures for various invertebrate and finfish species and for contamination due to sanitary, dioxin, and PSP reasons, ranging from strait-wide closures for lingcod to local beach closures for clams. We recommend an analysis using a spatial ecosystem model for the Strait of Georgia that would identify a cumulative threshold size above which the stability of the ecosystem is increased when subjected to stresses such as fishing. In addition, such a spatial model would permit identification of locations that appear to be more significant for the functioning of the Strait of Georgia (e.g. “hotspots”) and/or represent rare or unique habitats identified from the ERI program and other studies (e.g. ecologically and biologically sensitive areas, Figure 6; Jamieson and Levesque, In Prep.).

3.4.2 Commercial fishing

Management of, and controls on, fisheries for individual species need to continue, and to adopt broader ecosystem considerations such as the effects on predator species and habitat disruptions. In an ecosystem context, however, management also needs to be aware of and to take into account the potential impacts to the full ecosystem of fishing a particular species. Such potential impacts may be observable directly, but usually only after some time lag. Potential ecosystem impacts can, however, be simulated and assessed with the use of computer models and some (model-based) measure of ecosystem integrity or stability. The use of multiple ecosystem models with diverse structures is recommended to assess the uncertainty around the threshold level at which undesirable changes occur to the (modeled) ecosystem. An example application is provided below (Section 3.5).

3.4.3 Nutrient loading / eutrophication

In the 1970s and 1980s, a major debate concerned the possible eutrophication of the Strait of Georgia (e.g. Parsons et al., 1980). Subsequent studies by several authors during the 1990s generally concluded that eutrophication of the Salish Sea by anthropogenic nitrogen inputs was unlikely because ambient nitrate concentrations are already high (2-20 μM N) so that total primary productivity is relatively insensitive to moderate changes, and natural inputs of nitrogen by the estuarine circulation are much larger than all anthropogenic sources combined (e.g. about 2600 t N per day from natural sources versus 285 t N per day from anthropogenic sources; Mackas and Harrison, 1997). However, even though the Strait of Georgia may currently be well below a critical threshold with respect to nutrient enrichment, eutrophication continues to be a concern for many semi-enclosed marine systems (e.g. Snelgrove et al., 2009).

Therefore, a model-based assessment of the threshold at which anthropogenic nutrient loading to the Strait of Georgia system would significantly alter primary production and ecosystem processes is required. In addition, both anecdotal reports and survey observations suggest that dissolved oxygen concentrations in the Strait of Georgia fluctuate, and that at certain times of the year, particularly during winter, the oxygen concentration in the central deep waters can drop close to 2 ml l⁻¹ (Masson and Cummins, 2007). As noted by Johannessen and Macdonald (2009), dissolved oxygen concentrations of 3.2 ml l⁻¹ have been proposed as a threshold for hypoxic effects and less than 1.4 ml l⁻¹ to result in 'dead zones', therefore further small declines in oxygen in the deep waters of the Strait of Georgia may affect species in, or eliminate species from, those areas. Dissolved oxygen therefore needs to be monitored and the potential consequences assessed in an ecosystem context.

3.4.4 Fish culture activities (aquaculture, hatcheries)

Fish culture activities, such as finfish and shellfish aquaculture, are significant in specific regions of the Strait of Georgia, for example Baynes Sound. Three general types of disturbance can occur, relating to changes in material processes (feeding and production of wastes), pulse disturbances due to harvests, and alterations due to the addition of physical structures (Dumbauld et al., 2009). Impacts relating to the processing of materials can include deposition of sulphides in the sediment, changes in the abundance and biodiversity of benthic fauna (Sutherland et al., 2007a) and interactions with pelagic species via the exchange of pathogens (e.g. sea lice). Whereas the stress of intensive aquaculture activities may be significant to local areas, their impacts to the functioning (the carrying capacity for aquaculture) of the entire Strait of Georgia marine ecosystem is unknown. Both the local and Strait of Georgia-wide potential impacts need to be assessed (e.g. Sutherland et al., 2007a; 2007b) and the thresholds identified beyond which significant system-wide changes may be expected (e.g. by using coupled models focussed on a variety of stressors and expanding spatial scales; McKindsey et al., 2006; Ferreira et al., 2008).

Hatchery production in the Strait of Georgia is specific to salmon. It has been proposed that releasing large numbers of hatchery-reared salmon into the Strait of Georgia may impact wild coho salmon when marine productivity conditions are poor for juvenile salmon (Sweeting et al., 2003), and potentially might impact juveniles of other salmonid species during the time they co-occur in the Strait. An analysis is needed of the potential carrying capacity for wild and hatchery-released juvenile salmon in the Strait of Georgia, to identify a threshold beyond which addition of more juvenile salmon may alter the ecosystem.

3.4.5 Species introductions

The number of non-native species in the marine ecosystem of the Strait of Georgia has increased over 40 fold during the past century, although the rate of increase appears to be relatively stable (4-5 new species per decade; Johannessen and Macdonald, 2009). Some of these have been intentional introductions, such as the Pacific oyster *Crassostrea gigas*, but most others have been unintentional arrivals via ships, live trade of foods and plants, and expanding habitats as a result of climate warming. Such species include phytoplankton and other algae, invertebrates, fishes, birds and marine mammals (Johannessen and Macdonald, 2009). Habitat modelling has been conducted to assess the probability of establishment of some potential invasive species (e.g. the tunicate *Didemnum vexillum*; Herborg et al., 2009). Such modelling needs to be

conducted for a number of species with potential to invade the Strait of Georgia, and invasion vectors and locations of high invasion potential need to be identified. The potential impacts of invasive species to the marine ecosystem of the Strait of Georgia then need to be estimated using ecosystem models to identify threshold levels for numbers and types (i.e. roles in the ecosystem) of species.

3.4.6 Contaminants

Contaminant loading into the Strait of Georgia varies greatly, from high point source accumulations associated with industrial discharges (e.g. Burrard Inlet, Howe Sound) to dispersed sources relating to multiple smaller locations and storm water runoff. In addition, there are eleven ocean disposal sites in the Strait of Georgia regulated by Environment Canada (Burd et al., 2008). Other sources of contaminants include sewage outfalls, mine tailings and acid mine drainage, settled debris from logbooms, and pulp and paper mills (Burd et al., 2008). The impacts of many of these sources are monitored by surveys of benthic organisms and the fluxes of organic and inorganic materials from the sediments. The Strait also has a history of contamination by metals, organic compounds, and other chemicals, which often have characteristics temporal trends consisting of an identifiable entry date, increase to a maximum, and then decrease due to regulatory controls (Johannessen and Macdonald, 2009). At present, fire retardants such as PBDEs (polybrominated diphenylesters) are still increasing, with likely long residence times in high trophic level biota such as pinnipeds, as illustrated by the study of P. Ross. Novel pharmaceuticals, including endocrine disruptors, are also now appearing in the Strait, with as yet unknown consequences to the marine ecosystem (being investigated by the study of M. Ikononou). Threshold levels for impacts of contaminants to the Strait of Georgia system need to be modelled and assessed, likely at a range of spatial scales.

3.4.7 Habitat alterations

Effects of habitat alterations on the ecosystem of the Strait of Georgia can be direct, for example with changes to estuarine and coastal areas, or indirect caused by land use changes in upland drainage basins of rivers which flow into the Strait. DFO has management responsibility for the direct impacts, although this responsibility is often shared with other agencies such from the Province, Regional Districts, and local municipalities. We recommend an initial focus on assessing the effects of direct habitat alterations on the marine ecosystem of the Strait of Georgia. Levings and Thom (1994) used nine categories to quantify the loss or gain of aquatic habitats in the Strait of Georgia over the past 100 years. These categories were selected based on their importance as fish habitats. They are: sand, mud, rock/gravel, marsh, kelp beds, eelgrass, intertidal algae, riparian vegetation, and unvegetated subtidal habitats. They concluded there had been over 50 to 80% loss of riparian (bog, meadow) and saltmarsh habitats from the Fraser River estuary and lower river, and declines of 0.8 to 93% of the areas of marshes and estuaries in the rest of the Strait of Georgia over this time period (with an anomalous increase of 13% in the Campbell River estuary due to removal of log storage and creation of marsh habitats). The Strait of Georgia ERI project by G. Jamieson, J. Lessard, and E. Gregr defined and estimated the extents of subtidal sand, mud, and rock/gravel habitats to 50 m depth in the Strait of Georgia, which provides an assessment of the present situation for comparison with the estimates from the 1990s and “the past” by Levings and Thom (1994), and which can be used as a baseline for moving forward in an ecosystem context. We follow Levings and Thom (1994) and recommend that changes in these habitat types be assessed (modelled) for their

impacts to the Strait of Georgia ecosystem, with a focus on those species most likely to depend on these habitats at some stage in their life history, e.g. herring, shallow water rockfish, juvenile salmon, Dungeness crab, Manila clams, geoducks, and waterfowl/shorebirds. Spatial modeling of habitat types and disturbances would be valuable to connect with areas identified as EBSAs or biological “hotspots”.

3.5 AN EXAMPLE APPLICATION

The Strait of Georgia Ecosystem Research Initiative has developed and expanded a number of models that can be used as tools to identify critical ecosystem thresholds and to evaluate proposed management actions. Two classes of models are Bayesian Belief Networks (e.g. Uusitalo, 2007; Langemead et al., 2009) and simulation models. The former are based on relationships among variables identified from data or expert opinion. They are inexpensive and easy to operate, and provide outputs in probabilistic formats, and so should be useful for in-season exploration of alternative management actions and, in particular, forecasts of the potential implications of environmental conditions to valued ecosystem components (e.g. the effect of state variables on the ecosystem). However, these models are based on the assumption that future conditions will behave as did past conditions; with increasing human development around the Strait of Georgia and with climate change, this assumption may not always be valid. Mechanistic simulation models which are based on first principles are therefore also needed to evaluate changes in underlying (correlative) relationships. Two such models that have been developed or expanded by the ERI program are the Object-oriented Simulator of Marine Ecosystems Exploitation OSMOSE (Shin and Cury, 2001) and Ecopath with Ecosim (EwE; Christensen and Walters, 2004). They are based on different approaches: OSMOSE simulates animal populations and their interactions based on spatial co-occurrence and the predator-to-prey size ratios, whereas EwE uses a dynamic mass balance approach to simulate the population effects of feeding interactions.

We recommended above that evaluation of the impacts of stressors on ecosystem properties, for example to identify potential critical thresholds, be based on simulation models. This assumes that some index of ecosystem state can be calculated from these models which would identify the level of the stressor at which the ecosystem has changed in some significant way. Such model-based whole-ecosystem indicators are still in development. They could be defined for each model and for each stressor, but it would be simpler if one or a few such indicators could be identified for all models and stressors. Shin et al. (2010a) proposed seven such indicators: mean length, trophic level of landings, proportion of under- and moderately exploited stocks, proportion of predatory fish, mean lifespan, the inverse of the coefficient of biomass ($1/CV$ Biomass), total (fish) biomass, and the fish biomass per unit of catch (which indicates total fishing pressure at the fish community level). Fu (Appendix A14) examined these ecological indicators within her OSMOSE model, and added some additional indices. She concluded that biomass (B), biomass per unit of catch (yield: B/Y), and the normalized fishing pressure [$1-(Y/B)$] produced the more predictable properties with consistent patterns across a range of fishing and climate regime simulations. These indices should be considered as initial model-based indicators to assess ‘significant ecosystem change’ when determining critical thresholds for ecosystem stressors that involve aspects of fishing. Other indicators, such as the inverse of the coefficient of variation of total biomass, should be considered as measures of ecosystem stability when the stressors do not involve fishing (Shin et al., 2010b).

Here we provide an example of how this approach might work when applied to fishing (on herring) as the stressor, and using total fish biomass as the index of ecosystem resilience. The data are from the OSMOSE model simulations by Fu (Appendix A14) using her scenarios 1-3, i.e. fishing on herring only with fishing mortalities of 0.25M, 0.5M, and at M, with M defined as the natural mortality of the Strait of Georgia herring stock (here taken as 0.4), and without considering regime-scale climate variations. Note that natural mortality rates (M) on this herring stock have been estimated to be between 0.4 and 0.8 yr⁻¹, with recent fishing mortality rates (F) of about 0.2 (Schweigert et al., 2009). The OSMOSE model results (Figure 9) suggest declining total fish biomass with increasing exploitation of herring, with perhaps an increasing rate as fishing mortality approaches natural mortality. A potential critical threshold for 'significant' ecosystem impacts of fishing on herring might then be defined based on where the rate of decline in total biomass increases (e.g. Figure 9). Similar simulations could be run for fisheries on other species, and for combinations of fisheries, and their impacts to total fish biomass assessed.

4. CRITICAL DATA/KNOWLEDGE GAPS, APPLICATION OF THIS FRAMEWORK, NEXT STEPS

Considerable progress has been made over the past few years by projects within and outside of the Ecosystem Research Initiative in understanding how the Strait of Georgia marine ecosystem functions, however significant gaps in knowledge remain. The framework proposed in this document relies heavily on modeling, since to date there are no alternatives to such models to explore ecosystem-based management scenarios and to identify thresholds of effects in a multi-species context. However, these models remain largely developmental and can be complex and difficult to validate. Further work in the Strait of Georgia should focus on coupling the physical, lower trophic level and upper trophic level models, i.e. on developing a 'full ecosystem', or end to end model for the Strait. Such a model (or models) would benefit a number of issues, e.g. identification of anomalous environmental conditions and their potential implications to upper trophic levels, would have specific biological applications such as in predicting harmful algal blooms (e.g. as done for the Juan de Fuca eddy; Jochens et al., 2010), could be used for examination of ocean conditions during periods of anomalous biological events (e.g. Fraser River sockeye), and are the only way to forecast potential impacts of climate change (e.g. by coupling with atmospheric climate change models).

Specific knowledge gaps with high influence for understanding the ecosystem of the Strait of Georgia include seal diets, Pacific hake, and juvenile salmonids. Seals have significantly increased in abundance since the 1980s, when the last study of seal diets in the Strait of Georgia was conducted (which found the majority of their diet was Pacific hake, and Pacific herring during those months when it occurred in the Strait; Olesiuk, 1993). Given the changes that have occurred in the Strait since the 1980s, the diets of harbour seals and sea lions need to be re-investigated. Similarly, Pacific hake have variously been described as having the largest biomass of resident fish in the Strait, although this has not been assessed recently and the last analyses indicated declining size at age for hake in the Strait (King and McFarlane, 2006). Considering the importance of hake as prey for seals and as predators for many species of fish, a concerted effort is needed to determine the present biomass and feeding relationships of hake in the Strait. Salmon are cultural icons to the people living around the Strait of

Georgia and can be important ecosystem components, in particular during the spring when they enter the ocean. Beamish et al. (2007, p. 50) defined ecosystem management as “management that appreciates the dynamic relationships among the key species and their environment”. Consequently, they suggested this means, for example, that managing coho salmon requires understanding the natural processes that affect the production of coho in the ocean, including changes in ocean productivity such as the timing of the spring bloom and determining the abundance and interactions of potential competing stocks (such as hatchery-reared coho) and species (such as other species of salmon). Salmon would provide an excellent example of how to integrate single species concerns and management into an ecosystem context, initially by considering impacts of ecosystem changes to the species but ultimately extending to how changes in the target species impact the ecosystem.

The ecosystem-based management framework proposed here is not intended to replace present efforts to expand single-species management to take account of ecosystem interactions (e.g. by addressing by-catch and habitat disruption issues) and efforts to identify and manage rare or unique species or habitats (e.g. corals and sponges). These efforts must continue. This framework is intended to evolve as an additional assessment and management layer, examining how management actions may affect the entire ecosystem (and critical components therein). It is intended to provide an over-arching context and evaluation of how important stresses may interact with the ecosystem. In applying this framework, we recommend an initial focus on observing the key state variables identified above, and forecasting their impacts on a regular basis through Bayesian and simulation models. In regards to the key stressors, we recommend an incremental approach which selects a few key stressors and builds the models to identify critical thresholds, and the management procedures to respond when these thresholds are approached. Central to both of these activities is a system which identifies key variables to monitor, when and how frequently they should be monitored, and where they should be monitored, and an analysis system to forecast the implications of these observations. Although it is not the purpose of this document to propose such a monitoring and analysis system, candidate key variables are identified in this framework. Building an ecosystem-based approach to managing the Strait of Georgia will not succeed without such a monitoring system.

The approaches and tools developed by the Strait of Georgia ERI program could be applied relatively easily to other areas of the B.C. coast to form the core of a coast-wide ecosystem-based management framework. Physical circulation models have already been developed for the north coast and open ocean areas off of B.C., as have initial Ecopath with Ecosim models. Recent assessments of environmental status and trends have been completed for the north coast of B.C. (Cummins and Haigh, 2010) and the west coast of Vancouver Island (Ianson and Flostrand, 2010), and considerable background information has been compiled for the north coast (e.g. Lucas et al., 2007). This information could be used to develop Bayesian Belief Network models for these regions to begin assessing the potential impacts of current environmental conditions.

5. GOVERNANCE ISSUES FOR ECOSYSTEM-BASED MANAGEMENT

Governance issues are a central part of applying an ecosystem-based management approach to any marine system. Although relatively few examples exist for marine systems, they do indicate the need for strengthening their core existing approaches and

developing new ones. For example, in Australia the Great Barrier Reef (GBR) marine park has moved from management of selected individual reefs to an approach which treats and manages the entire reef complex as an integrated ecosystem (Olsson et al., 2008). This transformation was necessitated by increased pressures on the GBR system from terrestrial runoff, over-harvesting, and global warming, and the recognition of a new sense of urgency. The new strategies involved internal reorganization and management innovation, which enabled the agency to better coordinate scientific activities, to increase public awareness of environmental problems in the area which led to the involvement of a broader range of stakeholders, and to increased political support (Table 5). Olsson et al. (2008) concluded that enabling legislations are essential but are not sufficient for shifting governance towards adaptive management of complex marine ecosystems. In Western Australia, Fletcher et al. (2010) used a process of structured stakeholder inputs to identify over 600 ecological, social, economic, and governance issues, which were subsequently integrated into 60 regional risks and 24 Department level priorities ranked from very low to urgent. These priorities now form the basis for the planning process of the relevant government agencies in Western Australia.

An ecosystem-based approach to managing human interactions with the Strait of Georgia should focus on implementing the DFO sustainable fisheries framework, the precautionary approach to the setting of fisheries management advice, and DFO policies relating to fisheries on forage species and benthic habitat disruptions. It should also adhere to the many non-fisheries policies and directions relating to Canada's marine environments, such as outlined by Jamieson (2010). In addition, an ecosystem-based approach would include elements of area-based management/marine zoning, and of the potential impacts of stressors on trophic relationships and functioning of the system. Key steps to implementing this framework involve identifying ecosystem-level priorities among the stakeholders and agencies with interests and responsibilities for the Strait of Georgia, design and implementation of an integrated monitoring program, improvements to the scientific knowledge base (in particular of seal diets, Pacific hake, juvenile salmon ecology and their use of the Strait), development of ecosystem models and risk assessment frameworks to identify critical effects thresholds, and engagement with the public regarding education of the important issues in the Strait of Georgia. In addition, governance approaches need to be sufficiently flexible to deal with unexpected 'surprises' and with directional changes, for example due to increasing urbanization of the Strait and to climate change.

6. CONCLUSIONS

This framework is intended to provide strategic direction to the development of an ecosystem-based approach to managing human interactions with the Strait of Georgia marine system. It emphasizes five central components: 1) continuing management practices to ensure conservation of individual stocks; 2) preventing by-catch of non-target species; 3) avoiding habitat disruptions; 4) developing a more integrated approach to spatial management; and 5) considering the impacts of anthropogenic stressors to trophic interactions and ecosystem function. The first three of these are already included in DFO policies relating to the sustainable fisheries framework, fisheries on forage species, and benthic habitat disruptions, and aspects of spatial management and marine zoning are frequently used by DFO, although often without reference to the connections among these various areas or with the broader Strait of Georgia ecosystem. Trophic interactions have generally not been integrated in an ecosystem context for

management of the Strait of Georgia; this framework provides several recommendations for how this may be accomplished. Significant next steps to implementing this framework involve clarifying ecosystem-level priorities and objectives for the Strait of Georgia, design and implementation of an integrated monitoring and analysis program, improvements to the scientific knowledge base (in particular of seal diets, Pacific hake, juvenile salmon ecology and their use of the Strait), and development of ecosystem models and risk assessment frameworks to identify critical effects thresholds.

It must be noted this framework is intended to be allied with, and potentially integrated into, broader initiatives to monitor, report on, and manage the Salish Sea system, including its air shed and terrestrial watershed, for example by the Puget Sound Georgia Basin Ecosystem partnership (<http://www.psp.wa.gov/>). This framework has not emphasized the potential future changes to the Strait of Georgia, for example by climate change and the increasing human population and urbanization around the Strait. These are very important issues on decadal time scales. They need to be monitored by the 'status' indicators and their potential impacts and management responses evaluated by simulation and risk assessment modeling and scenario development. Although these are still early days in the application of an ecosystem-based approach to the Strait of Georgia, the outline of such an approach and its elements are becoming clearer, and several of the policy underpinnings are already in place. What is needed now is to move forward with the next key steps, as identified by this framework.

7. RECOMMENDATIONS

The framework proposed here adopts the general concepts of the Integrated Ecosystem Analysis approach, with an initial focus on the first 3-4 steps (scoping, indicators, thresholds, and risk analyses). Accordingly, we recommend the following:

- selecting the following as indicators of the state of the Strait of Georgia ecosystem:
 - sea surface temperature
 - near surface stratification
 - dissolved oxygen in deep basin
 - date to reach 50% of the Fraser River flow
 - timing of the spring phytoplankton bloom
 - total zooplankton biomass,
 - herring population abundance
 - abundance of harbour seals in the Strait
- Reporting on each of the above indicators each year by the CSAP Fisheries and Oceanography Working Group (FOWG).
- these indicators be run through a Bayesian Network model to obtain probabilities of their impacts. This could also be done annually for the FOWG report, but it could also be done immediately and regularly during the year once the appropriate status indicator values are available

- the FOWG should regularly assess the predictive skill of these methods by comparing forecasts with observed outcomes once these observations are available (i.e. a learning and updating activity).
- identifying and considering the impacts of the various stressors, and highlighting the response time scales of the ecosystem and its components compared with the time scales of the stressors.
- continuing and enhancing the existing species and stock-focused fisheries management practice.
- a focus on the concept of “critical thresholds”, and the adoption of an approach similar to the precautionary approach used in Canadian Fisheries management (DFO, 2006; Figure 8) as modified for ecosystem properties and pressures by Rice (2009).
- management indicators be based on the threats and stressors identified above, and include identification of thresholds beyond which the ecosystem is impacted in some way, a periodic assessment of where we are currently in relation to these thresholds, and an assessment of how management actions may change this relative position.
- the use of multiple ecosystem models with diverse structures to assess the uncertainty around the threshold level at which undesirable changes occur to the ecosystem.
- a model-based assessment of the threshold at which anthropogenic nutrient loading to the Strait of Georgia system would significantly alter primary production and ecosystem processes
- assessment of the changes in habitat types for their impacts to the Strait of Georgia ecosystem, with a focus on those species most likely to depend on these habitats at some stage in their life history
- an analysis using a spatial ecosystem model for the Strait of Georgia that would identify critical hotspots as well as a cumulative threshold size above which the stability of the ecosystem is increased when subjected to stresses such as fishing
- continue the development of mechanistic simulation models which are based on first principles and which are needed to evaluate changes in underlying (correlative) relationships among the various ecosystem components, and to estimate impact of future environmental conditions,
- consider the application of the approaches and tools developed by the Strait of Georgia ERI program to other areas of the B.C. coast which could form the core of a coast-wide ecosystem-based management scheme.

8. REFERENCES

- Burd, B., Barnes, P., Wright, C., Thomson, R. 2008. A review of subtidal benthic habitats and invertebrate biota of the Strait of Georgia, British Columbia. *Marine Environmental Research* **66**: S3–S38.
- Christensen, V., Walters, C. 2004. Ecopath with Ecosim: methods, capabilities and limitations. *Ecological Modelling* **172**: 109–139.
- Cummins, P., Haigh, R. 2010. Ecosystem status and trends report for North Coast and Hecate Strait ecozone. *Canadian Science Advisory Secretariat, Research Document 2010/045*. 67p.
- DFO. 2002. Canada's Ocean Strategy. Fisheries and Oceans Canada. Oceans Directorate, Ottawa, Ont.
- DFO, 2006. A Harvest Strategy Compliant with the Precautionary Approach. DFO Canadian Science Advice Secretariat, *Science Advisory Report 2006/023*. 7p.
- DFO. 2007a. A new ecosystem science framework in support of integrated management. Fisheries & Oceans Canada, Ottawa, Ont. ISBN 978-0-662-46285-9.
- DFO, 2007b. Guidance document on identifying conservation priorities and phrasing conservation objectives for Large Ocean Management Areas. DFO Canadian Science Advisory Secretariat, *Science Advisory Report 2007/010*. 13p.
- DFO. 2010a. Sustainable fisheries framework. Fisheries & Oceans Canada. <http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/sff-cpd/overview-cadre-eng.htm>
- DFO. 2010b. Policy on new fisheries for forage species. Fisheries & Oceans Canada. <http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/sff-cpd/forage-eng.htm>
- DFO. 2010c. Policy for Managing the Impacts of Fishing on Sensitive Benthic Areas. Fisheries & Oceans Canada. <http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/sff-cpd/benthi-eng.htm>
- Diekmann, R., Möllmann, C. (Eds). 2010. Integrated ecosystem assessments of seven Baltic Sea areas covering the last three decades. *ICES Cooperative Research Report No. 302*. 90p.
- Dumbauld, B., Ruesink, J., Rumrill, S. 2009. The ecological role of bivalve shellfish aquaculture in the estuarine environment: a review with application to oyster and clam culture in West Coast (USA) estuaries. *Aquaculture* **290**: 196–223.
- Ferreira, J., Hawkins, A., Monteiro, P., Moore, H., Service, M., Pascoe, P., Ramos, L., Sequeira, A. 2008. Integrated assessment of ecosystem-scale carrying capacity in shellfish growing areas. *Aquaculture* **275**: 138–151.

- Fletcher, W.J., Shaw, J., Metcalf, S., Gaughan, D. 2010. An ecosystem based fisheries management framework: the efficient, regional-level planning tool for management agencies. *Marine Policy* **34**: 1226-1238.
- Fluharty, D., Harvey, C., Jamieson, G., Jin, X., Livingston, P., Makino, M., Radchenko, V., Zhang, C.-I. 2010. In: Jamieson, G., Livingston, P. Zhang, C.-I. (Eds). Report of Working Group 19 on ecosystem-based management science and its application to the North Pacific. *PICES Scientific Report No. 37*: 3-7.
- Herborg, L.-M., O'Hara, P., Therriault, T. 2009. Forecasting the potential distribution of the invasive tunicate *Didemnum vexillum*. *Journal of Applied Ecology* **46**: 64–72.
- Hilborn, R. 2011. Future directions in ecosystem based fisheries management: A personal perspective. *Fisheries Research* (In press).
- Ianson, D., Flostrand, L. 2010. Ecosystem status and trends report: coastal waters off the west coast of Vancouver Island, British Columbia. *Canadian Science Advisory Secretariat, Research Document 2010/046*. 62p.
- Jamieson, G., O'Boyle, R., Arbour, J., Cobb, D., Courtenay, S., Gregory, R., Levings, C., Munro, J., Perry, I., Vandermeulen, H. 2001. Proceedings of the National workshop on objectives and indicators for ecosystem-based management. *Canadian Science Advisory Secretariat Proceedings Series 2001/009*. Ottawa. 142p.
- Jamieson, G. 2010. Canada. In: Jamieson, G., Livingston, P. Zhang, C.-I. (Eds). Report of Working Group 19 on ecosystem-based management science and its application to the North Pacific. *PICES Scientific Report No. 37*: 8-34.
- Jamieson, G., Lessard, J. 2000. Marine protected areas and fishery closures in British Columbia. *Canadian Special Publication of Fisheries and Aquatic Sciences* **131**. 414p.
- Jamieson, G., Levesque, C. In preparation. Identification of Ecologically and Biologically Significant Areas on the West Coast of Vancouver Island and the Strait of Georgia, and in some nearshore areas on the North Coast: Phase II – Designation of EBSAs. Fisheries & Oceans Canada Technical Report.
- Jamieson, G., Livingston, P. Zhang, C.-I. (Eds). 2010. Report of Working Group 19 on ecosystem-based management science and its application to the North Pacific. *PICES Scientific Report No. 37*, 166p.
- Jochens, A. Malone, T., Stumpf, R., Hickey, B., Carter, M., Morrison, R., Dyble, J., Jones, B., Trainer, V. 2010. Integrated ocean observing system in support of forecasting harmful algal blooms. *Marine Technology Society Journal* **44**: 99-121.
- Johannessen, S., Macdonald, R. 2009. Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia, Canada. *Climate Research* **40**: 1–21.
- Johannessen, S. C. and McCarter, B. 2010. Ecosystem Status and Trends Report for the Strait of Georgia Ecozone. *DFO Canada Scientific Advisory Secretariat Research Document 2010/010*. vi + 43p.

- King, J., McFarlane, G. 2006. Shift in size-at-age of the Strait of Georgia population of Pacific hake (*Merluccius productus*). *CalCOFI Reports* **47**: 111-118.
- Langemead, O., et al. 2009. Recovery or decline of the northwestern Black Sea: A societal choice revealed by socio-ecological modelling. *Ecological Modelling* **220**: 2927–2939.
- Levin, P., Fogarty, M., Matlock, G., Ernst, M. 2008. Integrated ecosystem assessments. U.S. Dept. Commerce, NOAA Tech. Memo. **NMFS-NWFSC-92**. 20p.
- Levin, P., Fogarty, M., Murawski, S., Fluharty, D. 2009. Integrated ecosystem assessments: developing the scientific basis for ecosystem-based management of the ocean. *Public Library of Science Biology* **7**: e1000014, 6p.
- Levings, C., Thom, R. 1994. Habitat changes in Georgia Basin: implications for resource management and restoration. In: Wilson, R., Beamish, R., Aitkens, F., Bell, J., (eds). Review of the marine environment and biota of the Strait of Georgia, Puget Sound and Juan de Fuca Strait: *Canadian Technical Report Fisheries and Aquatic Sciences* **1948**: 330-349.
- Link, J.S. 2010. *Ecosystem-based Fisheries Management. Confronting Trade-Offs*. Cambridge University Press, Cambridge, UK. 207p.
- Lucas, B., Verrin, S., Brown, R. (eds). 2007. Ecosystem overview: Pacific North Coast Integrated Management Area (PNCIMA). *Canadian Technical Report of Fisheries and Aquatic Sciences* **2667**. 104p.
- Mackas, D.L., Harrison, P.J. 1997. Nitrogenous nitrate sources and sinks in the Juan de Fuca Strait/Strait of Georgia/Puget Sound estuarine system: assessing the potential for eutrophication. *Estuarine, Coastal and Shelf Science* **44**: 1-21.
- Masson, D., Cummins, P.F. 2007. Temperature trends and interannual variability in the Strait of Georgia, British Columbia. *Continental Shelf Research* **27**:634–649.
- McClure, M., Ruckelshaus, M. 2007. Collaborative science: moving ecosystem-based management forward in Puget Sound. *Fisheries* **32**: 458-462.
- McKindsey, C., Thetmeyer, H., Landry, T., Silvert, W. 2006. Review of recent carrying capacity models for bivalve culture and recommendations for research and management. *Aquaculture* **261**: 451–462.
- McLeod, K., Leslie, H. (Eds) 2009. *Ecosystem-based Management for the Oceans*. Island Press, Washington. 370p.
- McLeod, K. L., Lubchenco, J., Palumbi, S. R., Rosenberg, A. A. 2005. Scientific Consensus Statement on Marine Ecosystem-Based Management. Signed by 221 academic scientists and policy experts with relevant expertise and published by the Communication Partnership for Science and the Sea at <http://compassonline.org/?q=EBM>.

- O'Boyle, R., Jamieson, G. 2006. Observations on the implementation of ecosystem-based management: experiences on Canada's east and west coasts. *Fisheries Research* **79**: 1-12.
- Olesiuk, P.F. 1993. Annual prey consumption by harbor seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. *Fisheries Bulletin, U.S.* **91**: 491-515.
- Olsson, P., Folke, C., Hughes, T. 2008. Navigating the transition to ecosystem-based management of the Great Barrier Reef, Australia. *PNAS* **105**: 9489-9494.
- Parson, T.R., Albright, L.J., Parslow, J. 1980. Is the Strait of Georgia becoming more eutrophic? *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 1043-1047.
- Perry, R.I., Barange, M., Ommer, R.E. 2010. Global changes in marine systems: a social-ecological approach. *Progress in Oceanography* **87**: 331-337.
- Rice, J. C. 2009. A generalization of the three-stage model for advice using the precautionary approach in fisheries, to apply broadly to ecosystem properties and pressures. *ICES Journal of Marine Science* **66**: 433-444.
- Rockström, J., et al. 2009. A safe operating space for humanity. *Nature* **461**: 472-475.
- Schweigert J, Christensen LB, Haist V. 2009. Stock assessment for British Columbia herring in 2008 and forecasts of the potential catch in 2009. *DFO Canadian Science Advisory Secretariat, Research Document* **2009/019**. 61 p.
- Shin, Y-J., Shannon, L. J., Bundy, A., Coll, M., Aydin, K., Bez, N., Blanchard, J. L., Borges, M. F., Diallo, I., Diaz, E., Heymans, J. J., Hill, L., Johannesen, E., Jouffre, D., Kifani, S., Labrosse, P., Link, J. S., Mackinson, S., Masski, H., Möllmann, C., Neira, S., Ojaveer, H., Mohammed Abdallahi, K., Perry, I., Thiao, D., Yemane, D., and Cury, P. M. 2010a. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2. Setting the scene. *ICES Journal of Marine Science*, **67**: 692–716.
- Shin, Y-J., Bundy, A., Shannon, L. J., Simier, M., Coll, M., Fulton, E. A., Link, J. S., Jouffre, D., Ojaveer, H., Mackinson, S., Heymans, J. J., and Raid, T. 2010b. Can simple be useful and reliable? Using ecological indicators to represent and compare the states of marine ecosystems. *ICES Journal of Marine Science* **67**: 717–731.
- Smith, A., Fulton, E., Hobday, A., Smith, D., Shoulder, P. 2007. Scientific tools to support the practical implementation of ecosystem-based fisheries management. *ICES Journal of Marine Science* **64**: 633-639.
- Tallis, H., Levin, P., Ruckelshaus, M., Lester, S., McLeod, K., Fluharty, D., Halpern, B. 2010. The many faces of ecosystem-based management: making the process work today in real places. *Marine Policy* **34**: 340-348.
- Shin, Y.-J., Cury, P. 2001. Exploring fish community dynamics through size-dependent trophic interactions using a spatialized individual-based model. *Aquatic Living Resources* **14**: 65-80.

- Snelgrove, P. 2009. Governance and management of ecosystem services in semi-enclosed marine systems. In: Urban, E.R., Jr., Sundy, B., Malanotte-Rizzoli, P., Melillo, J. (eds). *Watersheds, Bays, and Bounded Seas*. SCOPE 70. Island Press, Washington, p. 49-76.
- Sutherland, T., Levings, C.D., Petersen, S.A., Poon, P., Piercy, B. 2007a. The use of meiofauna as an indicator of benthic organic enrichment associated with salmonid aquaculture. *Marine Pollution Bulletin* **54**: 1249-1261.
- Sutherland, T., Petersen, S.A., Levings, C.D., Martin, A. 2007b. Distinguishing between natural and aquaculture-derived sediment concentrations of heavy metals in the Broughton Archipelago, British Columbia. *Marine Pollution Bulletin* **54**: 1451-1460.
- Sweeting, R., Beamish, R., Noakes, D., Neville, C. 2003. Replacement of Wild Coho Salmon by Hatchery-Reared Coho Salmon in the Strait of Georgia over the Past Three Decades. *North American Journal of Fisheries Management* **23**: 492-502.
- Uusitalo, L. 2007. Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling* **203**: 312–318.

Table 1. Unpacking of conceptual to operational ecosystem-based management objectives and their indicators, as proposed for Canada by O'Boyle and Jamieson (2006).

Unpacking of Conceptual Objective	Characteristic	Indicator	Operational Objective (Consists of Verb, Indicator and Reference Point)
<ul style="list-style-type: none"> • Conserve each component of ecosystem so that it can play its historical role in foodweb <ul style="list-style-type: none"> ○ Maintain Production of Forage Species supporting Food Chain in IM Area <ul style="list-style-type: none"> ▪ Maintain Herring Population Biomass above Minimum level 	<p>Herring Population</p> <p>Biomass</p>	<p>Age 3+ Biomass</p> <p>Estimate from Population Analysis (e.g. VPA)</p>	<p>Maintain Age 3+ Herring Population Biomass above 50,000t</p>

Table 2. Typology of ecosystem approaches to management of marine systems and issues (from Fluharty et al., 2010).

EBM component	I. Traditional single factor management	II. Sectoral Management in an Ecosystem Context	III. Integrated Management in an Ecosystem Context
Species	Considers only the factor or species being used	Considers prey, dependent predators and food supply, and impacts on ecosystem	Considers impacts of other activities on the status of the species being used and across the ecosystem
Physical habitats	Only considered if a surrogate for population parameters	Considers productive capacity and impacts of activity on the habitat	Accommodates spatial needs and habitat impacts of other activities
Environmental conditions	Not considered	Considers productivity regime and forcing	Considers direct and indirect effects
Biodiversity	Not considered	Considers impacts on species not being used directly	Considers status of communities and resilience of the community/system
Other components	Not considered	Considers other components as they affect the particular sector	Considers all components and all sectors and the interactions among them relative to agreed ecosystem management goals

Table 3. Details of the critical elements and their thresholds, as identified by Rockström et al. (2009).

PLANETARY BOUNDARIES				
Earth-system process	Parameters	Proposed boundary	Current status	Pre-industrial value
Climate change	(i) Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	(ii) Change in radiative forcing (watts per metre squared)	1	1.5	0
Rate of biodiversity loss	Extinction rate (number of species per million species per year)	10	>100	0.1–1
Nitrogen cycle (part of a boundary with the phosphorus cycle)	Amount of N ₂ removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (part of a boundary with the nitrogen cycle)	Quantity of P flowing into the oceans (millions of tonnes per year)	11	8.5–9.5	~1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (km ³ per year)	4,000	2,600	415
Change in land use	Percentage of global land cover converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	For example, amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in, the global environment, or the effects on ecosystem and functioning of Earth system thereof	To be determined		

Boundaries for processes in red have been crossed. Data sources: ref. 10 and supplementary information

Table 4. ‘Natural’ and ‘Direct anthropogenic’ threats (pressures, stressors) that may prevent management agencies from achieving the overarching goal of protecting ecosystems and their components from serious or irreversible harm, but also allowing for the sustainable use of these ecosystems. Also identified is whether the particular stressor is solely the management responsibility of DFO.

Stressor	Agency responsibility
<i>“Natural”:</i>	
- ‘natural’ environmental variability, in particular at longer (e.g. decadal) time scales)	- DFO
- environmental change (e.g. climate change; ocean acidification; sea level rise)	- DFO
<i>“Direct anthropogenic”:</i>	
- natural resource use	
- shellfish and finfish harvest – commercial	- DFO
- shellfish and finfish harvest – recreational	- DFO
- introductions of non-native species	- DFO
- fish culture activities:	- DFO
- aquaculture – shellfish; finfish	
- hatcheries – salmonids	
- contaminants	
- eutrophication	- (partly) DFO
- agricultural runoff	- (partly) DFO
- industrial effluents	- (partly) DFO
- sewage and urban storm water	- (partly) DFO
- marine debris	- (partly) DFO
- hazardous and accidental spills	- (partly) DFO
- development/land use	
- residential development	- (partly) DFO
- commercial and industrial activities	- (partly) DFO
- tourism and recreation	- (partly) DFO
- shoreline modification	- (partly) DFO
- agriculture, silviculture	- (partly) DFO
- transportation infrastructure	- (partly) DFO

Table 5. Strategies used by the great Barrier Reef marine park (Australia) to aid the transition to ecosystem-based management (from Olsson et al., 2008).

Strategies	Actions	Examples of barriers to change
Making internal organisational changes	Establishing Senior Managers Forum and four regional teams Providing clear and transparent leadership at the relevant levels within the organization Communicating a shared vision and goals	Resource constraints Inability to innovate or deal with surprise Lack of direction, shared vision, engagement, trust, leadership, cross-sector cooperation, communication Having few leaders exacerbates vulnerability
Bridging science and policy	Drawing on existing networks of scientists, managers and industry to promote dialogue Workshops and forums for synthesizing knowledge Communicating shared vision and goals	Science is fragmented Lack of scientific certainty Different perceptions and views among scientists and managers, lack of trust
Changing public perceptions	Clear, simple, and tailored stakeholder information Visualizing the entire GBR as an interconnected ecosystem Creating a sense of urgency for conservation	Different knowledge and interests among stakeholder groups Low awareness of problems, threats, and ecological interactions
Facilitating community participation and public consultation	Building trust with communities Community information sessions Recasting problems as opportunities Periodic updates on the rezoning process Innovative submission routines	Lack of trust Conflicting views among key actor groups, misinformation Outreach to local communities difficult Lack of leadership
Gaining political support	Prepared for change: timing actions, information ready Briefing key players before new zoning plans implemented Allying with other key groups Pollsters for leverage and monitoring public opinion	Change of people in power Lack of support from key politicians Zoning plans can be stopped Opposing views

Figure 1. Strait of Georgia



Figure 2. Potential (ecosystem-based) conservation objectives for Canada, as proposed by Jamieson et al. (2001).

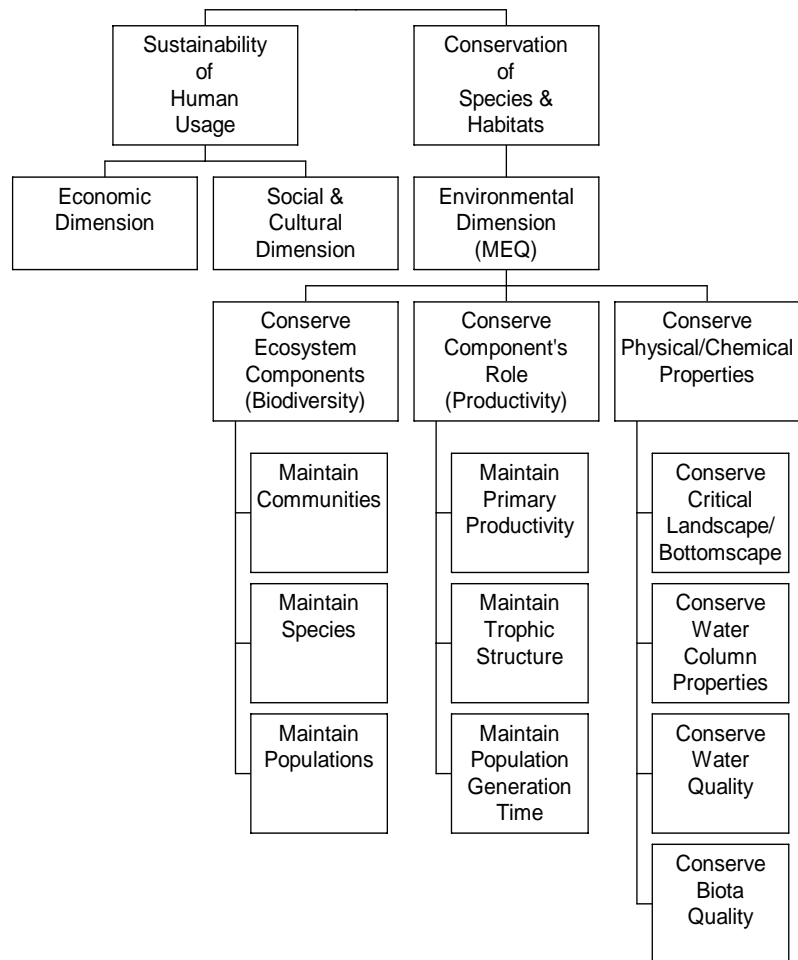


Figure 3. DFO Fisheries Management Sector conceptual approach to ecosystem-based management and links to the Sustainable Fisheries Framework.

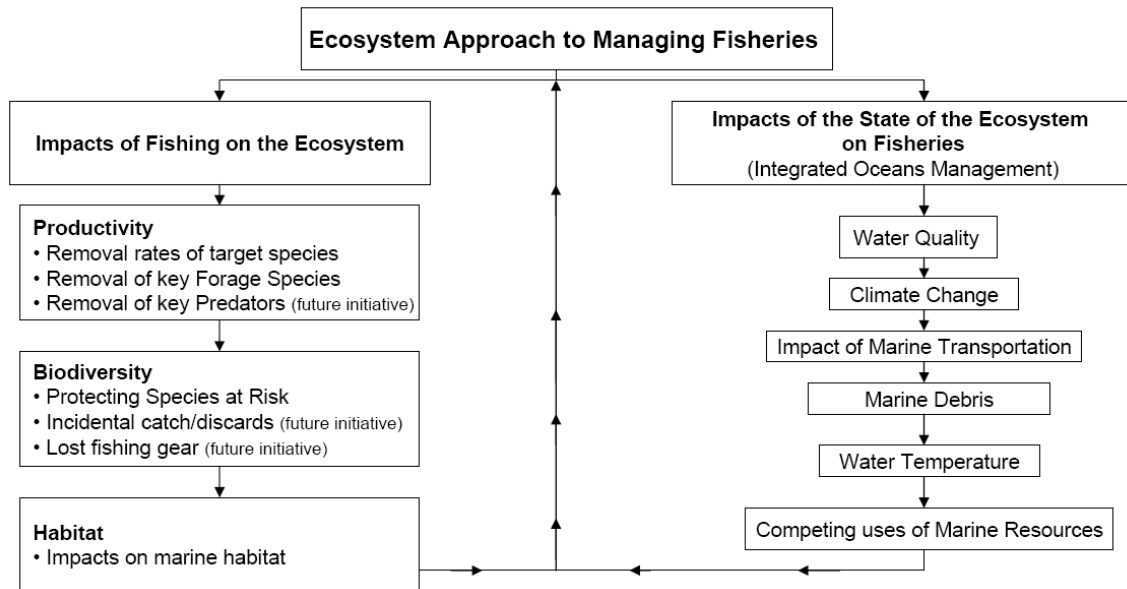


Figure 4. Orientation of tools, methods, and scope of ecosystem-based fisheries management (from Smith et al., 2007). "MSE" is management strategy evaluation.

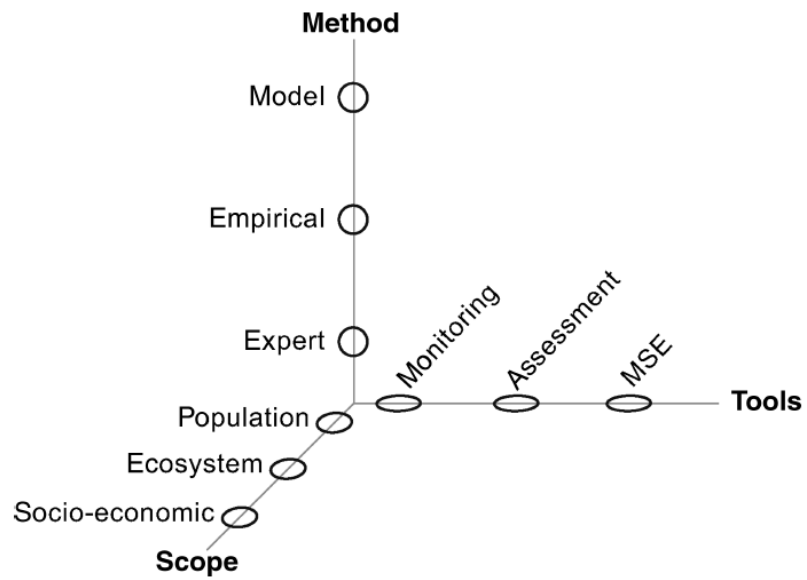


Figure 5. U.S. Integrated Ecosystem Assessment process (from Tallis et al, 2010, after Levin et al. 2009).

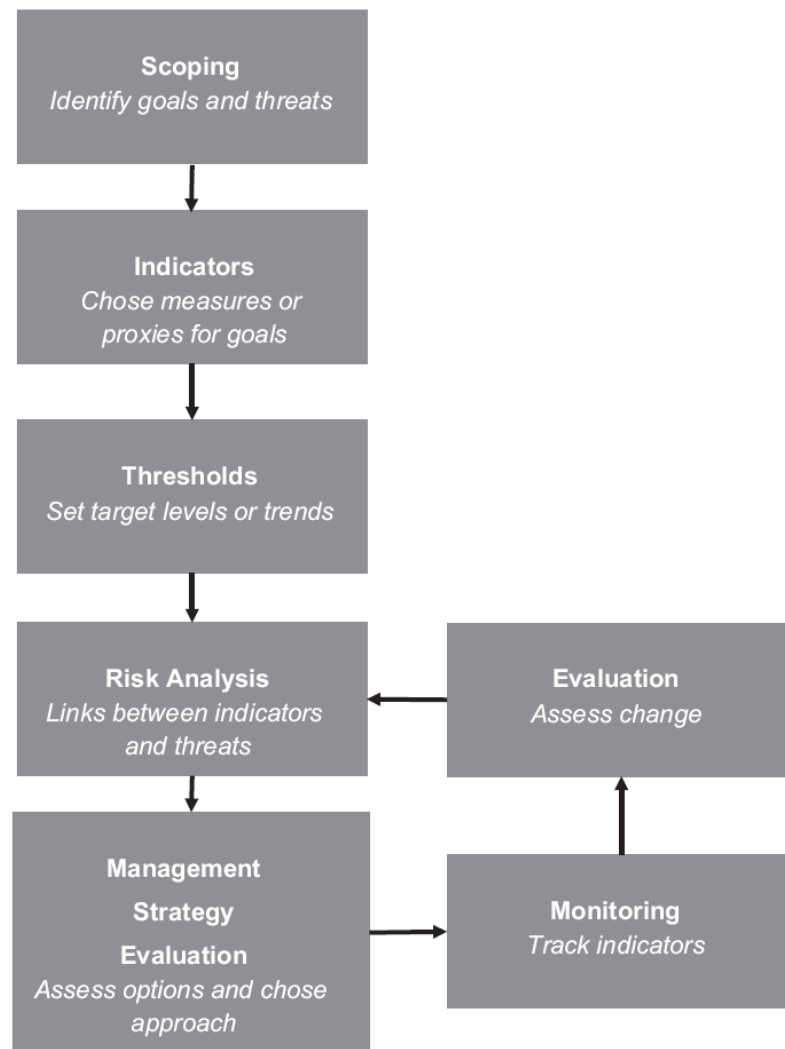


Figure 6. All EBSAs for the SoG, excluding River Mouths and Estuaries: 1) Discovery Passage Entrance, 2) Desolation and Pendrell Sounds, 3) Baynes Sound, 4) Sabine Channel, 5) Southern Gulf Islands, 6) Fraser River Estuary and Boundary Bay 7) Glass Sponge Reefs. (Courtesy Jamieson and Levesque, In preparation).

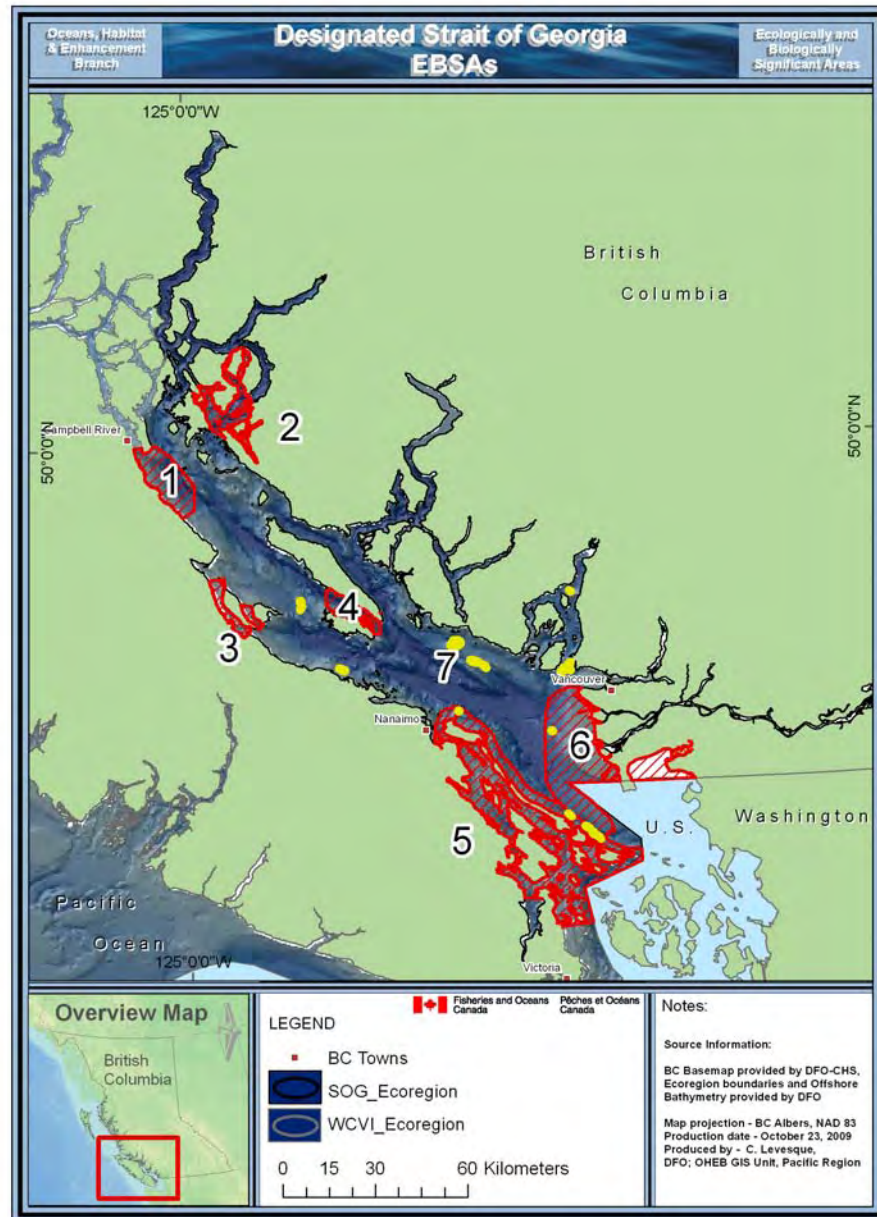


Figure 7. Example of a 'radar plot' of the nine critical processes/conditions identified by Rockström et al. (2009), and their assessment of where we are currently on a global basis.

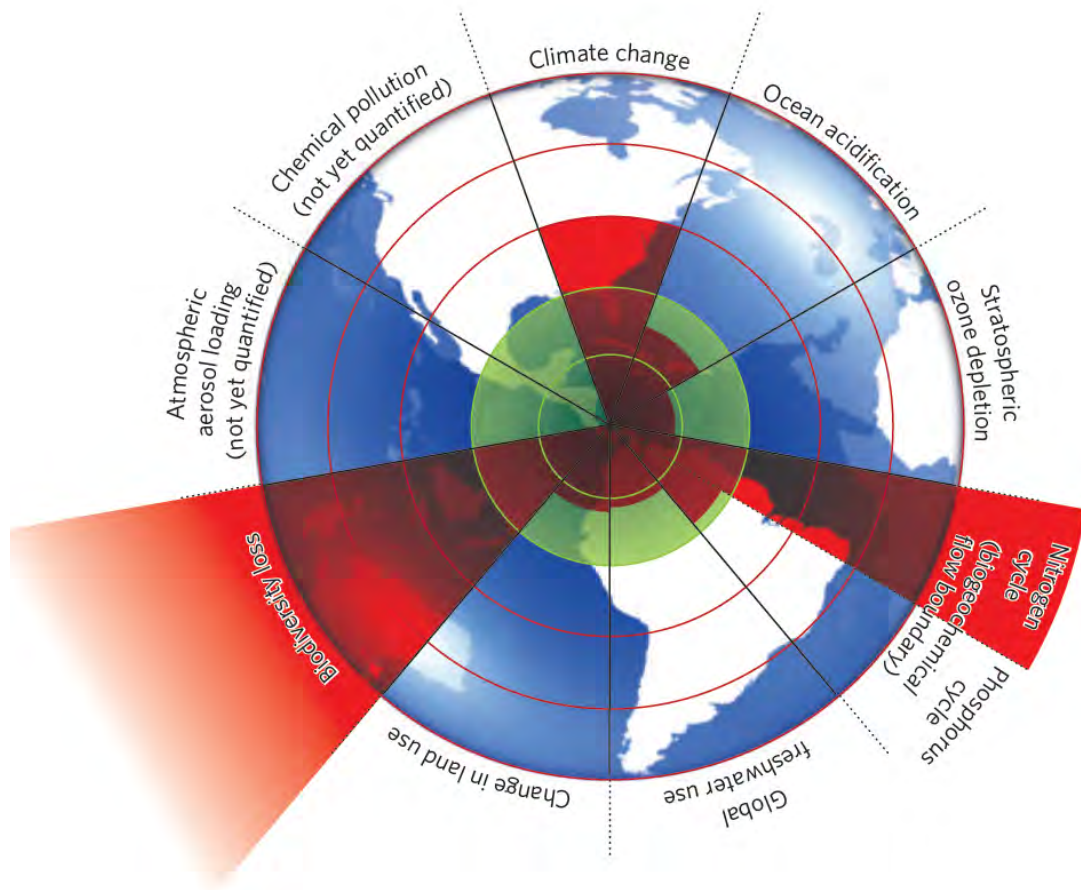


Figure 8. Fisheries management framework consistent with a precautionary approach (DFO, 2006).

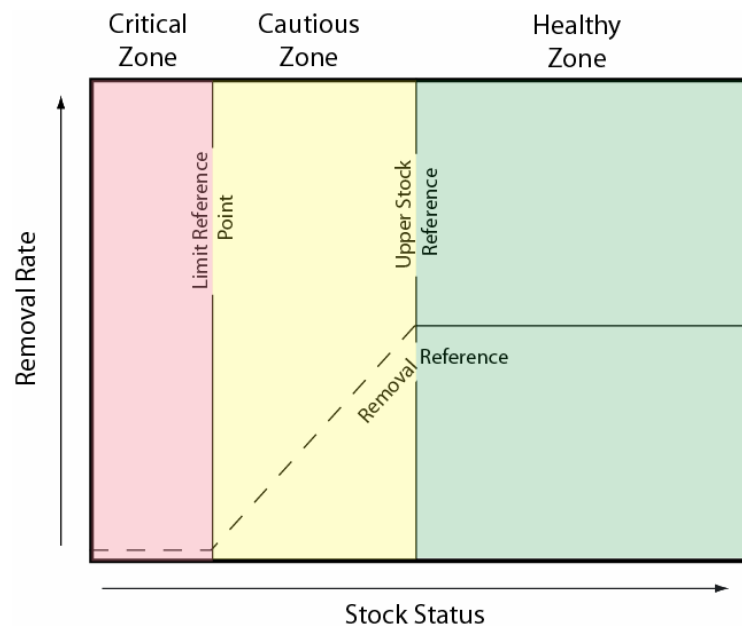
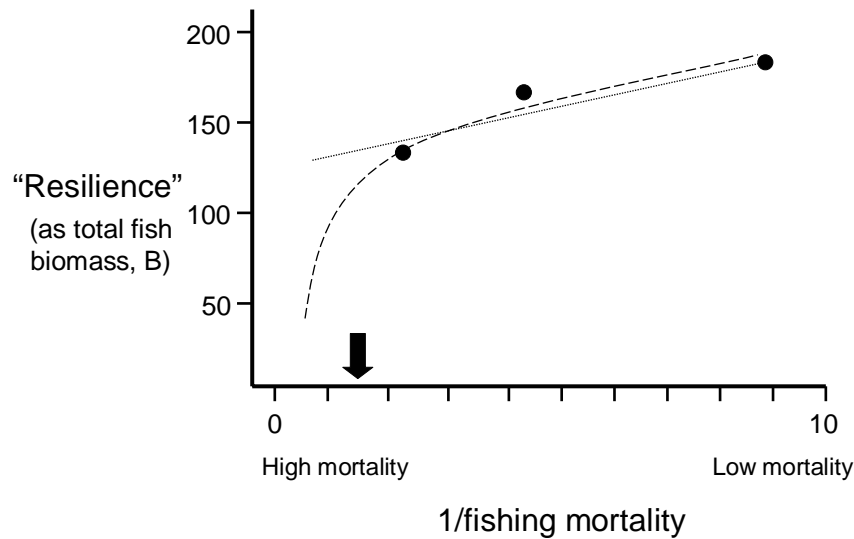


Figure 9. Example of applying the DFO precautionary approach concept for fisheries management advice to identifying critical ecosystem thresholds. This example represents an assessment of how fishing on the Strait of Georgia herring stock might affect total ecosystem fish biomass (as one indicator of ecosystem stability). The abscissa represents a measure of human impact on the Strait of Georgia ecosystem (here, as the inverse of fishing mortality on herring) and total fish biomass (averaged over the past 10 simulated years, without regime-scale climate variability) as the measure of ecosystem 'resilience'. Dots represent values obtained from OSMOSE model simulations when fishing herring at $0.25M$, $0.5M$, and M , where M is the annual rate of natural mortality. The dotted and dashed lines represent hypothetical trajectories through these three points; more simulations would be needed to identify the full shape of the curve. The arrow represents a possible critical threshold for the impacts to the Strait of Georgia ecosystem of fishing on herring. Data are from the ERI study by Fu (Appendix A14).



APPENDIX

A1: SHORT-TERM VARIABILITY IN THE STRAIT OF GEORGIA

Sophia Johannessen and Rob Macdonald DFO, Institute of Ocean Sciences, Sidney, B.C.

Field work

Moorings

Since June 2008, we have maintained two moorings in the Strait of Georgia, one in the central Strait under the strong influence of the Fraser River plume, and the other in the northern Strait, north of Texada Island (Figure 1). Using these moorings, we have collected continuous records of sinking particles and water properties. We have conducted 9 three-day mooring cruises to deploy, recover and maintain these moorings. Each mooring includes one sediment trap at 50 m, with instruments that measure temperature, salinity, pressure, fluorescence, turbidity and current velocity. At mid-depth on each mooring (150 m), there is an oxygen sensor. Since April 2009 we have deployed an additional instrument package at 300 m to measure oxygen, pH, salinity and temperature in the deep basins of the Strait. The southern mooring also includes an acoustic Doppler current meter near the bottom. For the first two years, we deployed paired sediment traps at 50 m on each mooring, one to collect sediment over 10-12 day intervals and the other to collect over 2-day intervals for a shorter total collection time. In August 2010, we decided to continue with only the 10-12 day sampling. Sediment trap samples were recovered from the traps and sieved onboard through a 500 μ m sieve to separate the zooplankton, which likely swam into the traps, from the other material collected. The two fractions were split into subsamples for chemical and biological analysis on return to the lab.

In addition to recovering and redeploying the moorings during the cruises, we measured water property profiles using a CTD and collected discrete water samples over the whole water column at each mooring site. Beginning in 2009 we also collected surface water samples at 10 stations along a transect from the Fraser River (1 mi upstream of the mouth; Figure 1), across the plume and into the central Strait. pH was measured spectrophotometrically in these water samples during the cruise. Other samples were returned to the lab for analysis of oxygen, dissolved inorganic carbon / alkalinity, dissolved organic carbon, particulate organic carbon, nutrients, coloured dissolved organic matter, chlorophyll and ^{18}O (oxygen stable isotope). The surface transect was conducted to quantify the role of the Fraser River in buffering the Strait of Georgia seawater against acidification.

River sampling

In June and October 2008 and April and June 2009, we collected water and suspended particles from 8 rivers that discharge into the Strait of Georgia (Figure 1). The timing of the sampling was chosen to correspond to different phases of river discharge.

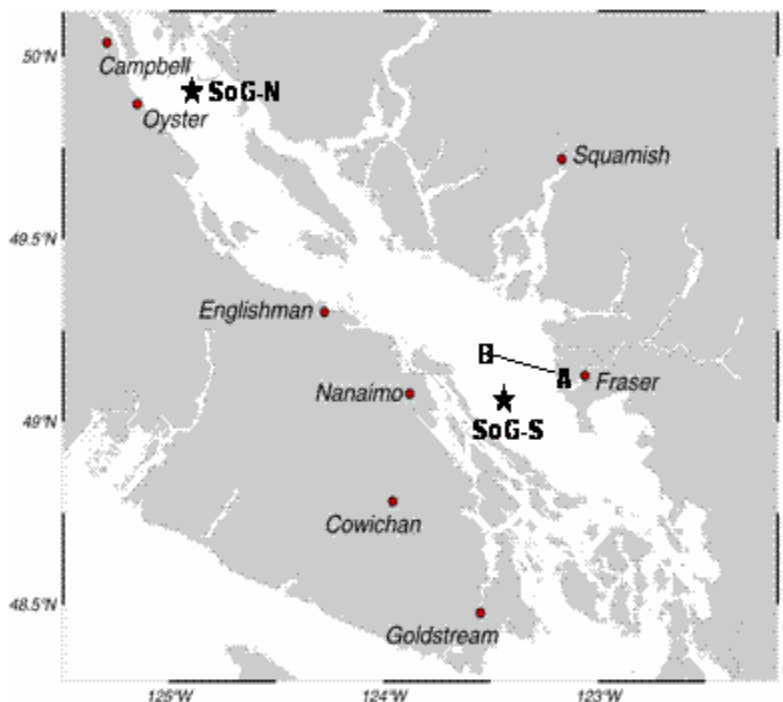


Figure 1. Map of study area. Mooring locations SoG-N and SoG-S are marked with stars. Line A-B represents the 10-station transect that begins 1 nmi upstream of the mouth of the Fraser River and crosses the river plume. Dots mark river sampling locations.

Laboratory analyses and data

Sediment trap samples from the first year and part of the second year (5 deployments x ~40 samples per deployment) have been analyzed for total dry weight flux, organic carbon, inorganic carbon, total nitrogen and stable isotopes of carbon and nitrogen. The same analyses are in progress for the remaining samples. Biological identification and enumeration has been completed for samples from the first deployment. All the coloured dissolved organic matter (CDOM) samples have been analyzed, as have most of the oxygen isotope samples. The dissolved inorganic carbon / alkalinity measurements are in progress.

River water samples have been analyzed for dissolved organic carbon, coloured dissolved organic matter, stable oxygen isotope and nutrients. Particulate samples from the rivers were analyzed for total suspended solids, particulate organic carbon, total nitrogen and stable isotopes of carbon and nitrogen.

Results

We are still waiting for some of the analytical data. Preliminary interpretation of the electronic records from the moorings indicates that windstorms can be very important to water properties in the mid-water column of the Strait. For example, a windstorm at the beginning of 2009 was immediately followed by a change in the water properties at the northern mooring site that is consistent with the downward mixing of surface water. The change occurred abruptly and lasted for months, until the water properties shifted gradually back to the pre-storm conditions in the spring. (Figure 2). In the southern

Strait, however, the windstorm only caused a brief dip in salinity and temperature, after which the water properties at that site continued their gradual trend into winter conditions. We speculate that the difference in response to the storm between the two locations was due to the much greater stabilizing influence of the Fraser River plume in the southern Strait. If this is correct, then it suggests that coastal seas that receive significant freshwater input may be more resilient to the effects of the increasingly frequent storms expected as climate changes.

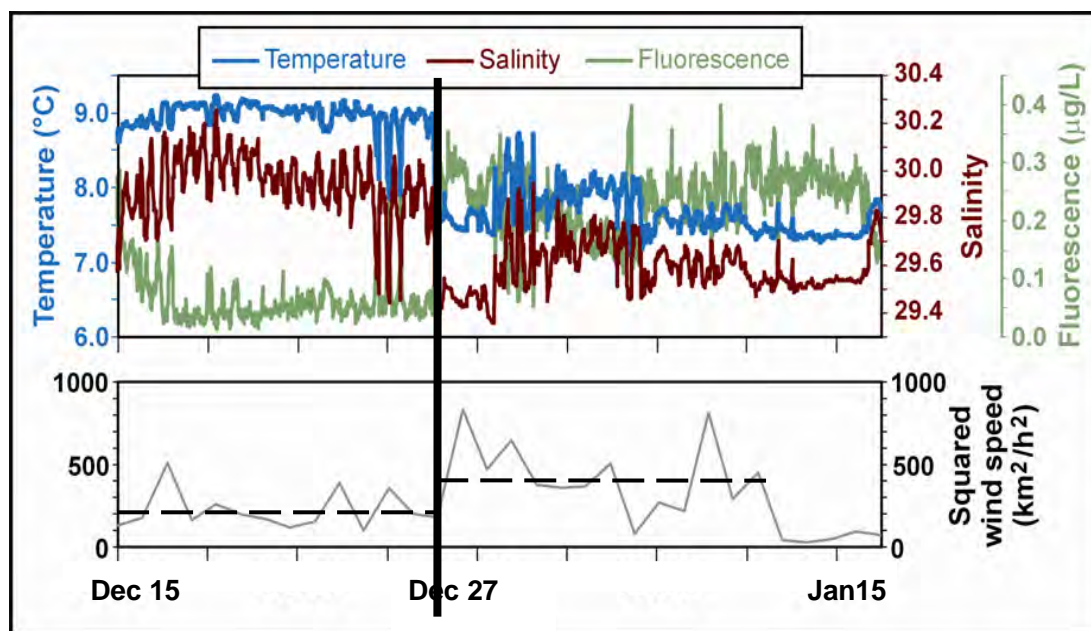


Figure 2. Change in T, S, fluor at 50 m and wind forcing

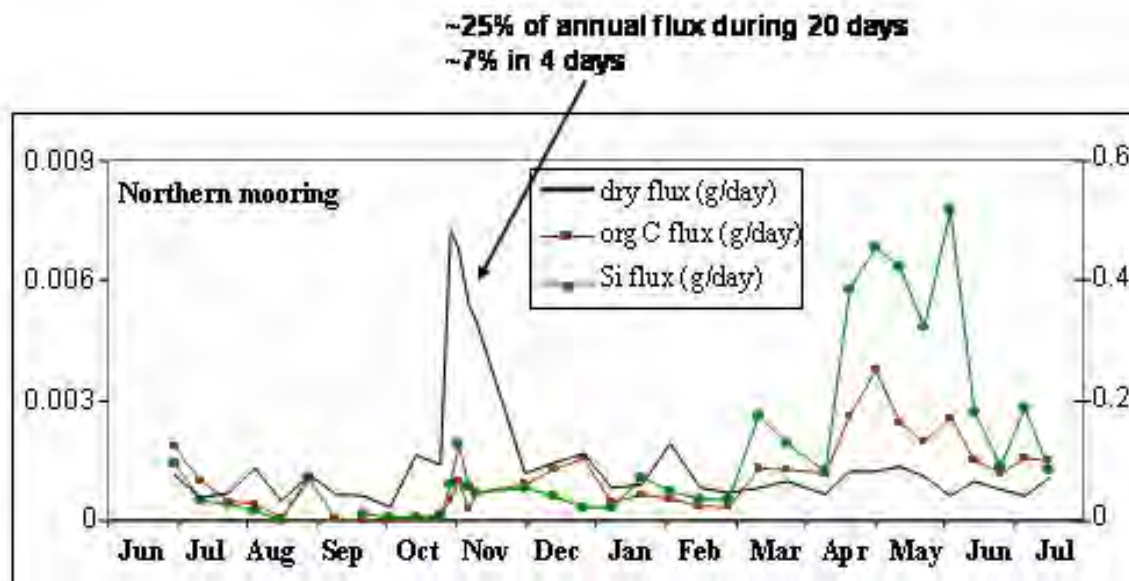


Figure 3. Total particle flux and organic component fluxes into the sediment trap at 50 m depth on the northern mooring, June 2008 – July 2009, showing the effect on the particle flux of the heavy rain in October 2008.

Rainstorms showed clear effects on the type and amount of sinking particulate matter, particularly in the northern Strait, where the main, direct input of freshwater comes from

dominantly rainfed, rather than snowfed, rivers. A series of rainstorms over 20 days in October 2008 was responsible for 25% of the annual flux of particles to the northern trap, with 7% of the annual flux accumulating in just 4 days (Figure 3).

Our interpretation is still in progress, but it is clear that events on the timescale of a few days can contribute disproportionately to the water properties and type and amount of particulate matter in the mid-water column of the Strait.

Dissemination of Results

Presentations:

We have presented preliminary results of the mooring and river sampling work at the Canadian Meteorological and Oceanographic Society Congresses in Halifax in 2009 and Ottawa in 2010 and at an informal IOS seminar in October, 2010.

Publications in progress and planned:

1. Short-term variability. We are preparing a paper about the effects of short-term events, such as windstorms, on the flux and composition of sinking particles, based on the data from the first two years of the mooring data and on data from an earlier sediment trap project (1996-1999).

2. Oxygen. In collaboration with Diane Masson, we are preparing a paper about the trends and variability in oxygen in the Strait of Georgia, based on a 40-year time series of measurements near Nanaimo and on the data from this ERI project. The paper will draw on previous work about water masses and organic carbon in the system.

3. pH. In collaboration with Debby Ianson, we are preparing a paper about the inorganic carbon system of the Strait of Georgia, including the roles of the Fraser River and inflowing Pacific Ocean water on pH. The paper will integrate data from the water column sampling and moored instruments of this ERI project with separate measurements of dissolved inorganic carbon and will draw on previous work on circulation and organic carbon.

4. Spring bloom and productivity. In collaboration with Angelica Peña, we are planning a paper about the timing and quality of primary production in the Strait, including the timing of the spring bloom at the surface and when the export flux from the bloom arrives deeper in the water column. This paper will combine fluorescence and sediment trap composition data from the moorings with independent water column measurements and satellite imagery.

5. Other records that may lead to thematic publications

- stable isotopes in sinking particles captured in the sediment traps, which could be compared with isotopic data collected for trophic dynamics and zooplankton history work
- incidental zooplankton record (> 500 m fraction) from 1996-1999 and 2008-2011,
- dinoflagellate cyst record (< 500 m fraction)
- the application of $\delta^{18}\text{O}$ composition as a tracer of freshwater sources and mixing in the Strait of Georgia
- total nitrogen and nitrogen stable isotope records in sediment traps, in combination with data from sediment cores, water column nutrients and effluent to produce broad-scale nitrogen budget

Data

The calibrated, quality-controlled dataset will be prepared this year and next. In addition to the journal publications that will result from this project, the data will be archived in the IOS data archive and summarized in a data report.

Funding

In addition to the funding from the Strait of Georgia ERI, this project was partly funded by the DFO – Metro Vancouver Ambient Monitoring Programme.

A2: SPRING BLOOM PATTERN AND TIMING IN THE STRAIT OF GEORGIA

J. Gower and S. King, DFO, Institute of Ocean Sciences, Sidney, B.C.

Brief report, January 2011

We call the bloom pattern the “Malaspina Dragon” after its shape in satellite imagery in 2005, 2008 and 2009 (Figure 1) shortly after it enters the Strait, and present evidence that the inlet blooms result in earlier spring blooms in the Strait.

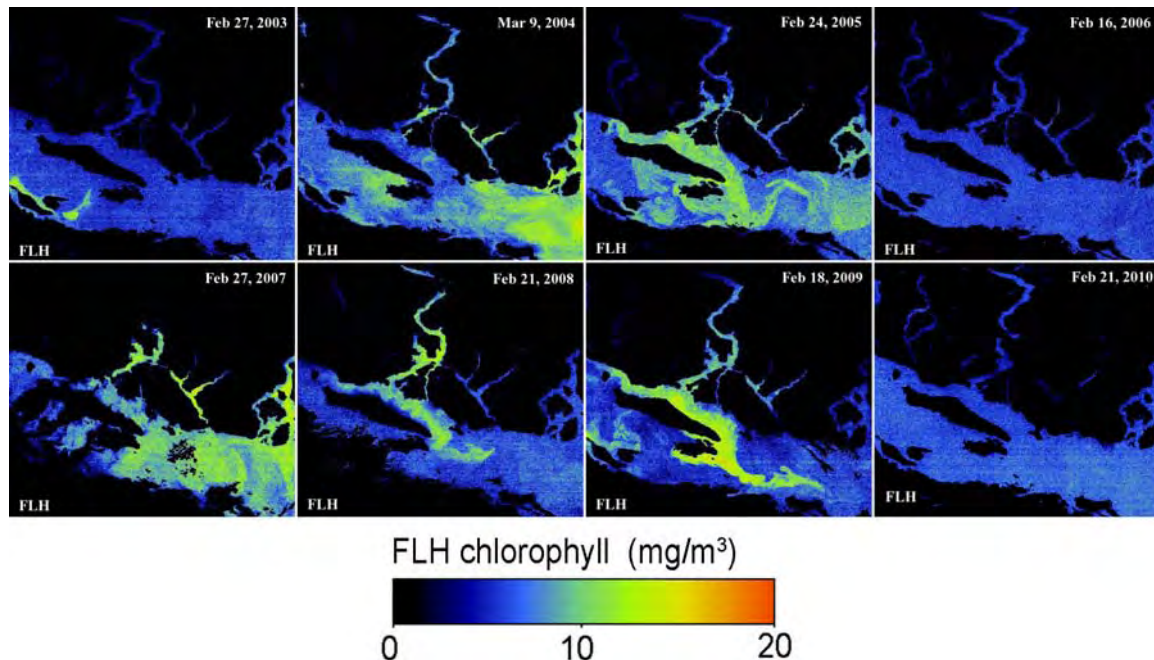


Figure 1. MERIS full resolution (300 m) FLH images for years 2003 to 2010. A single, relatively cloud-free day in late February is shown for each year. The Malaspina Dragon pattern is visible in FLH images for 2005, 2008 and 2009. Blooms are visible in Jervis or Sechelt Inlets or both, in all years except 2003, 2006 and 2010. The colour scale relates FLH to mg.m^{-3} of chlorophyll.

In 2005, 2008 and 2009, high chlorophyll values were first observed in Jervis and Sechelt inlets in mid-February, and were later observed in Malaspina Strait which is an arm of the Strait of Georgia, before spreading across the main body of the Strait in late February and early March.

The satellite image data that we use consist of the fluorescence signal (FLH, for Fluorescence Line Height) computed to show the added radiance at 685 nm due to solar-stimulated chlorophyll fluorescence. MODIS and MERIS satellite FLH (1 km resolution) images are essential for monitoring timing and pattern of the spring bloom in

the Strait. We find FLH performs better in these coastal waters than the standard chlorophyll algorithms based on blue-to-green radiance ratios. Higher resolution (300m) images from the MERIS satellite are needed for detecting the early blooms in Jervis and Sechart Inlets. Time series of chlorophyll data from in-situ recording fluorometers are useful for confirming the satellite data and for measuring through time gaps due to cloud.

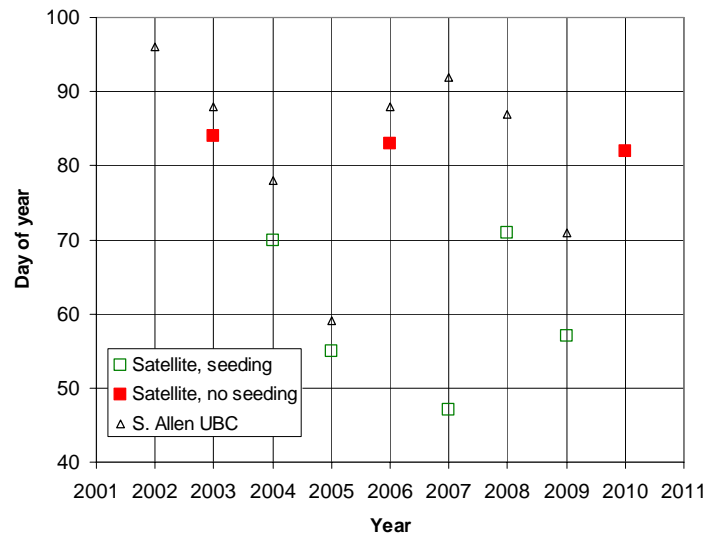


Figure 2. Dates of the start of the spring bloom, showing later blooms (red) in years when no seeding is observed. Dates by Allen are based on ship observations of when nitrate is drawn to zero, and so are slightly later than the satellite dates of spring bloom start, except in 2007 when a major delay indicates disagreement.

From satellite data in Figure 2 it appears that the main spring bloom in the Strait of Georgia occurs earlier in the years when the Dragon is active, suggesting that seeding from inlets should be added to the list of factors controlling timing. Observations by Allen show less correlation. In four years they show a small delay after the satellite dates, as expected for nitrate draw-down. In 2007, ship observations missed an early bloom, and in 2008 and 9 the delay is longer.

Plans for 2011

Our results suggest a need for improved in-situ monitoring of phytoplankton in February and March of each year, in Sechart and Jervis Inlets as well as in the main body of the Strait. We will continue to monitor the area using satellite imagery. We have deployed fluorometers to the south of the area shown in Figure 1, on a BC ferry (SOVI) and on ODAS buoy 46134 in Saanich Inlet. These will continue through 2011. In 2010 we set up a fluorometer at Egmont in Jervis Inlet to monitor the inlet blooms. We plan to repeat this in 2011 and to add a fluorometer to ODAS buoy 46146 in the Strait of Georgia. In 2009 and 2010 we deployed a glider in the Strait with partial support from ERI funds, to monitor the timing and spatial distribution of the spring bloom, including its distribution with depth. The glider now needs expensive servicing and will not be available in 2011.

A3: EFFECTS OF VARYING SMOLT RELEASE TIMING AND SIZE ON THE SURVIVAL OF HATCHERY-ORIGIN COHO SALMON IN THE STRAIT OF GEORGIA

J. R. Irvine, M. O'Neill, L. Godbout, and J. Schnute, Fisheries and Oceans Canada, Pacific Biological Station, Nanaimo, British Columbia

Introduction

Hatcheries contribute 22 – 37 % of the total production of Pacific salmon (*Oncorhynchus* spp.) production (Eggers 2009; Ruggerone et al. 2010). In 2007, the most recent year for which complete data are available, 5.1 billion salmon were released by hatcheries, of which 2.1 billion were from North America (Irvine et al. 2009). Surprisingly perhaps, there have been relatively few long term studies evaluating the effects of different release strategies on salmon survival. Canada has a relatively long history of Pacific salmon enhancement, with its first major production facility constructed in the early 1970's (Sandher et al. 2010). Numbers of coho salmon (*O. kisutch*) released during 1980-2008 averaged 17 million annually (Irvine et al. 2009). Hatchery managers in southern British Columbia continue to apply release guidelines developed in the 1970s and 1980s (e.g. Bilton 1980; Bilton et al. 1982; Bilton et al. 1984) although individual hatchery managers and enhancement staff have carried out numerous small scale experiments and adjusted their release programs accordingly (Greg Bonnell, DFO Oceans, Habitat and Enhancement Branch, pers. comm., Jan. 2009).

The marine ecosystem, in particular the Strait of Georgia where many Canadian coho salmon are released has changed significantly during the period of salmon enhancement. We have seen warmer temperatures (Masson and Cummins 2007), earlier peaks in Fraser River discharge (Morrison et al. 2002), decreases and earlier timings of zooplankton blooms (El-Sabaawi et al. 2009), and a precipitous decline for many commercially important species including herring (Therriault et al. 2009), Chinook salmon (Beamish et al. 1995), as well as coho salmon. The environmental changes in the

Strait of Georgia have been so severe that, in the mid-1990's, juvenile coho salmon that had normally spent their entire life-cycle within the Strait of Georgia, began leaving the straight (Beamish et al. 1999). An acoustic tag study by Chittenden et al. (2009) implied that any coho salmon that remained in the Strait of Georgia died before reaching maturity.

Coho salmon, once an economically significant component of the fishery in the Strait of Georgia (Beamish et al. 1999), are currently at very low population levels (Beamish et al. 2008). Their current poor status is chiefly the consequence of hugely reduced marine survivals during the past 20 years (Simpson et al. 2001), exacerbated by recent declines in early marine survival (Beamish et al. 2010). Several authors have speculated that decreases in marine survival of coho salmon may be related to mismatches between fixed ocean entry timing of hatchery smolts and increasingly early peaks in zooplankton biomass (Beamish et al. 2006; Johannessen and Macdonald 2009). Density dependent effects may also be affecting the survival of coho salmon in the Strait of Georgia. Beamish et al. (2008) found that juvenile hatchery origin coho salmon were caught more frequently in trawl surveys in the Strait of Georgia than wild fish during 1997-2002, but this pattern was reversed in 2004 and 2005. Declining proportions of hatchery fish in more recent years and uncertainty about the carrying capacity of the Strait of Georgia for hatchery coho salmon suggested to these authors that a more experimental approach to the operation of hatcheries should be considered. We wanted to evaluate whether Strait of Georgia hatcheries could be better used to benefit the coho salmon resource in southern BC. The long time series of coho salmon releases from major hatchery facilities provided an excellent data source to examine

whether release strategies developed in the 1970's and 1980's were still appropriate. Our primary objective was to evaluate the effects of smolt release size and timing on survival of coho salmon in the Strait of Georgia, and whether these effects have changed over the time. If we found insufficient evidence to support altering hatchery release strategies for coho salmon, we wished to consider alternate uses for hatcheries that might improve our understanding and hence management of coho salmon.

Methods

Data from the Mark Recovery Program (MRP) database (Kuhn et al. 1988) for coho salmon (ocean entry years (OEY) 1979-2006) from five Strait of Georgia hatchery populations were supplemented with data from one wild population as a comparison. The wild population, Black Creek, and three hatcheries (Big Qualicum River, Puntledge River, Quinsam River) are on the east coast of Vancouver Island while two hatcheries (Chilliwack River and Inch Creek) are in the lower Fraser River (Figure 1). Relevant data consisted of release information (CWT batch number, numbers of smolts released, mean weights of a sample of released smolts, and release date) and recovery data (observed and estimated numbers of fish caught in fisheries and returning to spawn (i.e. escapement)) (Table 1; supplemental Table A1). In order to reduce bias, we screened the data by excluding any hatchery release group with ventral fin clips, disease problems, and experimental treatments (e.g. sterilization), which might have affected survival. All Big Qualicum tag groups for OEY 1988-1991 were excluded due to anomalously low marine survivals resulting the release of poor quality smolts (Doug Lofthouse, DFO Oceans, Habitat and Enhancement Branch, pers. communication Jan 2009). Chilliwack tag groups for OEY 2003 and 2004 were excluded because of incomplete escapement surveys (Roberta Cook, Salmon Enhancement Program, pers. communication Dec 2008). Release groups were excluded when release timing exceeded 15 d or the release group size was < 8000 smolts. We combined some smaller release groups when release timing and smolt size were similar. We restricted the dataset to recoveries of jacks (precocious males) and three year old adults. After screening, we were left with information from 462 tagged release groups from the five hatcheries representing 6.7 millions smolts; survivals were estimated based on the recovery of >160,000 tagged fish in various fisheries and escapements (Table 1).

Smolt to adult survival (S) for a particular tag code was calculated as $S = \frac{E_r}{E_e}$ where E_r is the estimated number of fish caught in commercial and sport fisheries with that code, E_e is estimated number of fish that escape fisheries and return to the hatchery (or Black Creek) with that code, and E_r is the number of smolts released with that code.

We used analysis of covariance to test for differences in the rate of decrease in survival among release groups from the five hatcheries and Black Creek. To test for effects of weight and release timing on survival, we used simple multiple regression on logit transformed marine survival, with separate models for each hatchery. We had three explanatory variables for each hatchery release group; mean smolt size (g), release day (number of days beginning Jan 1 of a given year), and OEY. We limited examination of interactions among variables to first order interactions.

We developed a set of models that always included OEY as a parameter. We selected a best model for each hatchery based on the AICc criterion, $AICc = -2 \ln \left(\frac{RSS}{n} \right) + \frac{2k}{n-2k}$ where RSS is the residual sum of squares, n is the number of observations (ie. number of CWT groups), and k is the number of estimable parameters (i.e. number of covariates in the model, including each interaction term).

AICc rewards goodness of fit but also imposes a penalty for overfitting (Burnham and Anderson 2002). The lower the AICc value, the better the model. Models were ranked by rescaling the AICc values by calculating the difference between AICc's for each individual model i and the model with the minimum AICc

The best model was defined as the one with the fewest parameters within $2 \Delta i$ of the model with the lowest AICc value.

Continuing to follow the approach outlined in Burnham and Anderson (2002), we calculated the Akaike weights (w_i), $\exp(-\Delta i/2)$

$r = 1/R$ where R is the number of candidate models in the set, and w_i represents the relative likelihood of a model given the data, which can be interpreted as the approximate probability that model i is the best model within the set of models considered (Burnham and Anderson 2002).

Detrended survival plots displayed the residuals from separate univariate regressions of logit survival by OEY for each hatchery. Additional graphical analyses showed no pronounced patterns indicative of heteroscedasticity in the plots of residuals versus predicted values (Fig. S1). Scatterplots of observed versus predicted values showed no indications of non-linearity (Fig. S2). Quantile - quantile plots showed signs of departures from normality (Fig. S3), however ordinary least squares regression is fairly robust to this assumption (Quinn and Keough 2002). Because there were no serious violations of the assumptions of multiple linear regression, we proceeded with our modeling as planned. Statistical analyses were undertaken using R (version 12.1.2; <http://www.r-project.org>).

Results

Smolt release practices varied among hatcheries and years (Figure 2). In general, release weights and timing were less variable in later years than early in the study. Quinsam and Puntledge hatcheries tended to release a broader range of smolt sizes and timing groups than other hatcheries.

Marine survivals declined significantly for coho salmon released from all hatcheries over the course of the time series. This decline was similar in magnitude to declines for wild coho salmon from Black Creek (Figure 3). There was no significant difference in the rate of decrease in survival among coho salmon from the five hatcheries and Black Creek (ANCOVA, $P = 0.081$). Since these regressions were intended to illustrate how survivals varied among groups of fish of different release sizes and timings, the survival of each group (minimum of 8,000 smolts) was weighted equally. To compare hatcheries, one should weight the influence of individual release groups by the number of fish in a group.

Most hatcheries had different best models according to AICc selection (Table 2). Relatively low Akaike weights (w_i) of the various best models (0.223 – 0.459) indicated considerable model selection uncertainty, which is not surprising since our dataset did not originate from a balanced ² experiment. Nevertheless, the models explained a moderate amount of variation ($R^2_{adj} = 0.50 - 0.84$). OEY and mean release weight were variables in all best models. OEY consistently explained the most variation of the model variables (Table 3) with partial correlations ($R_{partial}$) between -0.70 and -0.91. Weight explained the second most variation at Chilliwack, Inch, and Quinsam while at Big Qualicum and Puntledge the interaction between OEY and day explained the second most variation in the best model.

Detrended survival plots (Figs. 4-6) that removed the effects of OEY enabled useful visualisation of important model results (Table 3). Positive partial correlations for mean weights at Big Qualicum, Chilliwack, Inch, and Quinsam and a negative partial correlation at Puntledge (Table 3) were reflected in the positive and negative slopes of detrended marine survival versus weight plots (Fig. 4). Thus, larger (heavier) smolts survived significantly better than smaller smolts at all hatcheries except Puntledge where the relationship was reversed. The benefits of being larger did not change over time, except for smolts released from Chilliwack hatchery, as represented by the significant interaction between OEY and weight. In the early years at Chilliwack, all smolts survived relatively well, regardless of size (Fig. 5). Later on, heavier smolts survived better than lighter smolts.

At Big Qualicum and Puntledge, a significant interaction between OEY and day (Table 3) indicated a time-varying change in the importance of release date. By the end of the study period at both locations, later migrating smolts had the highest survivals (Fig. 6).

Discussion

The most important variable influencing coho salmon marine survival was OEY; survivals declined significantly over time for all five hatchery populations plus the wild population. Before discussing the role of OEY further, we describe changes to the survival computation approach during the time period as these could affect the validity of our results.

Major fishery restrictions commencing in 1997 to protect declining populations of coho salmon included: closure of commercial fisheries targeting coho salmon in southern BC; mandatory release of coho salmon caught in other commercial fisheries; restricted bag limits, openings and locations for sport fisheries targeting coho salmon; and the required release by sport fishermen of coho salmon with an adipose fin (Irvine et al. 2001). At Black Creek, coho salmon smolts continued to be CWT'd but since their adipose fin was no longer clipped, detector wands were used to identify returning adult fish with CWTs. These restrictions had the desired effect of reducing fishery exploitations. However, fewer CWTs were collected in fisheries than previously, and these were only from hatchery fish.

The uncertainty associated with marine survival estimates increases when fewer tags are recovered in the fishery or escapement (Reisenbichler and Hartman 1980; Bernard et al. 1998; Hankin et al 2005). PSC (2008) concluded that for Black Creek, while recent percent standard errors (standard error of estimate/estimate) associated with return estimates are high, the absolute precision (standard error) remains excellent given that few unclipped coho salmon are killed in selective fisheries. The situation is less clear for hatchery coho salmon although with the much lower exploitation rates of recent years, the relative role of fishery data compared to escapement data in estimating smolt to adult survivals is much reduced compared to earlier periods. In conclusion, we recognise that while the precision of exploitation (and hence survival) estimates post OEY 1996 has been reduced, comparisons among tag codes within years for individual populations are valid, and our detrending approach enabled an evaluation of the relative influence of release weights and sizes.

Based on studies of coho salmon released from Rosewall Creek Hatchery on Vancouver Island, Bilton et al. (1982) predicted maximum returns from releases of 25 g smolts on day 173 (22 June). Our data set was more truncated - we were unable to evaluate the success of releases that late in the season and only at Puntledge and Quinsam were 25

g smolts released (Fig. 4). Because of significant interactions between date of release and size at release, Bilton et al. (1982) also recommended the early release of smaller smolts and the later release of larger smolts. Our results were obtained over a much longer period (27 y) than these one year experiments of the 1970's. Our best models for coho salmon from Quinsam Hatchery differed from the other East Vancouver Island hatcheries in terms of parameters; OEY and size were significant while interaction terms were not. Labelle et al. (1997) also documented spatial patterns in survival on Vancouver Island with a separation point near the Puntledge River. The best models for coho salmon from Puntledge and Big Qualicum hatcheries were similar to each other, as were the best models for coho salmon from the nearby Chilliwack and Inch hatcheries. Big Qualicum and Puntledge were the only locations with a significant interaction between marine survival and release date; in recent years at these locations, smolts released in late May (Day 145+) tended to survive better than early releases (Fig. 6). The only location with a significant interaction between OEY and weight was Chilliwack Hatchery; here large (20-22 g) smolts did relatively well in recent years (Fig. 5). However, overall survivals have recently been low at all locations.

Bilton et al. (1982) noted that relationships between adult returns, release times and sizes for Rosewall Creek releases did not appear to be applicable to other hatcheries, suggesting that appropriate release strategies may vary among streams. Subsequent studies confirmed different optimum release strategies for even closely situated hatcheries or streams (Mathews and Ishida 1989; Tipping 2008). Our differing best models support the hypothesis of considerable differences in the optimal timing and size of release for coho salmon entering the Strait of Georgia at different locations.

We found that, with the exception of smolts from Puntledge Hatchery, larger (heavier) smolts survived better than smaller smolts. Increasing size at release does not always cause increases in survival (e.g. Mathews and Ishida 1989; Labelle et al. 1997; Holtby et al. 1990). Mathews and Ishida (1989) suggest that the optimum release date may be a "moving target". Our significant OEY by day interactions for coho salmon from the Big Qualicum and Puntledge hatcheries as well as the significant year by weight interaction for coho salmon from Chilliwack Hatchery support this "moving target" concept.

We do not recommend particular release dates or sizes for coho salmon hatchery smolts in the Strait of Georgia. Optimal hatchery release strategies depend on many factors, including economics (Bilton et al. 1982). It is clear that under current marine conditions in the Strait of Georgia, manipulation of smolt size and/or timing of their release will not return Strait of Georgia hatchery coho salmon survival rates to historical highs. Subtle differences resulting from alternate release strategies will be extremely difficult to detect given the current low survivals and the imprecision associated with their estimation. Given our limited ability to document benefits of altered release timing and size, we do not recommend further experiments with smolt release size and timing. We suggest a better use for Strait of Georgia hatcheries would be to use them as part of an experiment to evaluate interactions between hatchery and wild coho salmon. Over multiple years, pulsed releases of large and small numbers of hatchery origin coho salmon would enable researchers to evaluate density dependent effects on coho salmon growth and survival. This suggestion, which has been made previously, is timely and would improve our understanding and hence management of coho salmon resources in the Strait of Georgia.

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We appreciate the assistance of Roberta Cook and Greg Bonnell in helping us assemble and interpret results from the multiple releases of coho salmon from Strait of Georgia hatcheries.

Literature Cited

Beamish, R. J., G. A. McFarlane, and R. E. Thomson. 1999. Recent declines in the recreational catch of coho salmon (*Oncorhynchus kisutch*) in the Strait of Georgia are related to climate. *Canadian Journal of Fisheries and Aquatic Sciences* **56**:506-515.

Beamish, R. J., B. Riddell, C. M. Neville, B. L. Thomson, and Z. Zhang. 1995. Declines in chinook salmon catches in the Strait of Georgia in relation to shifts in the marine environment. *Fisheries Oceanography* **4**:243-256.

Beamish, R. J., R. M. Sweeting, K. L. Lange, and C. M. Neville. 2008. Changes in the population ecology of hatchery and wild coho salmon in the Strait of Georgia. *Transactions of the American Fisheries Society* **137**:503-520.

Beamish, R. J., R. M. Sweeting, C. M. Neville, and K. L. Lange. 2006. Hatchery and wild percentages of coho salmon in the Strait of Georgia are related to shifts in species dominance. *North Pacific Anadromous Fish Commission Document* 981. (Available at www.npafc.org)

Beamish, R. J., Sweeting, R. M., Lange, K. L., Noakes, Preikshot D., and Neville, C. M. 2010. Early marine survival of coho salmon in the Strait of Georgia declines to very low levels. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **2**:424-439.

Bernard, D. R., R. P. Marshall, and J. E. Clark. 1998. Planning programs to estimate salmon harvest with coded-wire tags. *Canadian Journal of Fisheries and Aquatic Sciences* **55**:1983-1995.

Bilton, H. T. 1980. Returns of adult coho salmon in relation to mean size and time at release of juveniles to the catch and the escapement. *Canadian Technical Report of Fisheries and Aquatic Sciences* 941.

Bilton, H. T., D. F. Alderdice, and J. T. Schnute. 1982. Influence of time and size at release of juvenile coho salmon (*Oncorhynchus kisutch*) on returns at maturity. *Canadian Journal of Fisheries and Aquatic Sciences* **39**:426-447.

Bilton, H. T., R. B. Morley, A. S. Coburn, and J. Van Tine. 1984. The influence of time and size at release of juvenile coho salmon (*Oncorhynchus kisutch*) on returns at maturity: Results of releases from Quinsam River hatchery, B.C., in 1980. *Canadian Technical Report of Fisheries and Aquatic Sciences* 306.

Burnham, K. P., and D. R. Anderson. 2002. *Model selection and inference: a practical information-theoretic approach*. 2nd ed. New York: Springer-Verlag.

Chittenden, C. M., R. J. Beamish, C. M. Neville, R. M. Sweeting, and R. S. McKinley. 2009. The use of acoustic tags to determine the timing and location of the juvenile coho salmon migration out of the Strait of Georgia, Canada. *Transactions of the American*

Fisheries Society **138**:1220-1225.

Eggers, D. M. 2009. Historical biomass of pink, chum, and sockeye salmon in the North Pacific Ocean. American Fisheries Society Symposium **70**:1-39.

El-Sabaawi, R., J. F. Dower, M. Kainz, and A. Mazumder. 2009. Interannual variability in fatty acid composition of the copepod *Neocalanus plumchrus* in the Strait of Georgia, British Columbia. Marine Ecology Progress Series **382**:151-161.

Hankin, D. G., J. H. Clark, R. B. Deriso, J. C. Garza, G. S. Morishima, B. E. Riddell, and C. Schwarz. 2005. Report of the expert panel on the future of the coded wire tag recovery program for Pacific salmon. Pacific Salmon Commission Technical Report No. 18.

Holtby, L. B., B. C. Andersen, and R. K. Kadowaki. 1990. Importance of smolt size and early ocean growth to interannual variability in marine survival of coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences **47**:2181-2194.

Irvine, J. R., C. K. Parken, D. G. Chen, J. R. Candy, T. Ming, J. Supernault, W. S. Shaw, and R. E. Bailey. 2001. 2001 stock status assessment of coho salmon from the interior Fraser River. Canadian Science Advisory Secretariat Research Document 2001/083.

Irvine, J. R., M. Fukuwaka, T. Kaga, J. H. Park, K. B Seong, S. Kang, V. Karpenko, N. Klovach, H. Bartlett, and E. Volk. 2009. Pacific salmon status and abundance trends. North Pacific Anadromous Fish Commission Document 1199, Rev. 1. (Available at www.npafc.org)

Johannessen, S. C. and R. W. Macdonald. 2009. Effects of local and global change on an inland sea: the Strait of Georgia, Canada. Climate Research **40**:1-21.

Kuhn, B. R., L. Lapi, and J. M. Hamer. 1988. An introduction to the Canadian database on marked Pacific salmonids. Canadian Technical Report of Fisheries and Aquatic Sciences 1649.

Labelle, M., C. J. Walters, and B. Riddell. 1997. Ocean survival and exploitation of coho salmon (*Oncorhynchus kisutch*) stocks from the east coast of Vancouver Island, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences **54**:1433-1449.

Masson, D. and P. F. Cummins. 2007. Temperature trends and interannual variability in the Strait of Georgia, British Columbia. Continental Shelf Research **27**:634-649.

Mathews, S. B. and Y. Ishida. 1989. Survival, ocean growth, and ocean distribution of differentially timed releases of hatchery coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences **46**:1216-1226.

Morrison, J., M. C. Quick, and M. G. G. Foreman. 2002. Climate change in the Fraser River watershed: flow and temperature projections. Journal of Hydrology **263**:230-244.
Pacific Salmon Commission Coded Wire Tag Workgroup. 2008. An action plan in response to Coded Wire Tag (CWT) Expert Panel Recommendations. Pacific Salmon Commission, Vancouver. Pacific Salmon Commission Technical Report 25.

Quinn, G. and M. Keough. 2002. Experimental design and data analysis for biologists. Cambridge: Cambridge University Press.

Reisenbichler, R. R. and J. Hartmann, N.A. 1980. Effect of number of marked fish and years of repetition on precision in studies of contributions to a fishery. *Canadian Journal of Fisheries and Aquatic Sciences* **37**:576-582.

Ruggerone, G. T., R. M. Peterman, B. Dorner, and K. W. Myers. 2010. Magnitude and trends in abundance of hatchery and wild Pink Salmon, Chum Salmon, and Sockeye Salmon in the North Pacific Ocean. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **2**:306-328.

Sandher, J., R. Cook, and J. R. Irvine. 2010. Canadian enhanced salmonid production during 1978-2009 (1977-2008 brood years). North Pacific Anadromous Fish Commission Doc. 1258. (Available at www.npafc.org)

Simpson, K., D. Dobson, J. R. Irvine, B. Holtby, and R. Tanasichuk. 2001. Forecast for southern British Columbia coho salmon in 2001. Fisheries and Oceans Canada. Canadian Science Advisory Secretariat Research Document 2001/107.

Therriault, T. W., D. E. Hay, and J. Schweigert. 2009. Biological overview and trends in pelagic forage fish abundance in the Salish Sea (Strait of Georgia, British Columbia). *Marine Ornithology* **37**:3-8.

Tipping, J. M. 2008. The effect of juvenile length in autumn on 2-year-old-male and adult coho salmon survival rates at three Washington hatcheries. *North American Journal of Aquaculture* **70**:111-114.

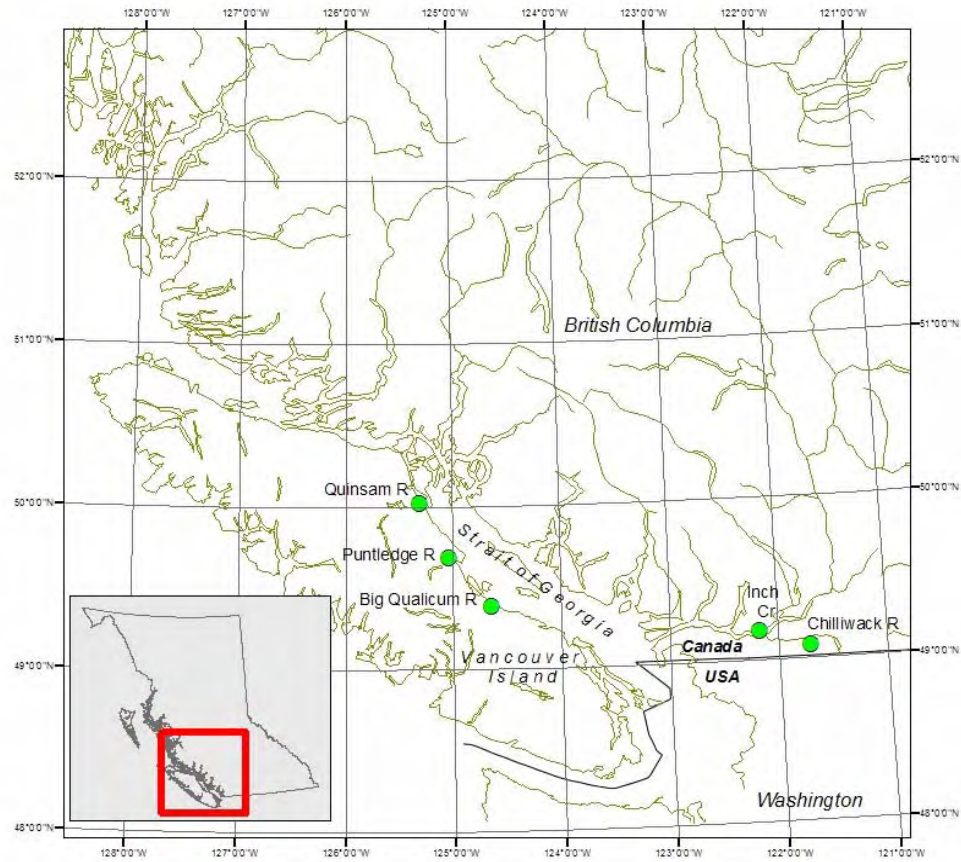


Figure 1. Study area in southeastern British Columbia showing locations of three Vancouver Island hatcheries (Quinsam, Puntledge and Big Qualicum) and two hatcheries on the lower Fraser River (Inch and Chilliwack).

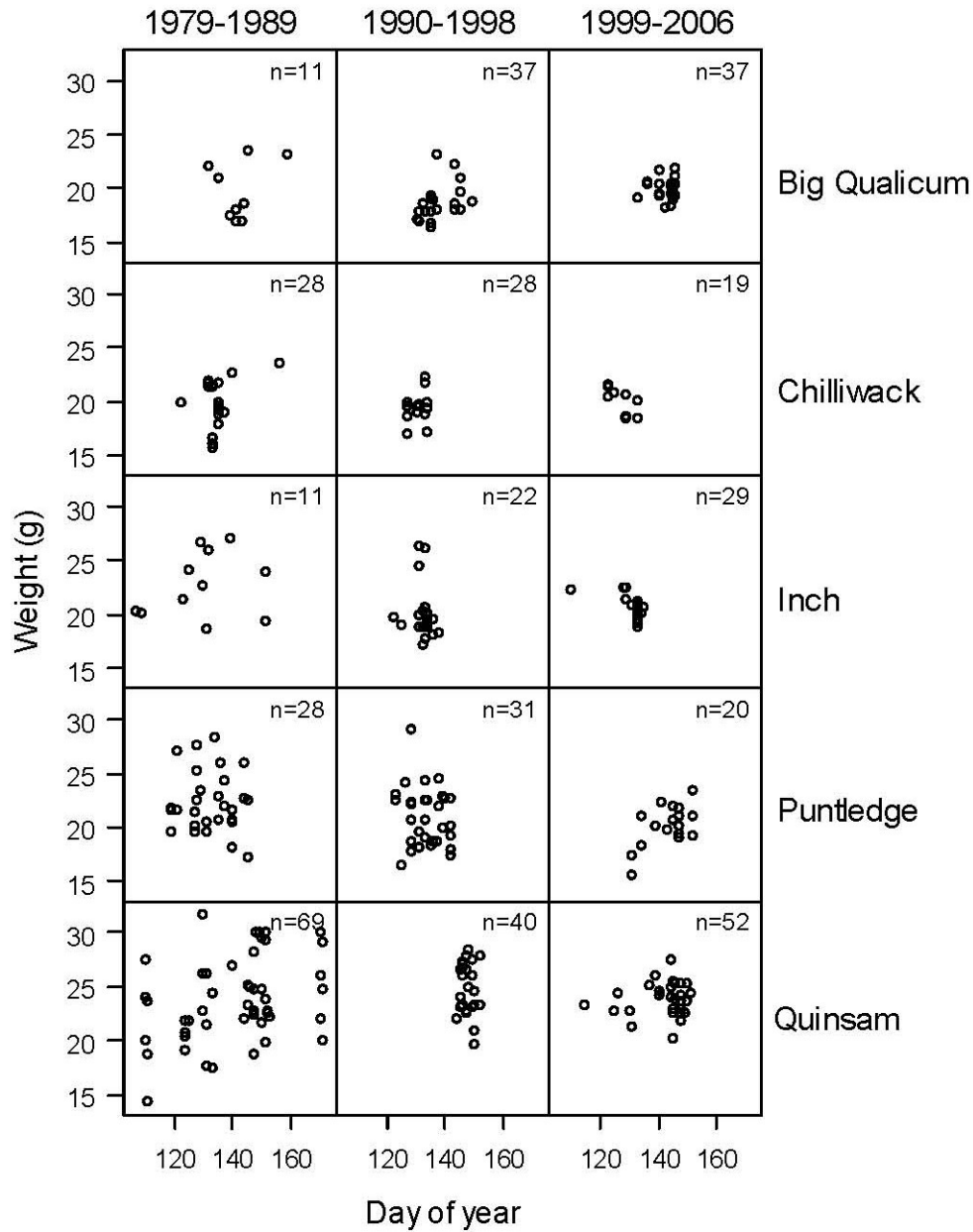


Figure 2. Coplot of mean release weight and day for coho salmon released from the five hatcheries (Big Qualicum, Chilliwack, Inch, Puntledge, and Quinsam) for three OEY periods. Each data point represents the mean value for one release group; n is the number of tag release groups for each hatchery and time period.

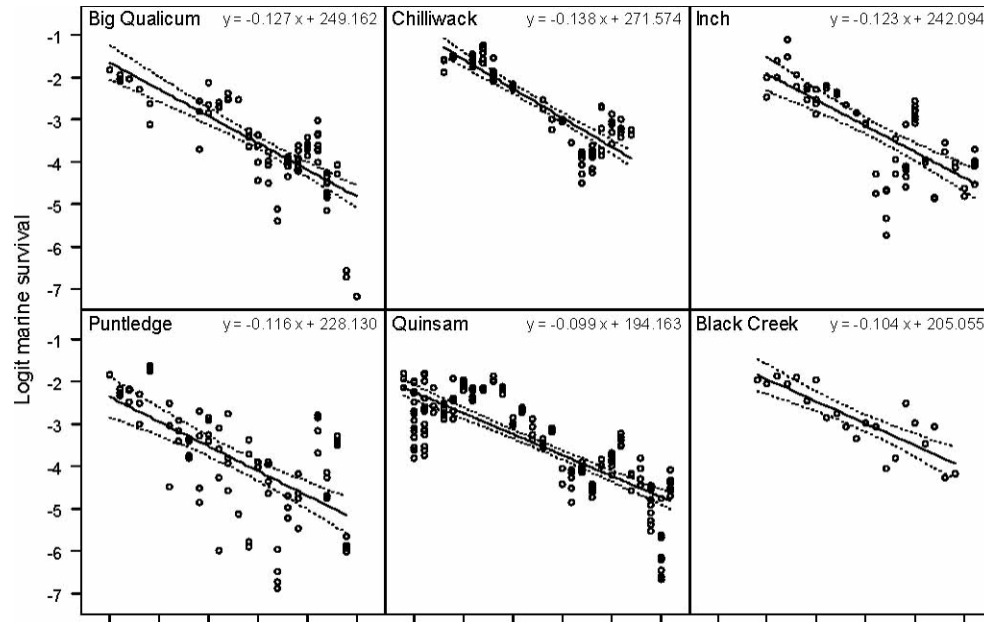


Figure 3. Logit marine survival of coho salmon groups released from each of the five hatcheries (Big Qualicum, Chilliwack, Inch, Puntledge and Quinsam), with wild coho salmon from Black Creek provided for comparison. Each data point represents one CWT release group. Solid lines are linear regressions of logit marine survival on release year and dotted lines are the 95% confidence intervals of the regression.

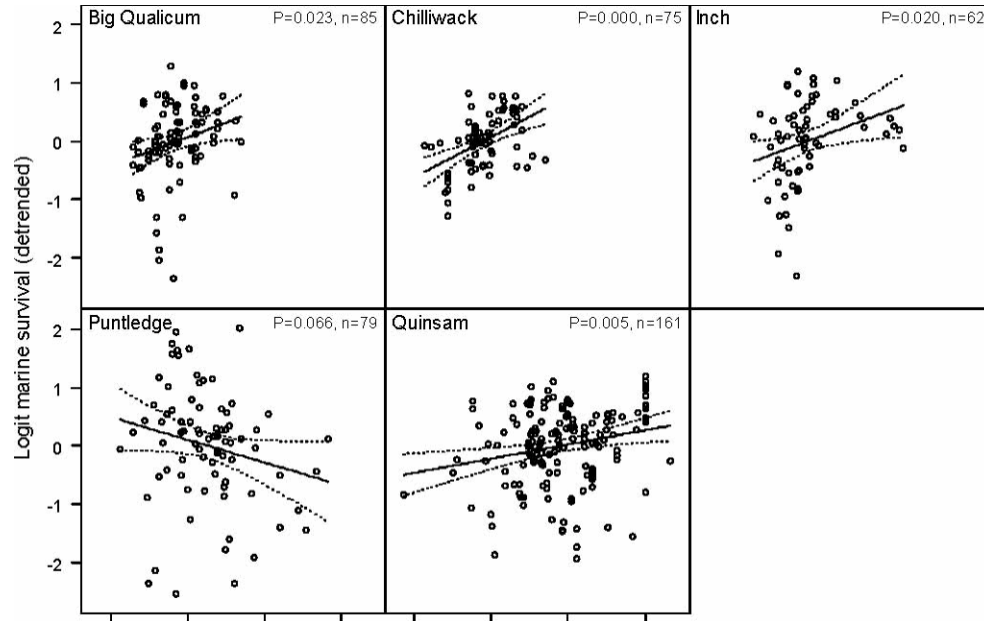


Figure 4. Detrended logit marine survival versus weight in grams for coho salmon groups released from each of the five hatcheries (Big Qualicum, Chilliwack, Inch, Puntledge and Quinsam). Each data point represents one CWT release group. Solid lines are linear regressions of detrended logit marine survival on OEY and dotted lines are the 95% confidence intervals of the regression.

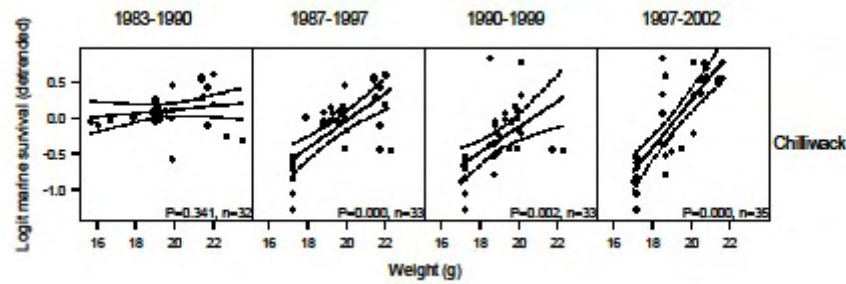


Figure 5. Coplot of detrended logit marine survival and weight for coho salmon released from the Chilliwack hatchery over various OEY intervals. Each data point represents one CWT release group. Solid lines are linear regressions of detrended logit marine survival on OEY and dotted lines are the 95% confidence intervals of the regression. The change in regression slope from the first interval illustrates the interaction between OEY and weight.

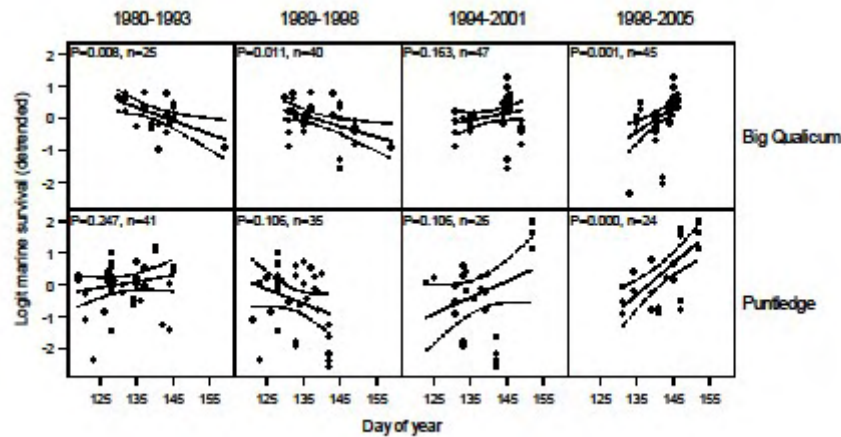


Figure 6. Coplot of detrended logit marine survival and day of year for coho salmon groups released from the Big Qualicum and Puntledge hatcheries over various OEY intervals. Each data point represents one CWT release group. Solid lines are linear regressions of detrended logit marine survival on OEY and dotted lines are the 95% confidence intervals of the regression. Changes in regression slopes over year intervals illustrate interactions between OEY and day of year for these two hatcheries.

Hatchery	OEY range	CWT codes	Total number of tagged smolts released	Mean weight (g)	Mean release day	Total number of observed tags in the fishery	Total number of observed tags in the escapement
Big Qualicum	1980 - 2005*	85	1,207,387	19.3	140.6	6,780	14,926
Chilliwack	1983 - 2002	75	1,111,053	19.5	131.9	11,411	31,961
Inch	1985 - 2006	62	1,073,064	20.8	131.6	4,717	17,995
Puntledge	1980 - 2004	79	1,089,276	21.3	135.6	8,293	15,687
Quinsam	1979 - 2006	161	2,200,061	24.6	143.7	16,227	35,393
Grand Total	1979 - 2006	462	6,680,841	21.7	138.2	47,408	115,962

*Data from Big Qualicum for OEY 1984 - 1987 not used.

Table 1. Summary of relevant data from the Mark Recovery Program database for coho salmon smolts released from 1979 - 2006. Shown for each of the five hatcheries is: the range of ocean entry years, total numbers of CWT codes released, total numbers of tagged smolts released, mean weight in grams, mean day of release, total number of tagged fish observed in the fishery, and total number of total number of tagged fish observed in the fishery, and total number of tagged fish in the escapement.

Hatchery	Best AICc Model Parameters	Δi	w_i	K	N	R^2_{adj}
Big Q	OEY, W, D, OEY×D	0.7	0.229	4	85	0.65
Chilliwack	OEY, W, OEY×W	0	0.335	3	75	0.84
Inch	OEY, W	1.4	0.223	2	62	0.54
Puntledge	OEY, W, D, OEY×D	0	0.459	4	79	0.50
Quinsam	OEY, W	0	0.249	2	161	0.66

Table 2. Best model parameters for each of the five hatcheries, Δi is the difference in AICc score between the top ranking model and the model with the lowest number of parameters within 2 AICc units, w_i is the Akaike weight, K is the number of parameters in the model, N represents the number of CWT groups, and adjusted R^2 is the adjusted coefficient of determination of the best model. OEY = Ocean entry year, W = Weight, D = Day

Hatchery	constant	Weight	$R_{partial}$	OEY	$R_{partial}$	P -	Day	$R_{partial}$	P -	OEYxWeight	OEYxDay
Big Qualicum	P <0.001	P +0.31	0.007	0.8	<0.001		0.01	0.907		$R_{partial}$ P	$R_{partial}$ +0.43 <0.00
Chilliwack	<0.001	+0.58	<0.001	-0.91	<0.001					+0.48	<0.001
Inch	<0.001	+0.3	0.018	-0.7	<0.001						
Puntledge	<0.001	-0.23	0.041	-0.72	<0.001		-0.33	0.003			+0.33 0.00
Quinsam	<0.001	+0.3	0.005	-0.7	<0.001						4

Table 3. Model parameter sign, significance (P-value) and partial correlation ($R_{partial}$) for each of the five hatcheries. OEY = Ocean entry year, W = Weight, D = Day

A4: ZOOPLANKTON DATA RECOVERY AND ANALYSIS

David Mackas, Deborah Faust, Moira Galbraith

Zooplankton have been sampled in the Strait of Georgia for more than four decades. This creates potential for a valuable retrospective analysis of how lower trophic level productivity and composition have changed, and of the consequences of these changes for higher trophic levels. Unfortunately, the long history of sampling is a discontinuous patchwork (done by many different investigators, using diverse sampling grids and sampling methods, and receiving differing levels of post-capture lab processing and taxonomic analysis). Until recently, zooplankton data files were also scattered among locations, and stored in differing formats.

The initial activities of our project have been to:

1. Consolidate recoverable zooplankton data into a single and secure digital archive.
2. Do quality control assessment for individual samples, and either hide or adjust records with large errors in reported flowmeter readings or extent of subsampling.
3. Document meta-data characteristics for the remaining “good” data (sampling gear, depth range, horizontal location, date and time of sampling, laboratory processing methods, and detail and breadth of taxonomic resolution), to help decide which subsets of samples, and aggregations of variables, are best intercomparable, and in what “currency” (in increasing information content: total biomass, biomass within major taxa, biomass within species). The largest blocks of data are summarized in Table 1
4. Classify the intercomparable samples into statistical categories based on season (month of sampling), depth, horizontal location, and taxonomic resolution. Fig 1 shows the spatial classification regions we have used.

<i>Source/Dates</i>	<i>Depth Range</i>	<i>Mesh Size</i>	<i>Region(s)</i>	<i>Taxa quantified</i>
PBS-1960s	Water column	0.35 mm	All	“Major Groups”
UBC 1970s-early 80s	Water column	0.35 mm	Central Strait	Copepods
IOS VNH 1980s-now	0-250 m	0.23 mm	All (but sparse)	Species
IOS BIONESS 1980s-now	0-250 m	0.23 mm	All (targetted)	Euphausiids & Amphipods
PBS- Herring 1990s-now	0-20 m	0.35 mm	All (but mostly nearshore)	Species (copepods were pooled 1990-94)
UBC&UVic 1990s-now	mix	0.23 mm	Central & Northern	Species
PBS-Trudel 2008-now	0-250 m	0.23 mm	Central & Northern	Species

Table 1. Meta-data comparison (coverage + sampling and processing methods) for the major blocks of data that have been recovered.



Figure 1. Subregions into which samples have been classified, to produce regional climatologies and anomaly time series. The Central and Northern Strait regions have by far the most complete coverage. An additional “Nearshore” region (not shown) includes all locations inshore of the local 50 m isobath.

The above steps are now largely completed (although we are still doing some minor QC screening based on ongoing identification of anomalous data points). Current work is mostly exploratory analyses of the Strait of Georgia zooplankton time series, following very closely methods we have previously applied to more homogeneous zooplankton data sets from the Vancouver Island outer coast and adjoining west coast regions (Mackas 1992, 1995; Mackas et al. 2001, 2004, 2007). Our approach has two major steps:

1. Calculate “climatologies (=monthly geometric averages across years of available monthly data within a region)” for the above spatial classifications and taxa. The goal is a set of baseline seasonal cycles against which we can assess interannual variability. Ideally, the climatologies would provide good approximations to “normal” seasonal cycles, showing which months and which species dominate the annual production. In practice, the very uneven distribution of sampling effort in the Strait of Georgia has produced some artifacts. For example, much of the winter sampling was done in years with higher than average zooplankton biomass (Fig 2), as was sampling within some of the inlets and in the Southern Strait. The resulted in high averages for those months and regions.

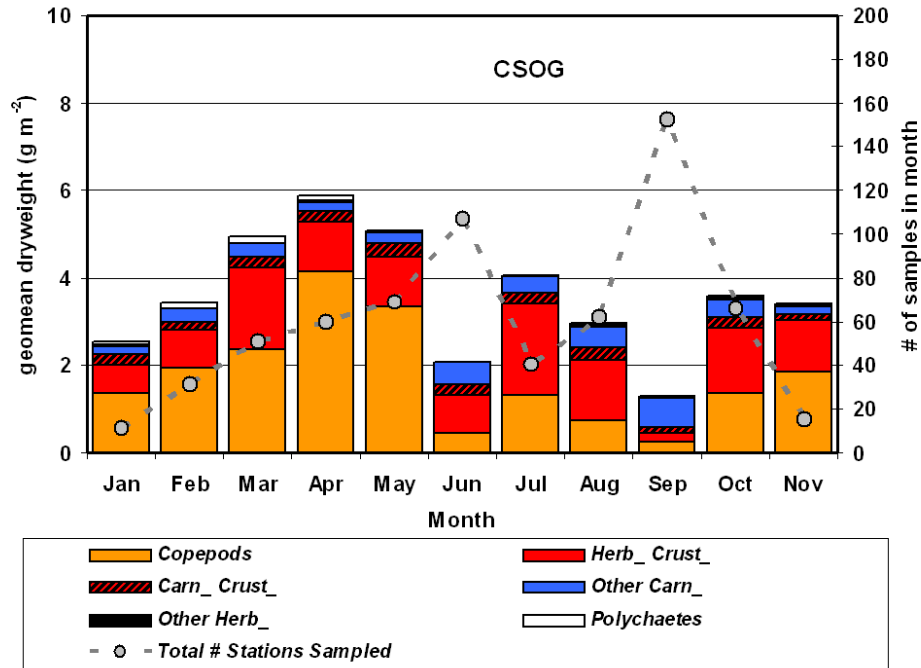


Fig. 2: Average seasonal cycles of coarsely-resolved zooplankton taxa within the Central Strait of Georgia. Bar graphs show total biomass subdivided by taxa. Circles and dashed line show number of samples within each monthly average. "Copepods" and "Herbivorous Crustacea" (mostly euphausiids) dominate the biomass in all months. Lower values in June and September are due to large numbers of samples in low biomass years. December values not shown because samples were few and non-representative.

2. Calculate "anomaly time series" that quantify log-scale deviations of the data from their respective climatologies. These time series are longer for a few individual taxa, and for the "major groups" taxonomic composite (Fig 3), and shorter if we attempt to compare a larger suite of species (Fig 4). However, both approaches suggest a large change in the Strait of Georgia zooplankton community before vs after 1998-2000. This change involves both decreases in total biomass of copepods and other crustacean, and changes in species composition within the major taxonomic categories such that the decade from 2000-2009 may have provided a "lean cuisine" diet for plantivorous predators.

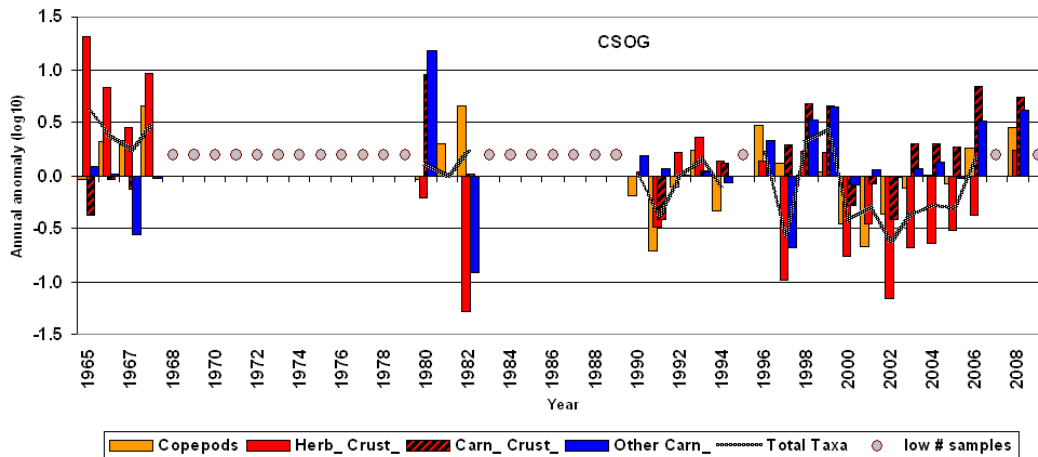


Fig 3. Anomaly time series (1965-present) for the four major taxonomic groups that account for most biomass. Circles indicate years with few or no samples

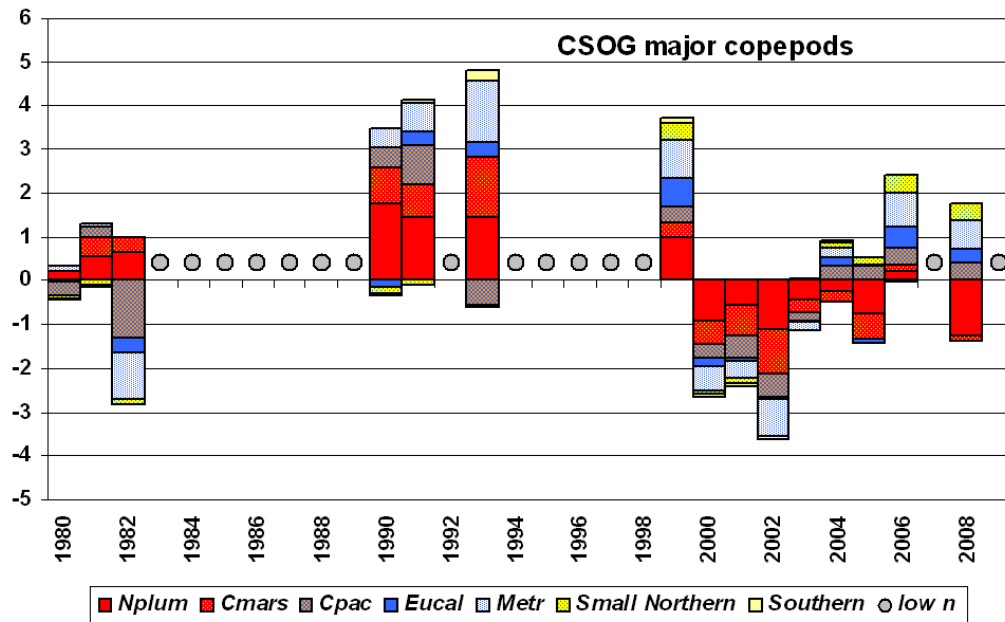


Fig 4. Anomaly time series for the dominant species and species groups within the copepods. Color bar ranks taxa by their expected food value from big and lipid rich (red) to small and low in lipids (yellow). Note that biomass of energy rich copepods has been low in most years since 2000.

A5: A SPATIAL FRAMEWORK FOR SPECIES-HABITAT STUDIES IN THE NEARSHORE REGION

E. Gregr¹, J. Lessard², G. Jamieson², J. Schweigert², P. Wills³

Introduction

The nearshore region (0 – 50 m depth) is a highly productive environment, providing both permanent (e.g., for shellfish) and transitory (e.g., for fish) habitat for many commercial species. It is also the region most directly affected by urbanization and up-land influences. As such, characterizing this nearshore ecosystem is essential to understanding of the Strait of Georgia (SoG). We are developing Habitat Patches (HaPs) to provide a physical context with which to represent our understanding of ecological processes in the nearshore. Given that it is likely to be decades before any comprehensive, systematic inventories are completed of this important and unique biome, the HaP data provides an important start to facilitating investigations of nearshore habitat for both flora and fauna.

The framework – creating the habitat patches

The HaPs currently describe the bottom type of the nearshore throughout the SoG, with variable resolution, determined by the source data. The HaPs are based on depth and bottom type (BType; Fig. 1) obtained from the best available physical bottom type data

sets. The result is a single representation of the nearshore, which integrates bottom type data at various spatial scales and attribute resolution. The approach is intended to be updatable to accommodate improvements in data quality and availability. A confidence surface provides an indication of the local reliability of the data. While we recognize that benthic habitat contain a biological component, initial design discussions indicated that a physical delineation of the nearshore region based on depth and bottom type would provide a suitable framework for subsequent models of ecological processes and the attachment of biota.

Depth data were obtained as polygons derived from CHS (Canadian Hydrographic Service) nautical charts. Five depth classes were defined for the nearshore: Intertidal (highest high water to lowest low water), 0-5 m, 5-10 m, 10-20 m and 20-50 m. Bottom type (i.e., substrate) data were obtained from 1) the BC Marine Ecosystem Classification (BC MEC); 2) CHS bottom quality (BQ) samples; 3) the ShoreZone classification; and 4) Field sampling. BC MEC is a polygon coverage derived primarily from the CHS BQ samples. It has been generalized to 1:500k resolution, and provides a comprehensive coastal coverage, but is poorly resolved showing only 'Hard', 'Mud', and 'Sand' classes. BQ samples are point data with variable resolution and patchy spatial coverage throughout the study area. They range from old, lead-line sampled data to more present day samples taken with mechanical grabs. There are 38 classes of substrate/sediment within this dataset. ShoreZone data are line features nominally associated with the high water line. They provide detailed information on the biophysical characteristics of the shoreline for the entire study area (CORI 2005. ShoreZone Mapping Data Summary, Southern Strait of Georgia National Marine Conservation Area. Coastal & Ocean Resources Inc. and Archipelago Marine Research Ltd. Report to Parks Canada. 12 Aug 2005. 30 pp.). These data formed the primary source of bottom type data for the Intertidal and 0-5 m depth ribbons, and also contributed to the 5-10 m depth ribbon. Substrate data are embedded within a form classification as this is a natural classification from comprehensive data sources such as video; there are 35 classes. Field sampling data are point data that include bottom type from shellfish and herring surveys provided by DFO Stock Assessment, Pacific Biological Station (PBS). There are 11 and 7 classes of substrate, respectively, within these datasets. An older survey of the southern Gulf Islands provided by Parks Canada was also included, though the data were recorded in narrative form we converted into comparable classes where possible.

A key challenge was defining the necessary attribute scale. The fields of ecology, marine geology, biology, hydrology, and cartography all view the ocean bottom through their own lenses. Unlike geology, for example, the ecological objectives of HaPs do not need the attribute resolution provided by detailed analyses of particle size. Rather, something less precise was necessary to 1) support the inclusion of different data sources; and 2) capture the biologically important features. To that end, we defined a Habitat Patch Bottom Type (Btype) as a two-tier feature based on hardness and rugosity (Fig. 1). This allows both poor and fine resolution attributes to be included, and provides two features that are more easily related to ecological processes.

Creating the Habitat Patches (HaPs) requires a number of steps. First, each source data set is converted into Thiessen Polygons (TPs), yielding a polygon coverage for each data source. These polygon coverages were intersected to generate a large number of polygon fragments, containing 1 to 4 bottom type values, depending on the number of overlaid data sources. Each fragment was assigned a generic bottom type, based on the source data types (BType; Fig. 1). The result was a single layer of polygons (Fig. 2), where each polygon is assigned a substrate and a rugosity (if sufficient data were

available) and a confidence rank. The original source data class is also included in the polygon fragment.

Preliminary results

The HaPs provide the first, high resolution representation of the nearshore in the SoG (e.g., Fig. 2). Preliminary analyses have been performed to determine how well the current version of the HaPs corresponds to existing biological data sets. Using fishing information provided by red sea urchin harvesters (not used as a data source), 65% and 21% of fished areas were overlaid HaP with hard and mixed substrate, respectively. Conversely, 73% of surveyed points from stock assessment surveys where geoduck were present overlaid HaP with soft substrate. These results show how the HaPs already give a suitable representation of nearshore substrate. These results are expected to improve as additional physical attributes are added.

The distribution of primary and secondary attributes in the SoG (Fig. 3) show that SoG is largely hard or soft, with mixed classes representing less than 10%. This reduces the importance of precisely defining the mixed classes. Bedrock dominated the hard classification, while softs largely distinguished between mud and sand.

Rugosity (secondary classification)	High	boulders (1c)	mainly hard some soft (2c)	
	Moderate		mainly soft some hard (2b)	sand (3b)
	Low	bedrock (1a)	Mix of small particles (2a)	mud (3a)
		Hard	Mixed	Soft
		Substrate (primary classification)		

Pending physical validation

Evaluating how well the HaPs represent the nearshore environment is essential to understanding their utility. A part of our collaboration with CORI, Brian Bornhold assembled eight independently classified bottom type products from historic side-scan and towed video surveys. Sites included: Tribune Bay, Pat Bay, Parksville (from Deep Bay to Northwest Bay), Gooch Island, and Sidney Harbour. A second validation will be any nearshore data from the CHS/Quester tangent backscatter classification for the Strait of Georgia. The goal is to evaluate both the assigned BType class and the HaP boundaries.

Conclusion

The current HaP layer provides a comprehensive spatial representation of the SoG to which other physical and biological attributes can now be added. As more attributes are

added, it will become possible to model ecological processes as well as unknown distributions of interest species. While much more work can be done to improve the HaPs in their present form, the current layer can be used to direct stock assessment surveys. Additional work to improve the HaP layer will include 1) considering the role of energy in bottom type, and as an attribute; 2) recalculating the HaPs based on physical validation and additional sediment data (i.e., herring surveys); 3) creating a seamless substrate map of the Strait of Georgia linking the HaPs in the nearshore to deeper CHS backscatter product; and importantly 4) connecting HaPs to the provincial watersheds (Watersheds BC product) to allow impacts from landscape development to be modeled.

Figure 1: Habitat Patch Bottom Type (BType) across Primary and Secondary axes. Rugosity is intended to add information to the substrate, in a proportional sense. This means that high rugosity (i.e., complexity) will be at different scales for the soft, mixed, and hard substrates. For example for soft substrate, rugosity provides a continuous scale that corresponds to particle size, the more common measure of sands and muds. Thus complexity will be orders of magnitude different less than in mixed or hard substrates.

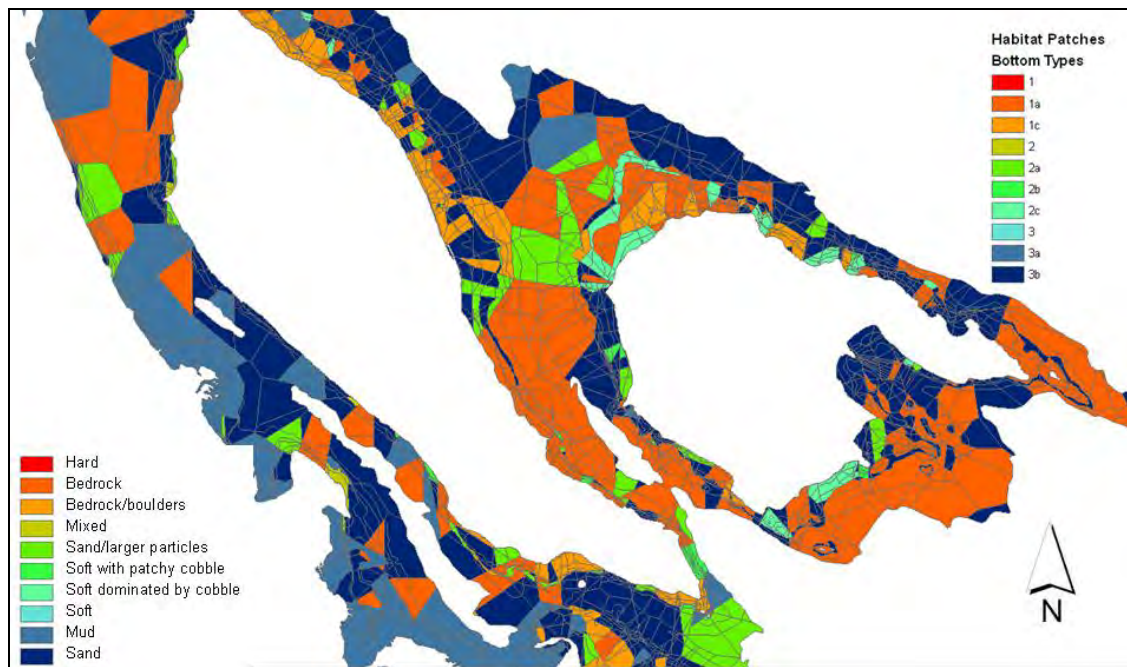


Figure 2. Habitat Patch (HaP) Bottom quality values for Denman and Horby Islands, in the Strait of Georgia.

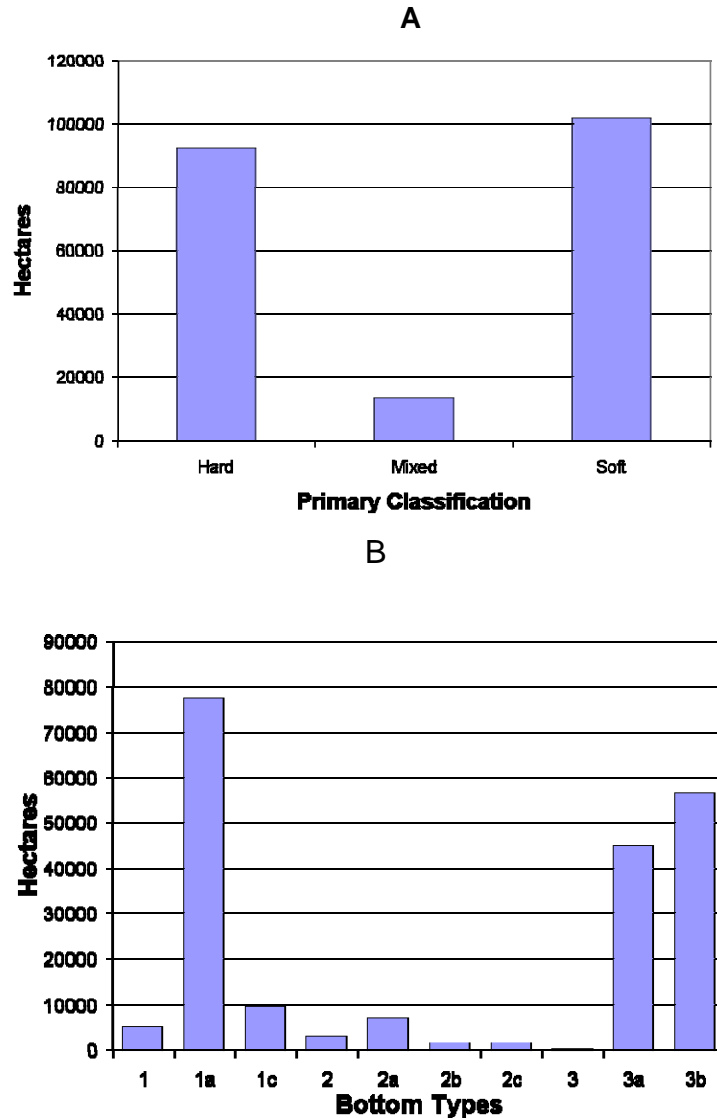


Figure 3: Distribution of primary (A) and secondary (B) BType in the Strait of Georgia.

A6: TEMPERATURE TRENDS IN THE STRAIT OF GEORGIA: WHAT CAN BE EXPECTED OVER THE MIDDLE TERM?

Patrick Cummins and Diane Masson

A key objective of the Strait of Georgia Ecosystem Research Initiative (ERI) is the construction of plausible scenarios for the Strait and the ecosystems it supports over the middle term. Here 'middle term' refers to the next two decades, the period out to 2030. Based on data from the Nanoose Station in the central Strait, Masson & Cummins (2007, *Cont. Shelf Res.*, **27**, 634-649) found a statistically significant warming trend of about 2-3°C/century through the entire 400 meter depth of the water column for the period 1970-2005. The salient question is whether this warming trend can be expected to continue over the middle term. This question is considered in terms of the some of the longest sea surface temperature records available from coastal British Columbia

lighthouses. Data from four representative stations were selected, each of which displays a statistically significant long-term warming trend. For each record, running temperature trends were computed based on least-squares fits of 20-, 30- and 40-year data windows. Averaged probability distributions were then constructed. It is found that all these distributions are skewed such that warming trends dominate. However, the results suggest that over periods of 20-30 years there is a significant chance (40-45%) of the occurrence of a period with zero or negative temperature trend (cooling). Over periods of 40 years, the probability of such an occurrence decreases substantially to 20%, but is still not negligible. These results are indicative of the dominant influence of low frequency variability on conditions in coastal British Columbia. Over periods of 20-30 years, the long-term secular trend associated with global warming can easily be overwhelmed by such variability. Our conclusion is that it can not be taken for granted that the strait will see continued warming over the middle term.

Masson, D. and P.F. Cummins (2007) Temperature trends and interannual variability in the Strait of Georgia, British Columbia. *Cont. Shelf Res.* **27**, 634-649.

A7: HARBOUR SEALS AS INDICATORS OF MARINE ENVIRONMENTAL QUALITY IN THE STRAIT OF GEORGIA

Peter S. Ross, DFO, Institute of Ocean Sciences, Sidney

Introduction

Persistent organic pollutants (POPs) refer to chemicals that possess four key properties: they are persistent, bioaccumulative, toxic, and subject to long-range transport. Members of this class include the polychlorinated biphenyls (PCBs), dioxins (polychlorinated dibenzo-p-dioxins or PCDDs), and DDT. While most POPs have been regulated in Canada and are presently subject to the international Stockholm Convention of 2001, concerns linger owing to the legacy of these persistent contaminants. The use of DDT as an insecticide led to complete reproductive failure of many fish-eating birds in North America and Europe (Anderson and Hickey 1972; Hickey and Anderson 1968). PCBs have been associated with reproductive failure, immunotoxicity and endocrine disruption in marine mammals (Reijnders 1986; Ross *et al.* 1996). Dioxins have been implicated in the failure of lake trout to reproduce in Lake Ontario during the period 1945-80 (Cook *et al.* 2003).

Food webs feature prominently in the characterization of transport, fate and effect functions for POPs, as these chemicals are lipophilic and partition readily into the fatty tissues of biota (Berglund *et al.* 2000). The metabolic recalcitrance of POPs results in their biomagnification from one trophic level to the next, with high trophic level species having up to 10^9 times higher concentrations than surrounding water (Braune *et al.* 2005; Fisk *et al.* 2001). Conservation concerns for wildlife, and human health risks associated with the consumption of fisheries products, provide a rationale for ecotoxicological research and monitoring programs. As POPs enter the environment from a combination of point and non-point sources, studies of biota provide an integrated signal of contaminants from all sources, and can inform regulations, mitigation, conservation and fisheries management (Ross *et al.* 2009; Hagen *et al.* 1997). In addition to local sources, long range transport via atmospheric processes (Noël *et al.* 2009) and biological migrations (Krummel *et al.* 2005; Christensen *et al.* 2005) bring contaminants into the Strait of Georgia.

Harbour seals (*Phoca vitulina*) are small pinnipeds that are widely distributed throughout the northern hemisphere. The approximately 35,000 harbour seals in the Strait of Georgia are omnivorous but have a preference for small, lipid-rich prey including Pacific hake (*Merluccius productus*), Pacific herring (*Clupea pallasii*), and Pacific tomcod (*Microgadus proximus*) (Cullon *et al.* 2005; Olesiuk *et al.* 1990). The harbour seal has become a useful 'sentinel' of marine food web contamination because of its abundance, distribution, high trophic level, non-migratory nature, and relative ease of handling (Ross 2000).

Our objectives with this study were:

- 1) collect biopsies from free-ranging harbour seals to characterize the concentrations of two priority POPs (PCBs and PBDEs) in the Strait of Georgia food web;
- 2) develop a new health 'toolbox' in collaboration with the University of Victoria using a harbour seal-specific genomics approach, and apply this to biopsies;
- 3) interpret contaminant and/or health findings through to the year 2030 in the context of effects thresholds.

Seal captures and sampling:

Free-ranging harbour seal pups were live-captured on intertidal haul out sites using a small craft and manual restraint as described elsewhere (Ross *et al.* 2004). Skin/blubber biopsies provided an integrated sample of the blubber layer to near the muscle using an Acu-Punch 6 mm (diameter) biopsy sampler (Acuderm, Ft Lauderdale, FL, USA) following appropriate cleansing of the site as described in detail elsewhere (Simms *et al.* 2000). Samples were wrapped in hexane-rinsed aluminum foil, placed in cryovials, and stored at -20° C until analysis. A second 3.5 mm blubber/skin biopsy was collected for genomics measurements. These were immediately placed into an RNA-Later solution in order to prevent RNA degradation until further analysis.

Measurement of priority contaminants (PCBs and PBDEs):

Harbour seal blubber biopsy samples were analyzed for congener-specific PCBs (n = 160), PBDEs (n = 44) and were reported as individual or co-eluting congeners using high-resolution gas chromatography/high-resolution mass spectrometry (HRGC/HRMS) at the DFO Laboratory of Expertise for Aquatic Chemical Analyses (LEACA). Total PCB and PBDE concentrations in seals from the Strait of Georgia are generally lower than those reported for Puget Sound but higher than those reported from remote sites on west coast of Vancouver Island or central coast of BC (Figure 1). However, the relatively high levels of PBDEs in Strait of Georgia seals relative to PCBs is consistent with a distillation of the legacy PCBs over time and space, and the more recent use of PBDEs.

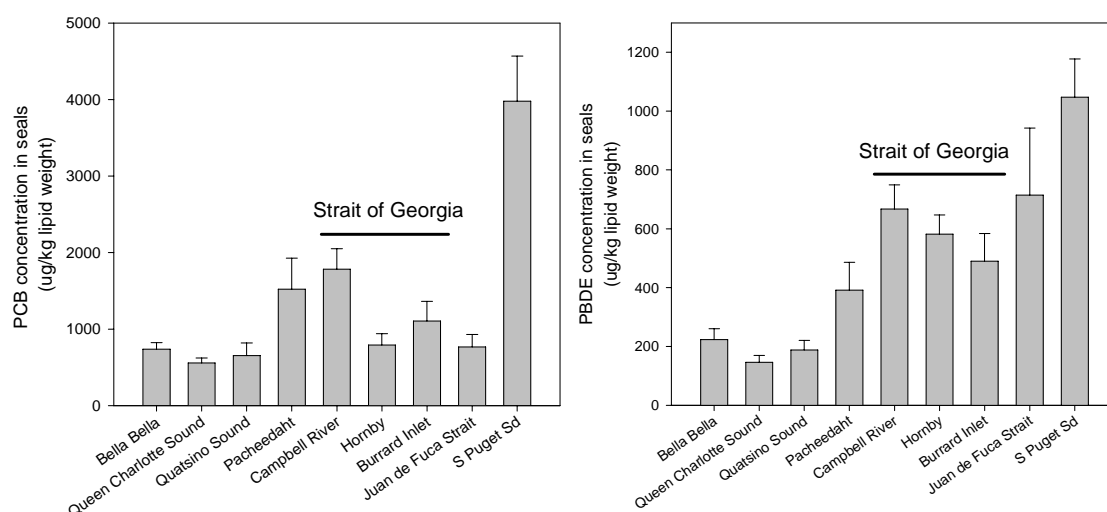


Figure 1: PCB (left) and PBDE (right) concentrations in harbour seal pups varied among study sites in British Columbia and Washington State. Highest concentrations of both contaminants were found in seals from Gertrude Island in the industrialized south Puget Sound, while the lowest concentrations were found in Central and North Coast of British Columbia.

Development and application of genomics-based health toolbox for harbour seals:

Gene expression can provide a powerful means of assessing the health impacts of environmental contaminants. Primers for eight genes were designed for harbour seals following published evidence of their role in toxicology. These included receptors for endpoints related to endocrine disruption, exposure to organic contaminants, and general stress (Table 1). Three additional genes were selected as normalizers. Primers were designed and assessed for their ability to amplify a single specific DNA amplicon using a three-tier quality control process. Details on the procedure can be found in Veldhoen *et al* (2009).

Tissues were homogenized and total RNA was isolated as described elsewhere (Veldhoen and Helbing 2001). cDNA was prepared using reverse transcription of RNA samples, and amplified using real-time PCR (Crump *et al.* 2002) using the gene-specific primers. Data was normalized to the expression of the gene encoding the ribosomal protein L8 using the comparative ($\Delta\Delta CT$) method (Livak and Schmittgen 2001). The expression of this gene was invariant in blubber tissue in the present study. Harbour seal blubber samples collected in 2008 -2009 as part of this Ecosystem Research Initiative (ERI) are presently being analyzed.

Gene	Amplicon Size (bp)	Pass / Fail	
		Blubber	Skin
Ribosomal protein L8 (L8)	126	Pass	Pass
Glyceraldehyde-3-phosphate dehydrogenase (GAPDH)	493	Pass	Fail

Cytoplasmic beta actin (β actin)	236	Pass	Pass
Estrogen receptor alpha ($Er\alpha$)	213	Pass	Pass
Aryl hydrocarbon receptor (AhR)	308	Fail	Pass
heat shock protein 70 (hsp 70)	392	Pass	Pass
Peroxisome proliferator-activated receptor gamma ($PPAR\gamma$)	398	Pass	Pass
Glucocorticoid receptor alpha (GR)	139	Pass	Pass
Vitamin D receptor (Vit D)	294	Fail	Pass
Thyroid hormone receptor alpha ($TR\alpha$)	231	Pass	Pass
Thyroid hormone receptor beta ($TR\beta$)	425	Fail	Pass ^a

^a - Passes the quality control but not highly efficient in replication. Results must be interpreted cautiously.

Table 1: Quality control results (blubber and skin) for the 11 harbour seal DNA primers.

Health risks in harbour seals:

Our development of a new health toolbox is currently being applied to seal biopsy samples from the Strait of Georgia. Earlier exploration of a more limited suite of toxicological endpoints has provided evidence of an effect of PCBs on hormones (thyroid hormone and vitamin A levels in circulation), gene expression (thyroid hormone receptor alpha, retinoic acid receptor, and Aryl hydrocarbon receptor), and immune function (phagocytosis, respiratory burst, T-cell function) in free-ranging seals (for example, Figure 2; (Tabuchi *et al.* 2006b; Mos *et al.* 2006; Simms *et al.* 2000)). A risk-based evaluation of these studies led to the generation of a new Tissue Reference Value (TRV) corresponding to a 5% Effects Concentration (1.3 mg/kg lipid weight) for PCBs in harbour seals (Mos *et al.* 2010). This corresponded to an estimated 0.025 mg/kg lipid weight tolerable daily intake in prey, with both of these values serving to guide status and trends as they relate to source controls or regulations.

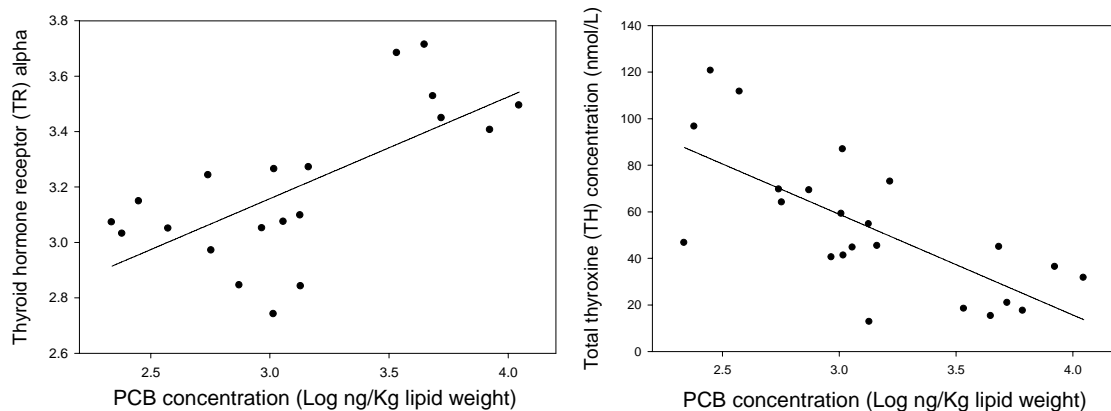


Figure 2: Thyroid hormone receptors (TR-alpha; left) in blubber biopsies increased with PCB concentrations in seals, while circulating thyroid hormone (thyroxine; right) concentrations decreased. These observations are consistent with the endocrine disrupting nature of PCBs and the vulnerability of thyroid physiology to environmental contaminants. Adapted from (Tabuchi et al. 2006a).

By comparing PCB concentrations in the seals at all sites against the TRV of 1.3 mg/kg, we can evaluate spatial variation in PCB-related health risks (Figure 3). We derive a 'Health Index' here as the proportion of pups sampled at each site that fall below the TRV, with results indicating that seals inhabiting the Strait of Georgia have moderate Health Index (falling between seals from remote sites and those from the industrialized Puget Sound). Sites with the lowest Index values have a heightened risk of adverse effects among seals.

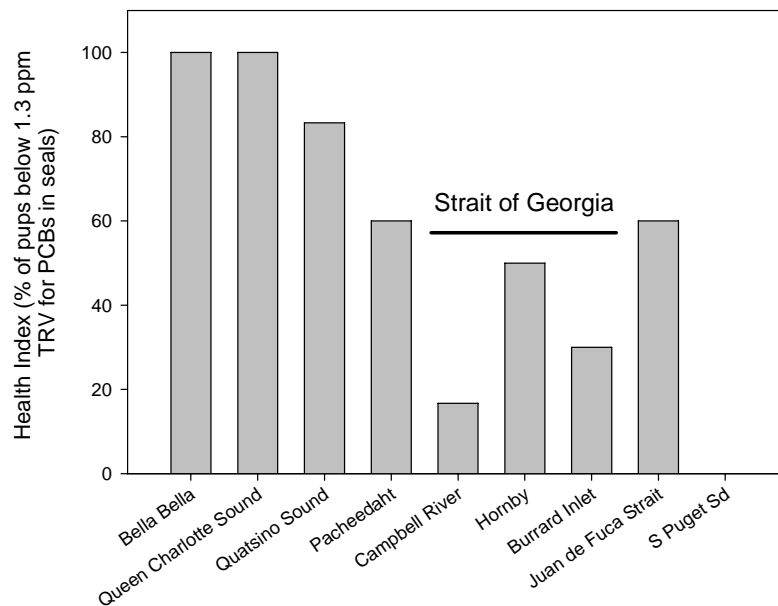


Figure 3: Current PCB concentrations in seal pups from different sites are compared to the recently developed harbour seal effects threshold (Tissue Residue Value or TRV for a 5% Effects Concentration). The proportion of pups at each site that fell below this TRV provides the Health

Index plotted here. Seals inhabiting the Strait of Georgia and Puget Sound had the lowest proportion of the population that fell below the TRV, suggesting that the risk of effects associated with endocrine disruption and immunotoxicity is higher in these regions.

A divergent history of uses, emissions and regulations provide an asynchronous backdrop for environmental PCB and PBDE concentrations in the Strait of Georgia (Johannessen *et al.* 2008), with consequent health implications for harbour seals. While climate-associated changes in productivity and in transport/fate functions for environmental contaminants may alter baselines and complicate predictions (Macdonald *et al.* 2002), a series of model-based future scenarios provides some guidance for managers, regulators and policymakers. We adapted for use in harbour seals a life history-based model that was developed for PCBs in other marine mammals (Hickie *et al.* 2007; Hickie *et al.* 2005). These earlier studies, focusing on PCBs, collectively demonstrate robust calibration and testing of the model's performance for predicting PCB concentrations.

Harbour seals in the Strait of Georgia are still at risk for health risks associated with exposure to legacy PCBs, but regulations enacted in 1977 will reduce these risks substantially by the year 2030 (Table 2). Predictions for the structurally-related PBDEs are more difficult, as regulations enacted today have yet to result in a clearly detectable temporal trend in environmental matrices. In the absence of any regulations, the current doubling time of 3.1 years in Puget Sound harbour seals would lead to a Strait of Georgia population at risk for health effects in 2030 (0% below TRV). However, if PBDE concentrations decline in seals with a half-life of 10 years beginning in 2006, 96% of seals are predicted to fall below the TRV by the year 2030. Initial indications suggest that PBDE levels have begun to respond to regulations and source control, increasing the likelihood that our second scenario may bear out. The main value of these scenarios is to illustrate that PBDE concentrations in harbour seals are likely to be similar to PCBs in 2030. In these scenarios, we assume a similar environmental response of PBDEs to the PCBs, and a similar health effects threshold. Further research is needed to clarify these assumptions.

	Healthy seals: Percent of seals below PCB TRV of 1.3 ppm (10 year half life scenarios)		Healthy seals: Percent of seals below PCB TRV (doubling of 3.1 years with no regulations)
	PCBs	PBDEs	PBDEs
2001	2%	84%	84%
2030	99%	96%	0%

*Table 2: The percent of seal pups in the Strait of Georgia with PCB or PBDE concentrations falling below the Tissue Residue Value (TRV) of 1.3 ppm for PCBs are presented here, assuming either an environmental half-life of 10 years for both chemicals (two left hand columns), or a doubling time of 3.1 years for PBDEs in seals (right hand column; this trend is reported for seals between 1984 and 2003 in Puget Sound; Ross *et al.*, in prep). The two left hand columns provide an indication of the response to regulations of PCBs (1977) and PBDEs (2004-2013), and suggest that the health of high trophic level seals will improve considerably by the year 2030. Trends for PBDEs under the scenario of no regulations suggest that all seals will exceed the TRV in the year 2030.*

REFERENCES

1. Anderson, D.W. and Hickey, J.J. 1972. Eggshell changes in certain North American birds. *Proc. Int. Ornithol. Congr.* 15: 514-540.
2. Berglund, O., Larsson, P., Ewald, G., and Okla, L. 2000. Bioaccumulation and differential partitioning of polychlorinated biphenyls in freshwater, planktonic food webs. *Can. J. Fish. Aquat. Sci.* 57: 1160-1168.
3. Braune, B.M., Outridge, P.M., Fisk, A.T., Muir, D.C.G., Helm, P.A., Hobbs, K., Hoekstra, P.F., Kuzyk, Z.A., Kwan, M., Letcher, R.J., Lockhart, W.L., Norstrom, R.J., Stern, G.A., and Stirling, I. 2005. Persistent organic pollutants and mercury in marine biota of the Canadian Arctic: An overview of spatial and temporal trends. *Sci. Total Environ.* 351-352: 4-56.
4. Christensen, J.R., MacDuffee, M., Macdonald, R.W., Whitticar, M., and Ross, P.S. 2005. Persistent organic pollutants in British Columbia grizzly bears: Consequence of divergent diets. *Environ. Sci. Technol.* 39: 6952-6960.
5. Cook, P.M., Robbins, J., Endicott, D.D., Lodge, K.B., Guiney, P.D., alker, M.K., Zabel, E.W., and Peterson, R. 2003. Effects of aryl hydrocarbon receptor-mediated early life stage toxicity on lake trout populations in Lake Ontario during the 20th century. *Environ. Sci. Technol.* 37: 3864-3877.
6. Crump, D., Werry, K., Veldhoen, N., Van Aggelen, G., and Helbing, C.C. 2002. Exposure to the herbicide Acetochlor alters thyroid hormone-dependent gene expression and metamorphosis in *Xenopus laevis*. *Environ. Health Perspect.* 110: 1199-1205.
7. Cullon, D., Jeffries, S., and Ross, P.S. 2005. Persistent organic pollutants in the diet of harbor seals (*Phoca vitulina*) inhabiting Puget Sound, Washington (USA), and the Strait of Georgia, British Columbia (Canada): A food basket approach. *Env. Tox. Chem.* 24: 2562-2572.
8. Fisk, A.T., Hobson, K.A., and Norstrom, R.J. 2001. Influence of chemical and biological factors on trophic transfer of persistent organic pollutants in the northwater polynya marine food web. *Environ. Sci. Technol.* 35: 732-738.
9. Hagen, M.E., Colodey, A.G., Knapp, W.D., and Samis, S.C. 1997. Environmental response to decreased dioxin and furan loadings from British Columbia coastal pulp mills. *Chemosphere* 34: 1221-1229.
10. Hickey, J.J. and Anderson, D.W. 1968. Chlorinated hydrocarbons and eggshell changes in raptorial and fish-eating birds. *Science* 162: 271-273.
11. Hickie, B.E., Muir, D.C.G., Addison, R.F., and Hoekstra, P. 2005. Modelling the temporal trends of persistent organic pollutants in Arctic ringed seal (*Phoca hispida*) populations. *Sci. Total Environ.* 351-352: 413-426.
12. Hickie, B.E., Ross, P.S., Macdonald, R.W., and Ford, J.K.B. 2007. Killer whales (*Orcinus orca*) face protracted health risks associated with lifetime exposure to PCBs. *Environ. Sci. Technol.* 41: 6613-6619.
13. Johannessen, S.C., Macdonald, R.W., Wright, C.A., Burd, B., Shaw, D.P., and van Roodselaar, A. 2008. Joined by geochemistry, divided by history: PCBs and PBDEs in Strait of Georgia sediments. *Mar. Environ. Res.* 66: S112-S120.
14. Krummel, E.M., Gregory-Eaves, I., Macdonald, R.W., Kimpe, L.E., Demers, M.J., Smol, J.P., Finney, B., and Blais, J.M. 2005. Concentrations and fluxes of salmon-derived polychlorinated biphenyls (PCBs) in lake sediments. *Environmental Science & Technology* 39: 7020-7026.
15. Livak, K.J. and Schmittgen, T.D. 2001. Analysis of relative gene expression data using real-time quantitative PCR and the 2(-Delta Delta C(T)) Method. *Methods* 25: 402-408.

16. Macdonald, R. W., Morton, B., Addison, R. F., and Johannessen, S. C. 2002. Marine environmental contaminant issues in the North Pacific: What are the dangers and how do we identify them? No. 22.
17. Mos, L., Cameron, M., Jeffries, S.J., Koop, B.F., and Ross, P.S. 2010. Risk-based analysis of PCB toxicity in harbor seals. *Integrated Environmental Assessment and Management* 6: 631-640.
18. Mos, L., Morsey, B., Jeffries, S.J., Yunker, M.B., Raverty, S., De Guise, S., and Ross, P.S. 2006. Chemical and biological pollution contribute to the immunological profiles of free-ranging harbor seals. *Environ.Toxicol.Chem.* 25: 3110-3117.
19. Noël, M., Dangerfield, N., Hourston, R.A.S., Belzer, W., Shaw, P., Yunker, M.B., and Ross, P.S. 2009. Do trans-Pacific air masses deliver PBDEs to coastal British Columbia, Canada? *Environ.Pollut.* 157: 3404-3412.
20. 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: 1-135.
21. Reijnders, P.J.H. 1986. Reproductive failure in common seals feeding on fish from polluted coastal waters. *Nature* 324: 456-457.
22. Ross, P.S. 2000. Marine mammals as sentinels in ecological risk assessment. *HERA* 6: 29-46.
23. Ross, P.S., Couillard, C.M., Ikonomou, M.G., Johannessen, S.C., Lebeuf, M., Macdonald, R.W., and Tomy, G.T. 2009. Large and growing environmental reservoirs of Deca-BDE present an emerging health risk for fish and marine mammals. *Mar.Pollut.Bull.* 58: 7-10.
24. Ross, P.S., De Swart, R.L., Addison, R.F., Van Loveren, H., Vos, J.G., and Osterhaus, A.D.M.E. 1996. Contaminant-induced immunotoxicity in harbour seals: wildlife at risk? *Toxicology* 112: 157-169.
25. Ross, P.S., Jeffries, S.J., Yunker, M.B., Addison, R.F., Ikonomou, M.G., and Calambokidis, J. 2004. Harbour seals (*Phoca vitulina*) in British Columbia, Canada, and Washington, USA, reveal a combination of local and global polychlorinated biphenyl, dioxin, and furan signals. *Environ.Toxicol.Chem.* 23: 157-165.
26. Simms, W., Jeffries, S.J., Ikonomou, M.G., and Ross, P.S. 2000. Contaminant-related disruption of vitamin A dynamics in free-ranging harbor seal (*Phoca vitulina*) pups from British Columbia, Canada and Washington State, USA. *Environ.Toxicol.Chem.* 19: 2844-2849.
27. Tabuchi, M., Veldhoen, N., Dangerfield, N., Helbing, C.C., and Ross, P.S. 2006a. PCB-related alteration of thyroid hormones and thyroid hormone receptor gene expression in free-ranging harbor seals (*Phoca vitulina*). *Environ.Health Perspect.* 114: 1024-1031.
28. Tabuchi, M., Veldhoen, N., Dangerfield, N., Jeffries, S.J., Helbing, C.C., and Ross, P.S. 2006b. PCB-related alteration of thyroid hormones and thyroid hormone receptor gene expression in free-ranging harbor seals (*Phoca vitulina*). *Environ.Health Perspect.* 114: 1024-1031.
29. Veldhoen, N. and Helbing, C.C. 2001. Detection of environmental endocrine-disruptor effects on gene expression in live *Rana catesbeiana* tadpoles using a tail fin biopsy technique. *Environ.Toxicol.Chem.* 20(12): 2704-2708.
30. Veldhoen, N., Ikonomou, M.G., Dubetz, C., MacPherson, N., Sampson, T., Kelly, B.C., and Helbing, C.C. 2009. Gene expression profiling and environmental contaminant assessment of migrating Pacific salmon in the Fraser River watershed of British Columbia. *Aquat.Toxicol.* 97: 212-225.

A8: STRAIT OF GEORGIA ECOSYSTEM RESEARCH INITIATIVE - FORAGE SPECIES

Schweigert, Therriault and Robinson

Project Overview

Identifying 'hotspots' of forage species distribution and production at various times of the year will be critical to understanding their interannual production, and ultimately to the rate of energy transfer to higher trophic levels within the Strait of Georgia ecosystem. An objective of this project is to begin to get an understanding of the locations within the Strait of Georgia Strait that are critical to the productivity of forage species. In this study, we have focussed effort on the ongoing data collections for Pacific herring and have attempted to collate information for other forage species as much as possible. We have also undertaken some exploratory surveys of presence and relative abundance of sand lance based on attempts to model their habitat preference from acoustic and bottom typing information. We have continued this aspect of the project in winter 2010 and 2011 and surveys are ongoing but no data summaries are available at this time.

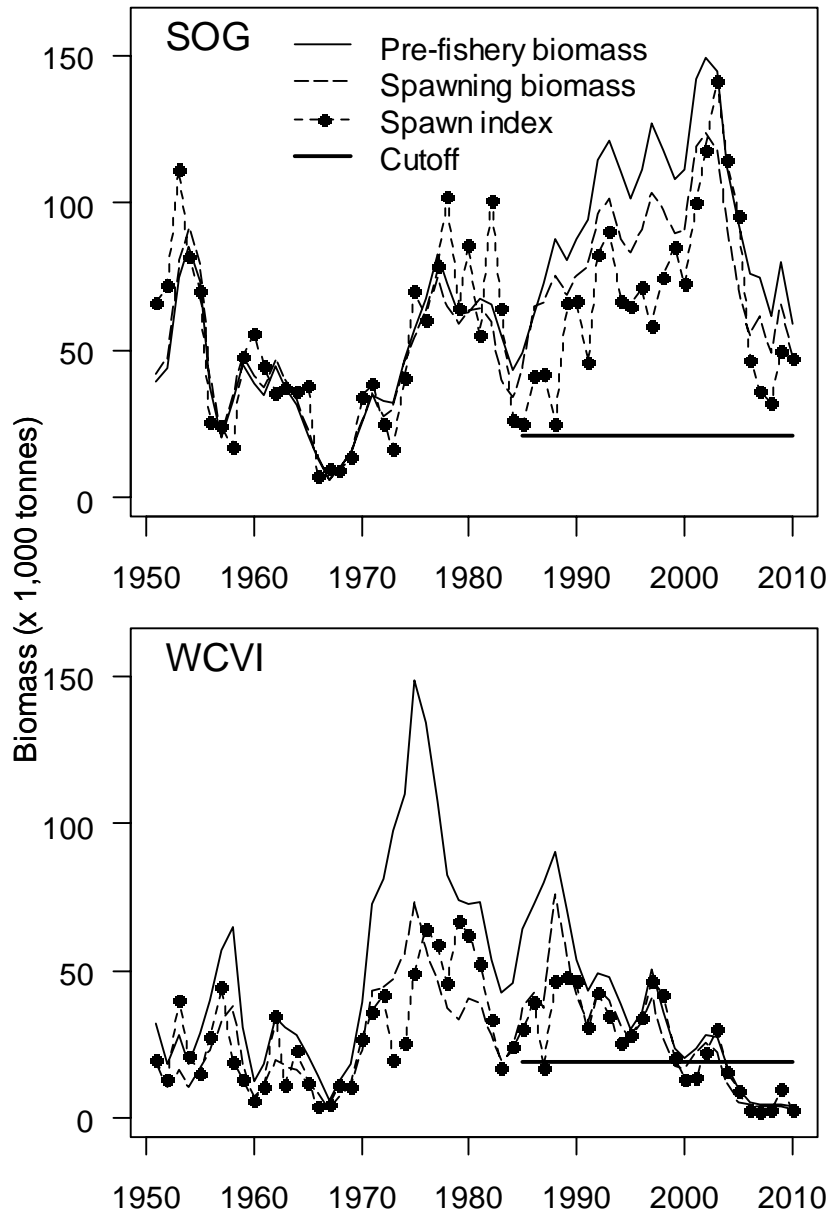


Figure 1. Abundance of Pacific herring stocks in the Strait of Georgia and west coast of Vancouver Island from 1951-2010.

The annual stock monitoring for Pacific herring was conducted during March 2010 and indicated abundance was similar to 2008, a slight decrease from last year. Indications were that a very weak 2007 year-class followed the strong 2006 year-class that recruited to the population in 2009 resulting in the abundance decrease (Figure 1). The distribution of herring eggs was widespread comparable to that in recent years with little spawning activity in the southern Strait of Georgia which we had seen in recent years (Figure 2).

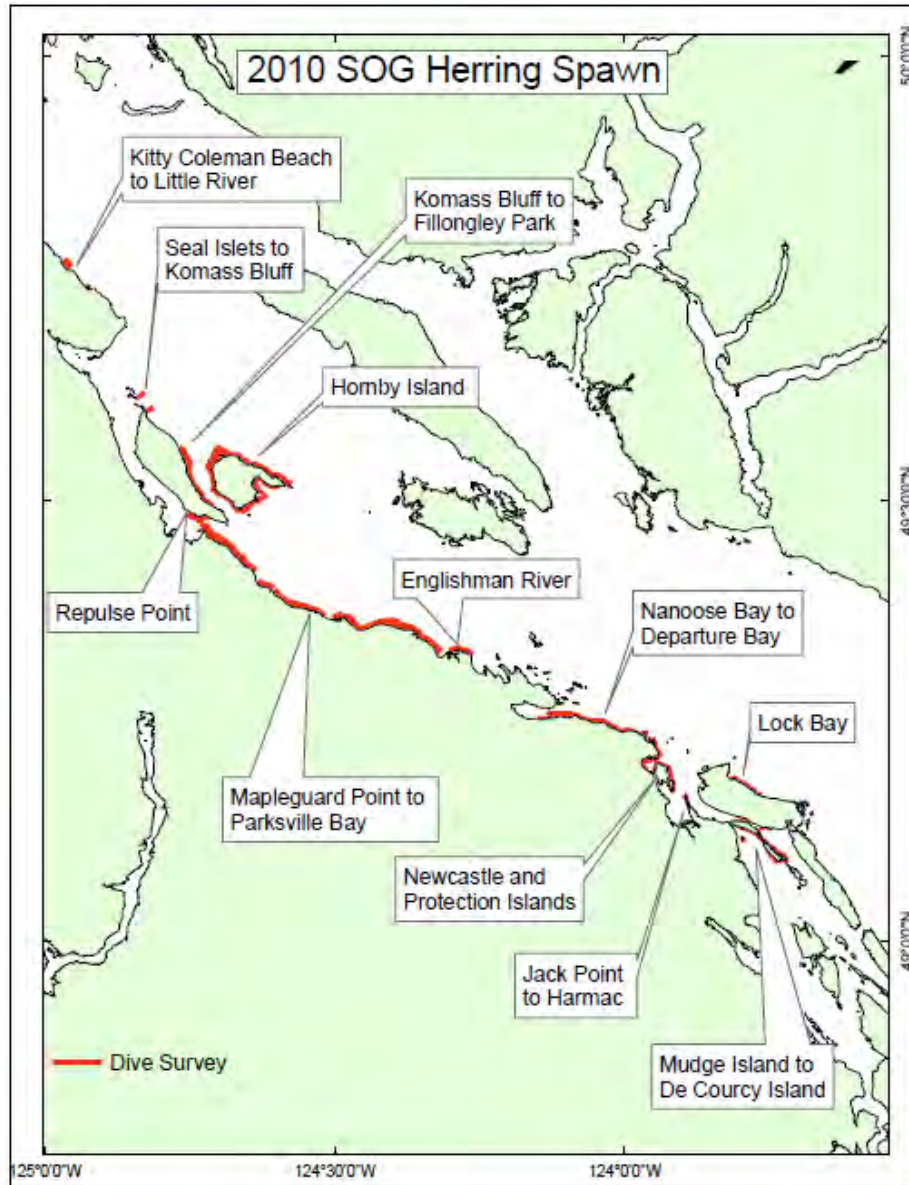


Figure 2. Distribution of herring spawning locations in the Strait of Georgia in 2010.

The abundance of the adult spawning run is heavily influenced by the number of age 3 recruits or fish spawning for the first time. An annual survey of juvenile herring relative abundance has been ongoing since 1991 and is conducted in the latter half of September. A series of 10 core transects are sampled with 5 sampling stations per transect. The surveys are conducted at night and collect plankton samples as well as enumerating any by-catch in the herring purse-seine sets. The time series of juvenile herring catches as determined from the seine set surveys (Schweigert) that are conducted inshore and those from the herring bycatch in the juvenile salmon offshore survey (Beamish) mesh nicely particularly in recent years supporting the observed strong 2006 year-class (Figure 3). Indication from these surveys is that the survival of herring from eggs to the subsequent sexually mature spawning population is determined largely during the first year in the Strait of Georgia. Understanding the key factors that influence survival of young herring during their first summer is critical to accurately

predicting their survival to the adult population and ultimately production. During 2010 attempts were made to correlate herring juvenile abundance and growth (Figure 4) with a number of oceanographic indices. To date, we have not been successful in determining the features that are most important in predicting herring survival and this work will continue.

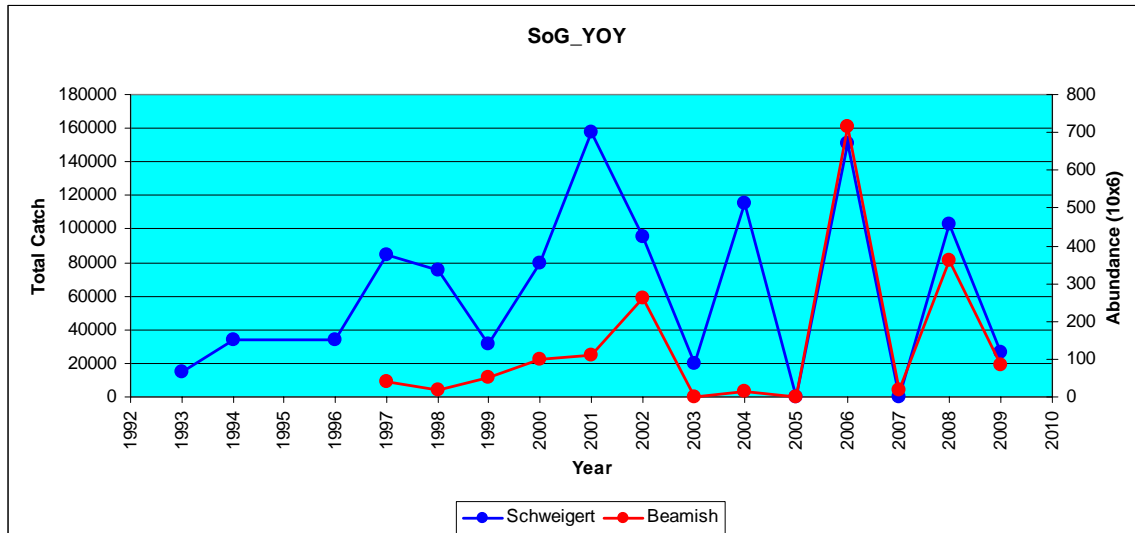


Figure 3. Indices of juvenile herring abundance as determined from purse seine surveys (Schweigert) and surface trawl (Beamish).

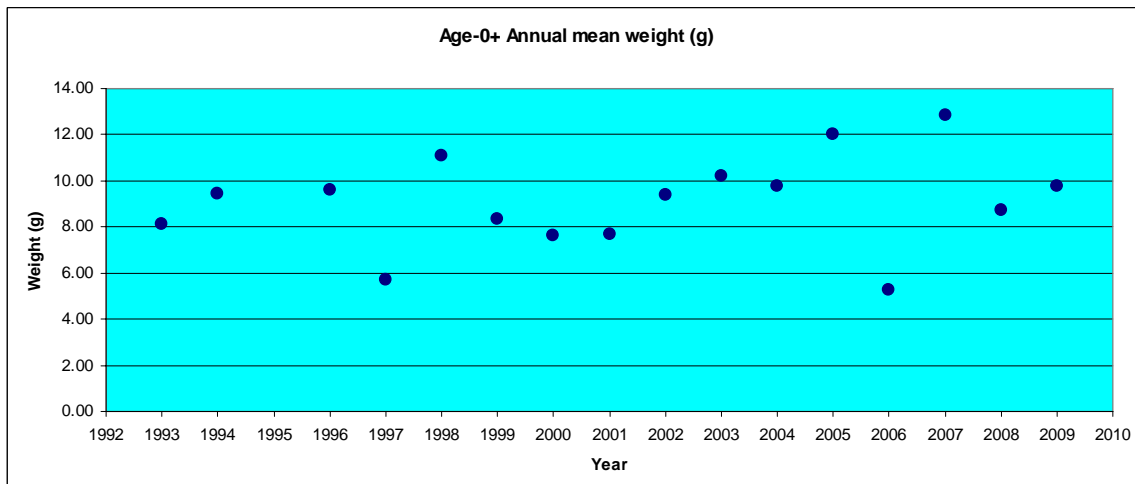


Figure 4. Weight of juvenile herring at the end of the first summer of life as an indicator of growth rate.

In the Pacific Northwest, Pacific Sand Lance (*Ammodytes hexapterus* Pallas) are an understudied species relative to their ecological importance as a highly efficient trophic link and much remains to be learned about their critical habitat requirements. This study set out to determine if sand lance in British Columbia are obligate intertidal spawners, as has been reported for Puget Sound, or if subtidal spawning also occurs. Sediment characteristics of both intertidal and subtidal habitats were investigated to shed light on critical habitat requirements. Spawn surveys were conducted in the mid and Southern Strait of Georgia both in the intertidal guided by a suitable habitat model developed for Puget Sound, and in the subtidal targeting areas thought to be sand wave fields with

boat based grab sampling. Sediment samples collected from beaches (n=57) and subtidal sand wave fields (n=69) were analyzed for spawn and dry-sieved to produce sediment size distributions and statistics. Spawn and fish present samples were compared to spawn and fish absent samples in terms of mean grain size, sorting coefficient, skewness and the proportions of coarse/medium sands and silts. All comparisons were made with nonparametric Mann-Whitney U Tests. Spawn was only found in the intertidal (n=8) and was associated with a higher mean particle diameter, lower proportion of coarse and medium sands and a greater skew towards fines than beaches without spawn. Due to a small sample size and methodological difficulties with the intertidal spawn survey, results must be interpreted with caution. Adult fish (n=23) were found in the subtidal at 4 sites. Fish present samples had a larger mean particle diameter, higher percent coarse and medium sands by weight and lower percent silts by weight than fish absent samples. Fish presence in samples is partly controlled by thresholds in percent coarse and medium sand (>80%) and percent silts (<1%). Fish were also absent from samples that fell within acceptable sediment class parameters suggesting that other variables must be investigated to predict sand lance presence and absence. This study demonstrates the importance of coarse, well-flushed subtidal sediments for adult sand lance burying and suggests directions for future investigations into sand lance critical habitat.

A9:PREY QUALITY AND FOOD WEB INTERACTIONS IN THE STRAIT OF GEORGIA (2008-2009)

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Objectives:

The long-term objectives of this research program are to assess the effects of prey quality on the marine survival of Strait of Georgia salmon. The short-term objectives of this study are to determine the extent of the spatial variability in stable isotopes of carbon and nitrogen at the base of the food chain and to compare prey quality at the base of the food chain and to quantify food web interactions in two contrasting pelagic ecosystems (the Strait of Georgia and the west coast of Vancouver Island). More specifically, we will test the hypotheses that prey quality is lower and that juvenile coho and Chinook salmon are feeding at a lower trophic level, have a lower growth rate and lipid content in the Strait of Georgia relative to west coast of Vancouver Island.

Approach:

We are using the carbon to nitrogen (C:N) ratio in zooplankton as an indicator of lipids produced at the base of the food chain [1] and of prey quality for salmon [2], and the stable isotopes of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) in zooplankton and juvenile coho salmon and Chinook salmon to determine their trophic position in the SoG and off WCVI. $\delta^{13}\text{C}$ is an indicator of food source, whereas $\delta^{15}\text{N}$ is an indicator of trophic position in aquatic ecosystems [3]. However, because $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of zooplankton may vary substantially over a broad geographic area [4], we are also examining the relationship between $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of zooplankton and various physical and biological factors namely temperature, salinity, nutrients, phytoplankton and zooplankton biomass, and

zooplankton community composition. We are also measuring the width of daily rings on the otoliths of juvenile coho and Chinook salmon collected during the fall to quantify summer growth [5], and relate these estimates of early marine growth to prey quality and trophic position.

Progress to date:

Sampling

Three integrated pelagic ecosystem surveys were conducted in the Strait of Georgia and off the west coast of Vancouver Island in 2008, and then again in 2009 (Table 1; Figure 1-4). The fall 2008-2009 and winter 2009 surveys were conducted on board the CCGS *W.E. Ricker*, whereas the summer 2008-2009 and winter 2008 surveys were conducted on board the *FV Viking Storm*. At oceanographic stations, the scientific crew (1) conducted CTD (conductivity-temperature-depth) casts, and (2) collected seawater samples at 10m with a Niskin bottle for salinity, chlorophyll a, and nutrient analysis (nitrate, phosphate, and silicate). CTD casts were conducted to within 5 m of the bottom or to a maximum depth of 250 m with a Seabird probe. Duplicate nutrient samples were collected in acid-washed glass test tubes, and duplicate chlorophyll a samples were collected on GF/F glass fiber filter disks, folded in half and placed in polypropylene scintillation vials. All these samples were stored frozen at -20°C and analyzed at the Institute of Ocean Sciences (Sidney, British Columbia). Chlorophyll a samples were stored in dark crates to prevent photosynthetic degradation prior to analysis. Vertical bongo tows were conducted with two 58 cm diameter Nitex nets (253 μm mesh) to within approximately 10 m of the bottom or a maximum depth of 150 m. One of the nets was equipped with a TSK flowmeter. Zooplankton collected from the net with the flowmeter were preserved in 10% formalin and sent to the zooplankton laboratory at the Institute of Ocean Sciences, Fisheries and Oceans Canada (Sidney, British Columbia) for species classification and enumeration. Zooplankton taken from the net without the flowmeter was sorted into four size fractions by successively sieving through 8.0, 1.7, 1.0, and 0.25 mm screens. Each size fraction was weighed wet, dried at 60°C for 48 hours, re-weighed, and stored in plastic bags for stable isotope analyses. Juvenile salmon and associated pelagic fish species were caught using a rope trawl that was towed at 5 knots at the surface for 30 minutes². Up to 30 juvenile Chinook, coho, and sockeye salmon were selected from each net tow. All the juvenile Chinook and coho salmon, and only juvenile sockeye with their adipose fin missing, were scanned for coded-wire tags (CWT) and passive integrated transponder (PIT) tags. Fork length (± 1 mm) and mass (± 1 g) were determined onboard the research vessel. Otoliths and scales were removed for age determination. A skin sample was also taken from the operculum using a hole-punch and preserved in 70% ethanol for stock identification [6-7]. Whole fish were then frozen individually at -20°C in pre-identified plastic bags for subsequent analyses. Additional samples of juvenile salmon were obtained from the July and September surveys conducted on board the CCGS *W.E. Ricker* by R.J. Beamish and R.M. Sweeting in the Strait of Georgia in 2008 and 2009.

Stable Isotopes

Stable isotopes of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) were measured in muscle samples of juvenile salmon and two size fractions of zooplankton (0.25-1.0 mm and 1.0-1.7 mm) at the University of Victoria using a mass spectrometer. Muscle samples of juvenile salmon and zooplankton were dried at 60°C to constant weight then ground in a food processor prior to chemical analyses. The C:N ratio is a byproduct of stable isotope analyses and an indicator of lipid contents in aquatic organisms [3].

Otolith analyses

Otoliths of juvenile coho and Chinook were mounted on a glass slide with a plastic resin, then polished with a fine lapping film sheet (60 µm) until the daily rings were visible. The freshwater age and ocean entry check were assessed visually under a microscope [5]. The width of twenty daily rings was measured in the zone of the otolith that corresponds to marine growth.

Preliminary results:

Oceanography

Nutrient and chlorophyll a concentrations, as well as zooplankton biomass were measured on all the samples collected in the Strait of Georgia and off the west coast of Vancouver Island in 2008, and in winter and summer 2009. Nitrate concentration was lower during summer compared to winter and fall, possibly due to nutrient uptake by phytoplankton during the growing season (Figure 5) [8]. In contrast to nutrients, the biomass of phytoplankton and zooplankton generally increased during the summer months (Figure 6-7). Regional and annual differences in phytoplankton and zooplankton biomass were apparent, but not always consistent. Overall, phytoplankton and zooplankton biomass were higher in the Strait of Georgia during winter, but higher off the west coast of Vancouver Island during fall (Figure 6-7). To date, 21% (45 out of 210) of the zooplankton samples collected in the Strait of Georgia during 2008 and 2009 have been processed for taxonomic analyses (M. Galbraith, IOS, personal communication). The remaining samples will be processed early during the 2010/2011. Analysis of the changes in zooplankton community composition will be presented in a subsequent report.

Juvenile salmon distribution

Few juvenile coho salmon, Chinook salmon, and sockeye salmon were collected during winter in the Strait of Georgia, possibly suggesting that they had left this area by March (Figure 2-4). The absence of juvenile coho salmon off the west coast of Vancouver Island during winter was surprising (Figure 2), as previous winter surveys conducted from 2001 to 2007 showed high abundances of juvenile coho salmon in this area at this time of the year [9]. Three hypotheses could explain these results: juvenile coho salmon 1) forage in deeper waters during winter, 2) migrate south of the west coast of Vancouver Island during winter, or 3) move beyond the shelf break. The first of these hypotheses will be tested in February 2010. As in previous years, very few juvenile sockeye salmon were recovered in Juan de Fuca Strait and off the west coast of Vancouver Island (Figure 4). DNA analyses performed on the juvenile sockeye salmon caught in November 2008 in Juan de Fuca Strait (n=9) and off the west coast of Vancouver Island (n=8) indicate that 100% of these fish originated from the Harrison River (M. Trudel, unpublished data). As juvenile Harrison River sockeye have only been recovered on the outer coast late in the fall and in winter [10], these results suggest that they remain in the Strait of Georgia for an extended period of time, and most likely migrate out of this area through Juan de Fuca Strait [10].

Stable isotopes in zooplankton

To date, a total of 537 zooplankton samples have been analyzed for stable isotopes and C:N ratios. Overall, the carbon and nitrogen isotopic signatures are higher by 0.7‰ and 0.5‰, respectively, in medium size zooplankton (1.0-1.7 mm) compared to small size zooplankton (0.25-1.0 mm) (Figure 8). This pattern was consistent among regions

(Figure 8). This suggests that larger zooplankton occupy a slightly higher trophic level. The higher $\delta^{13}\text{C}$ in medium size zooplankton may reflect a different carbon source for these species. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ increased in small and medium size zooplankton from winter to fall [Figure 8]. This may reflect a shift from autochthonous carbon to alloctonous carbon (i.e. Fraser River Plume).

Stable isotopes in juvenile salmon

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ signature varied among species, with lower values for juvenile sockeye salmon and higher values for juvenile coho salmon (Figure 10). These results are consistent with the expected diet of these fish: juvenile sockeye salmon are generally planktivorous, whereas juvenile coho salmon and Chinook salmon feed on a mixture of forage fish and zooplankton [11], and thus are expected to have a higher $\delta^{15}\text{N}$ than juvenile sockeye salmon (Welch and Parsons 1993). Interestingly, $\delta^{15}\text{N}$ of juvenile salmon was higher in the fall than during early summer (Figure 10), possibly due to the increase of $\delta^{15}\text{N}$ in zooplankton during that time, or may reflect a shift from a freshwater signature to a marine signature [Perry et al. 1996].

Otolith microstructure

A total of 1,307 pairs of otoliths have been collected on juvenile coho salmon (n=753), on juvenile Chinook salmon (n=458), and on juvenile sockeye salmon (n=96) in 2008 and 2009. The otoliths of 72 juvenile Chinook salmon and 53 juvenile coho salmon collected in 2008 have been processed in FY2008/2009. A contractor is currently analyzing the microstructure of a subsample of the fish caught in 2009. These results will be available at the end of the 2009/2010 fiscal year and will be reported next year.

Future plans:

Zooplankton community composition and copepod diversity will be compared among seasons, years, and regions once the taxonomic analyses are completed using univariate and multivariate statistics [13-14]. Similarly, the C:N ratio in zooplankton will be compared between the Strait of Georgia and the west coast of Vancouver Island to assess the variability in lipid contents at the base of the food chain between ecosystems. Correlation and regression analyses will be performed to determine how the factors affecting the variability in the stable isotope signature of zooplankton. Finally, early marine growth rates of juvenile Chinook and coho salmon will be compared between the Strait of Georgia and the west coast of Vancouver Island and among years.

Several years of observations will be needed to assess the effects of prey quality on the survival of SoG salmon. Consequently, we anticipate to measure the C:N ratio and stable isotopes in SoG plankton and juvenile salmon well beyond the 2009/2010 fiscal year.

References:

- [1] Post et al. 2007. *Oecologia* 152: 179-189; [2] Trudel et al. 2008. Annual Report Submitted to the Bonneville Power Administration; [3] Post. 2002. *Ecology* 83: 703-718; [4] Schell et al. 1998. *Mar. Ecol. Prog. Ser.* 162: 11-23; [5] Zhang and Beamish. 2000. *Fish. Res.* 52: 344-352; [6] Beacham et al. 2005. *Trans. Am. Fish. Soc.* 134: 1124-1146; [7] Beacham et al. 2006. *Trans. Am. Fish. Soc.* 135:1604-1621; [8] Whitney et al. 2005. *Deep-Sea Res. II* 52: 681-706, [9] Morris et al. 2004. NPAFC Doc. 780; [10] Tucker et al. 2009. *Trans. Am. Fish. Soc.* 138: 1458- 1480; [11] Brodeur et al. 2007. *Am. Fish. Soc. Symp. Ser.* 57: 183-204; [12] Perry et al. 1996. *Fish. Oceanogr.* 5: 73-98; [13] Hoof and

Peterson. 2006. Limnol. Oceanogr. 51: 2607-2620; [14] Mackas et al. 2007. Prog. Oceanogr. 75: 223-252.

Sampling date	Oceanographic station	Plankton station	Fish station
Strait of Georgia – Juan de Fuca Strait			
March 1-10, 2008	22	22	51
June 18 – July 5, 2008	46	46	6
October 24 – November 6, 2008	29	29	23
March 1-10, 2009	35	35	39
June 18 – July 5, 2009	39	39	6
October 24 – November 6, 2009	39	39	5
West Coast of Vancouver Island (inlets and shelf waters)			
March 11-18, 2008	48	48	56
June 19-24, 2008	44	44	44
November 7-12, 2008	27	27	44
March 1-10, 2009	32	32	43
June 18 – July 5, 2009	43	43	35
October 24 – November 6, 2009	46	46	48
Total	450	450	400

Table 1. Integrated pelagic ecosystem surveys conducted by the High Seas Salmon Program in the Strait of Georgia and off the west coast of Vancouver Island in 2008 and 2009.

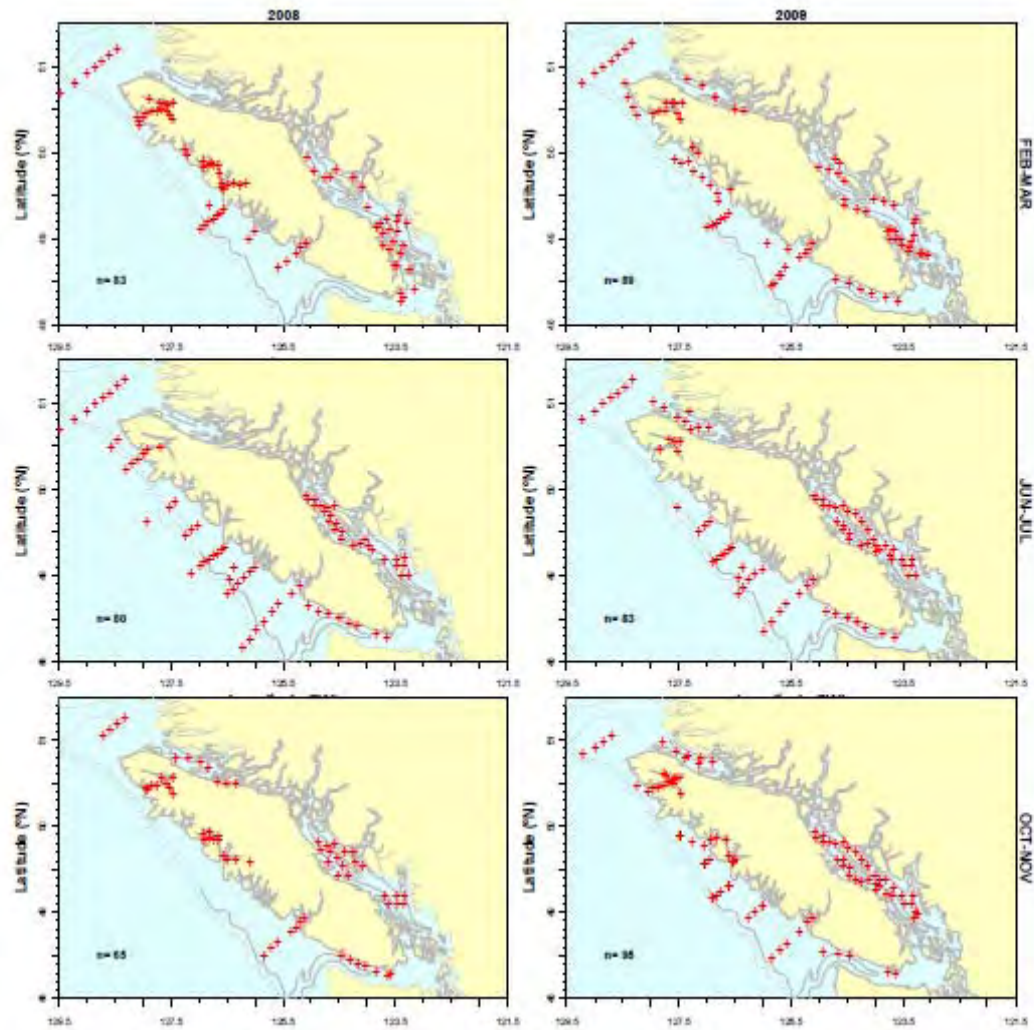


Figure 1. Locations of the plankton stations surveyed by the High Seas Salmon Program in 2008 and 2009 as part of the Strait of Georgia Ecosystem Research Initiative.

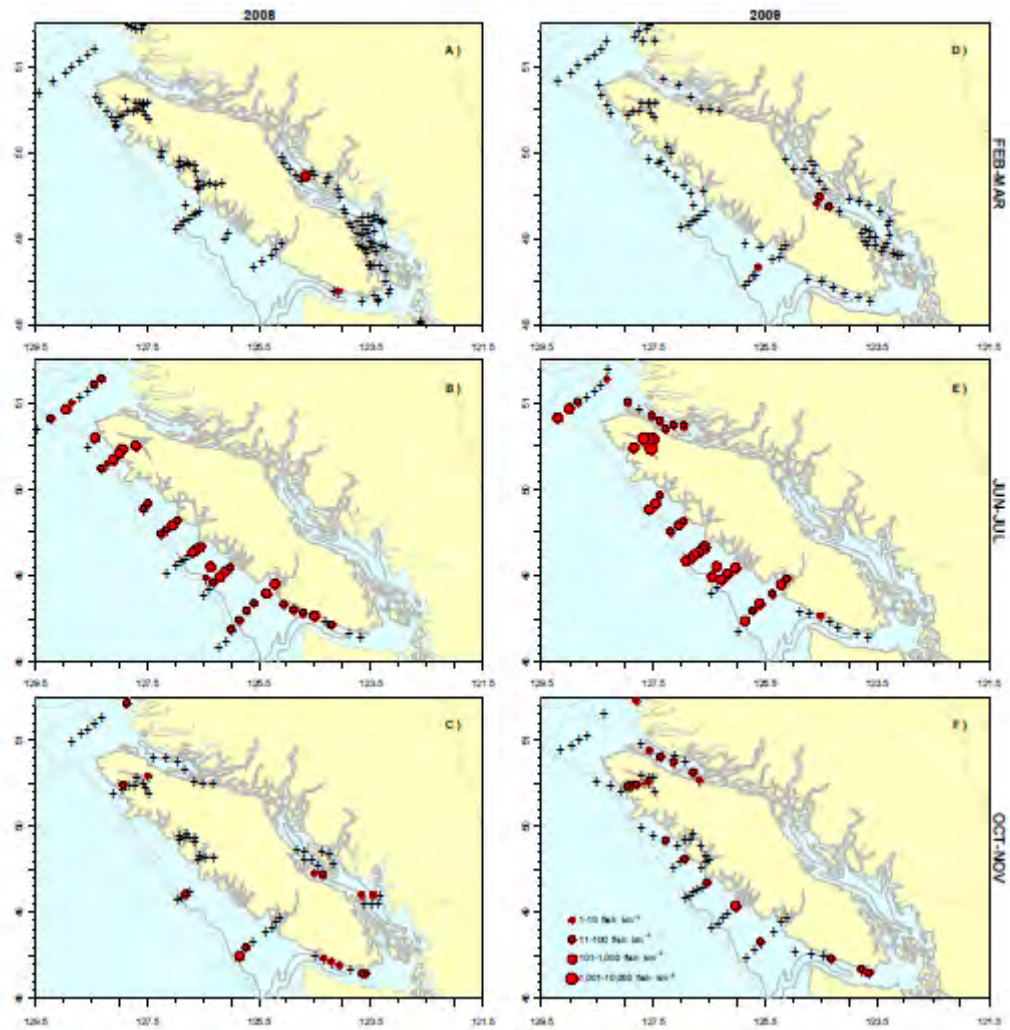


Figure 2. Distribution of juvenile coho salmon in the Strait of Georgia and off the west coast of Vancouver Island during winter (February-March), summer (June-July), and fall (October-November) 2008 and 2009. Circles are proportional to the catch-per-unit effort (fish/km²). The black cross indicates that no juvenile coho salmon were caught at this station.

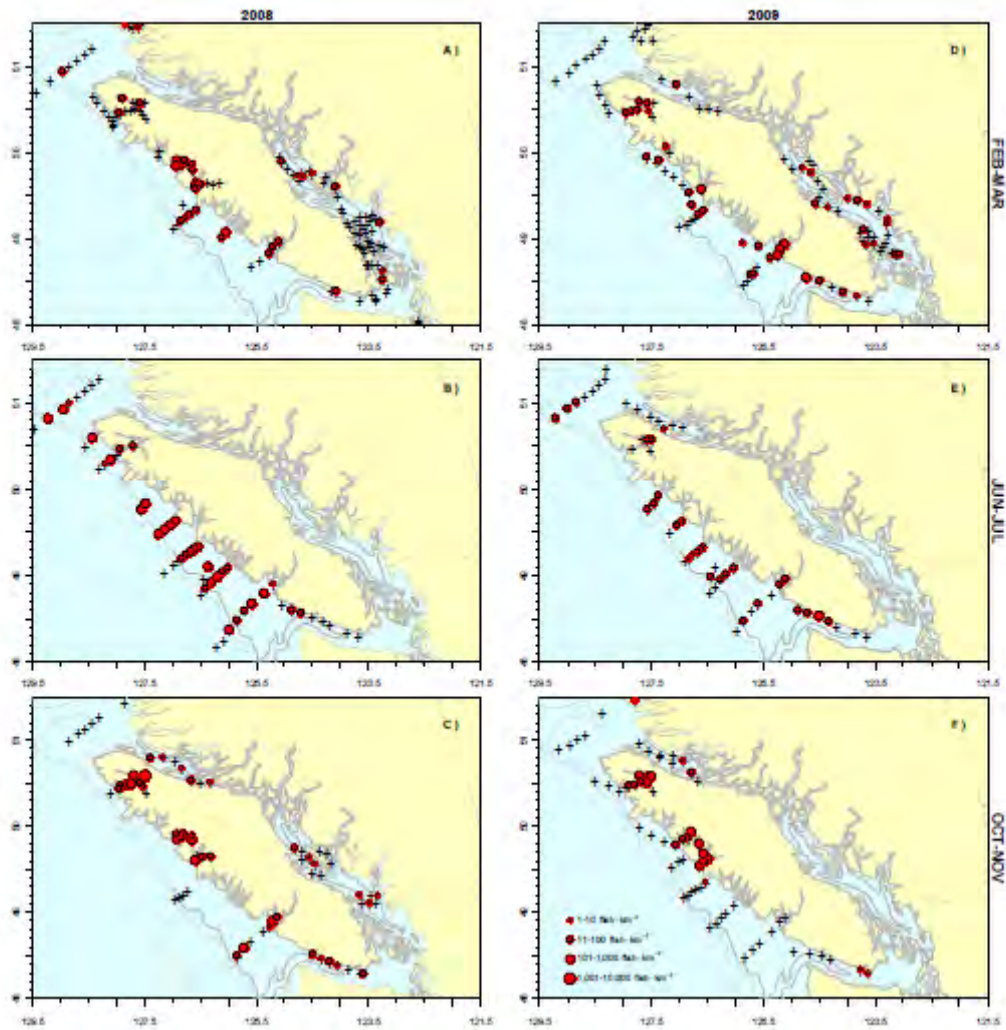


Figure 3. Distribution of juvenile Chinook salmon in the Strait of Georgia and off the west coast of Vancouver Island during winter (February-March), summer (June-July), and fall (October-November) 2008 and 2009. Circles are proportional to the catch-per-unit effort (fish/km²). The black cross indicates that no juvenile Chinook salmon were caught at this station.

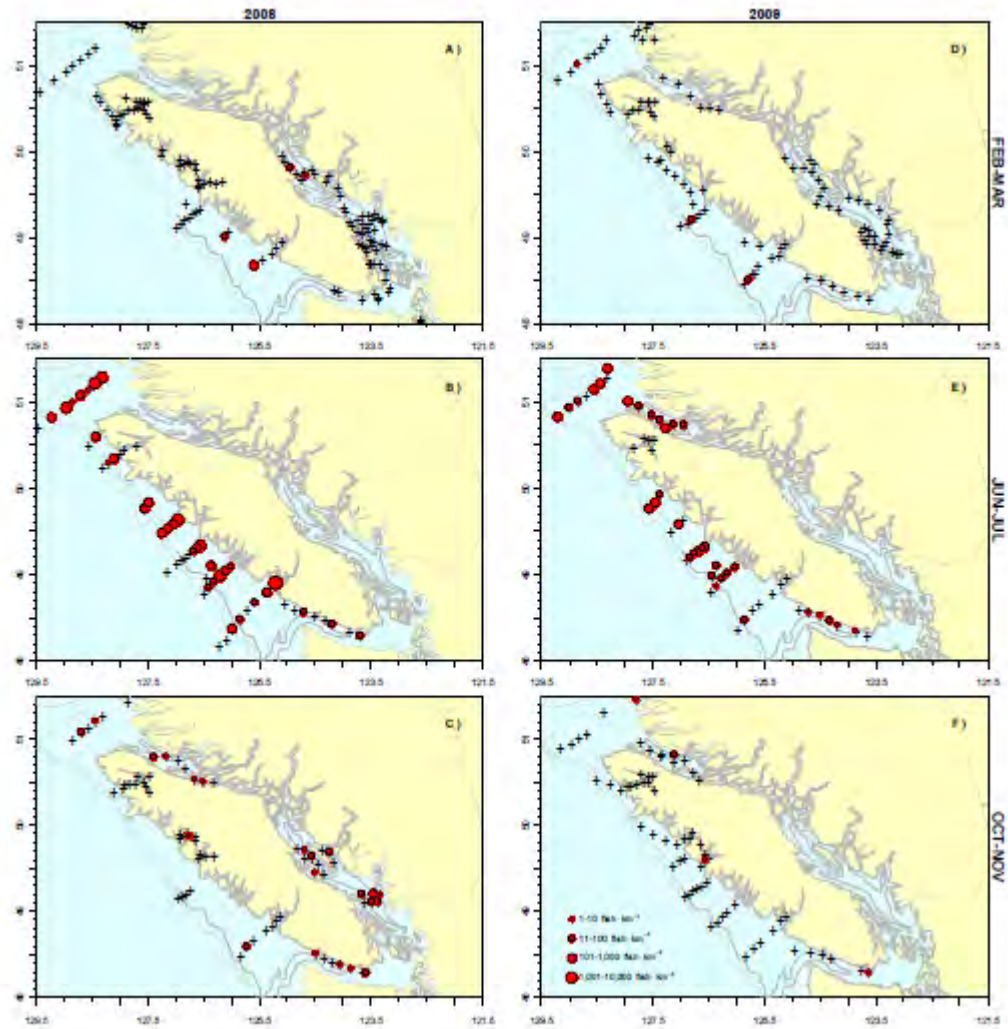


Figure 4. Distribution of juvenile sockeye salmon in the Strait of Georgia and off the west coast of Vancouver Island during winter (February-March), summer (June-July), and fall (October-November) 2008 and 2009. Circles are proportional to the catch-per-unit effort (fish/km²). The black cross indicates that no juvenile sockeye salmon were caught at this station.

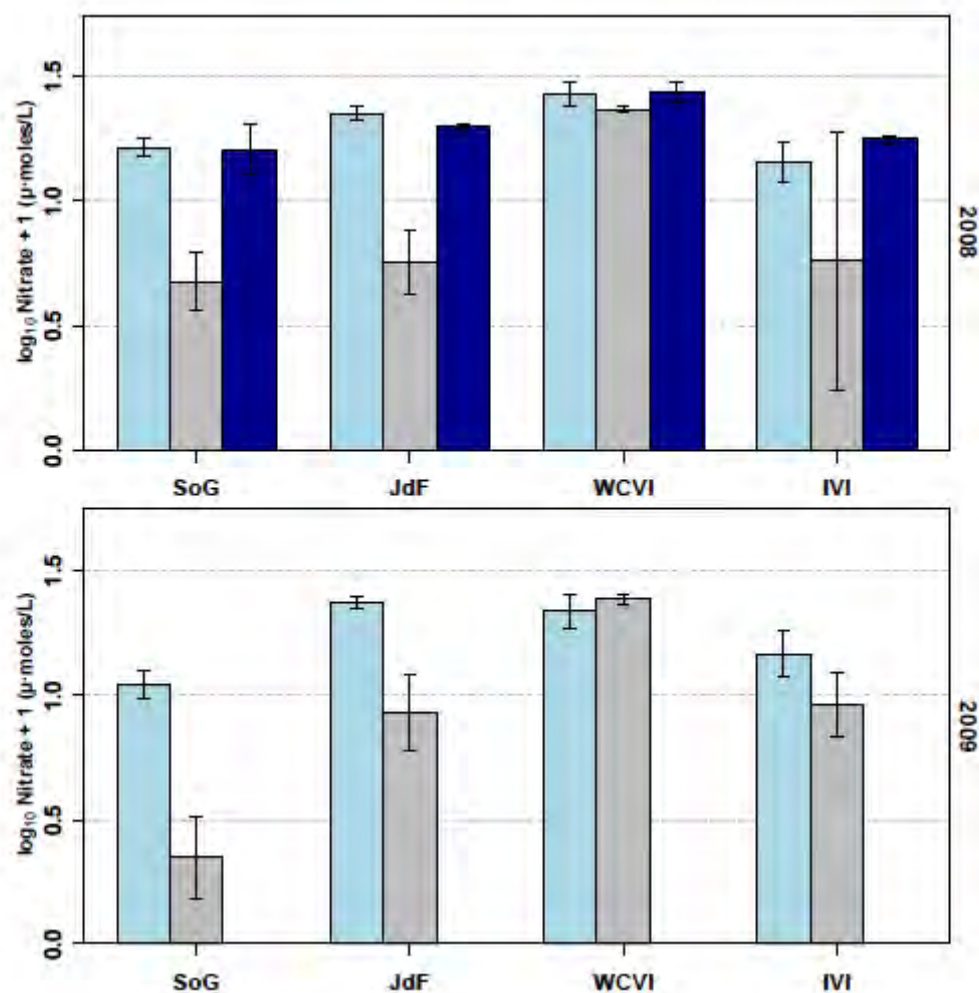


Figure 5. Nitrate concentration ($\mu\text{-mol}\cdot\text{L}^{-1}$) in surface waters (10 m) of the Strait of Georgia (SoG), Juan de Fuca Strait (JdF), off the west coast of Vancouver Island (VI), and in inlets of Vancouver Island (IVI) during winter (pale blue bars), summer (grey bars) and fall (dark blue bars) of 2008 and 2009. The error bars are $2 \cdot \text{SE}$. Samples collected during the fall of 2009 had not been processed by the contractor at the time this report was produced.

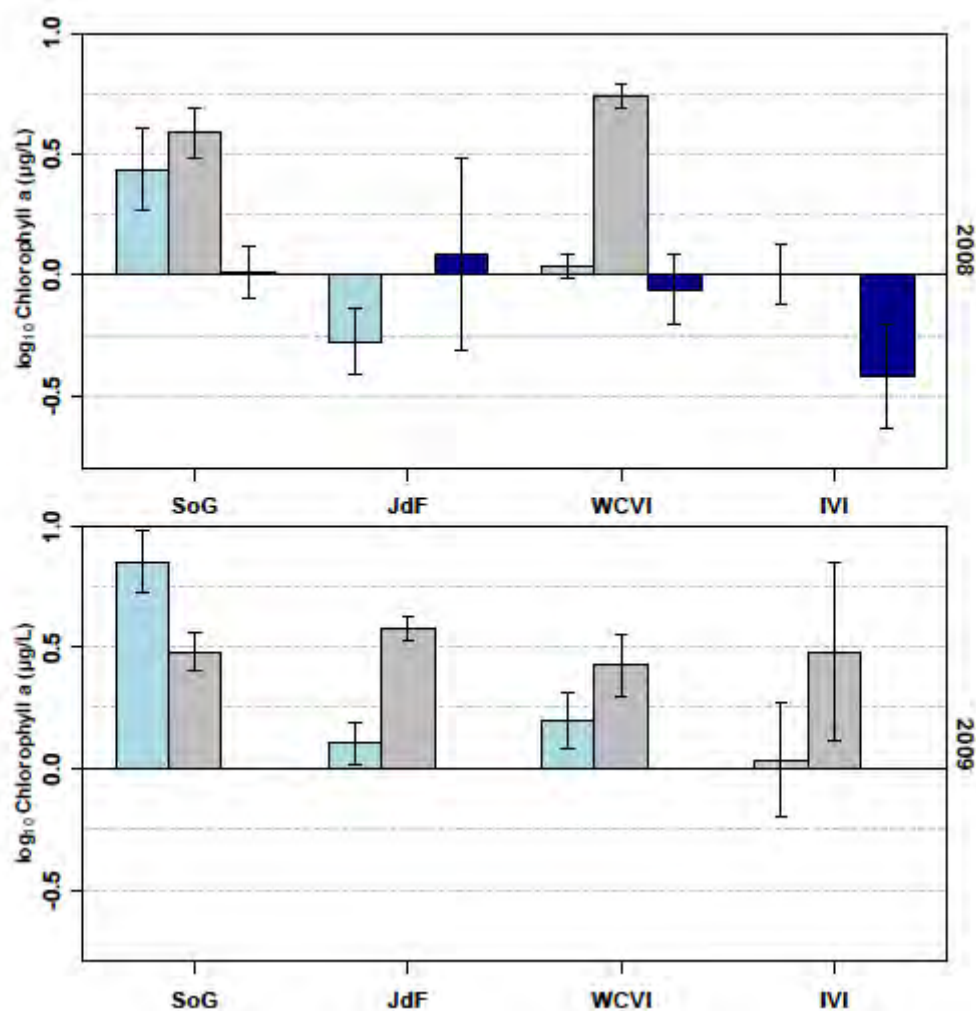


Figure 6. Chlorophyll a concentration (mg·L⁻¹) in surface waters (10 m) of the Strait of Georgia (SoG), Juan de Fuca Strait (JdF), off the west coast of Vancouver Island (VI), and in inlets of Vancouver Island (IVI) during winter (pale blue bars), summer (grey bars) and fall (dark blue bars) of 2008 and 2009. The error bars are 2·SE. Samples collected during the fall of 2009 had not been processed by the contractor at the time this report was produced.

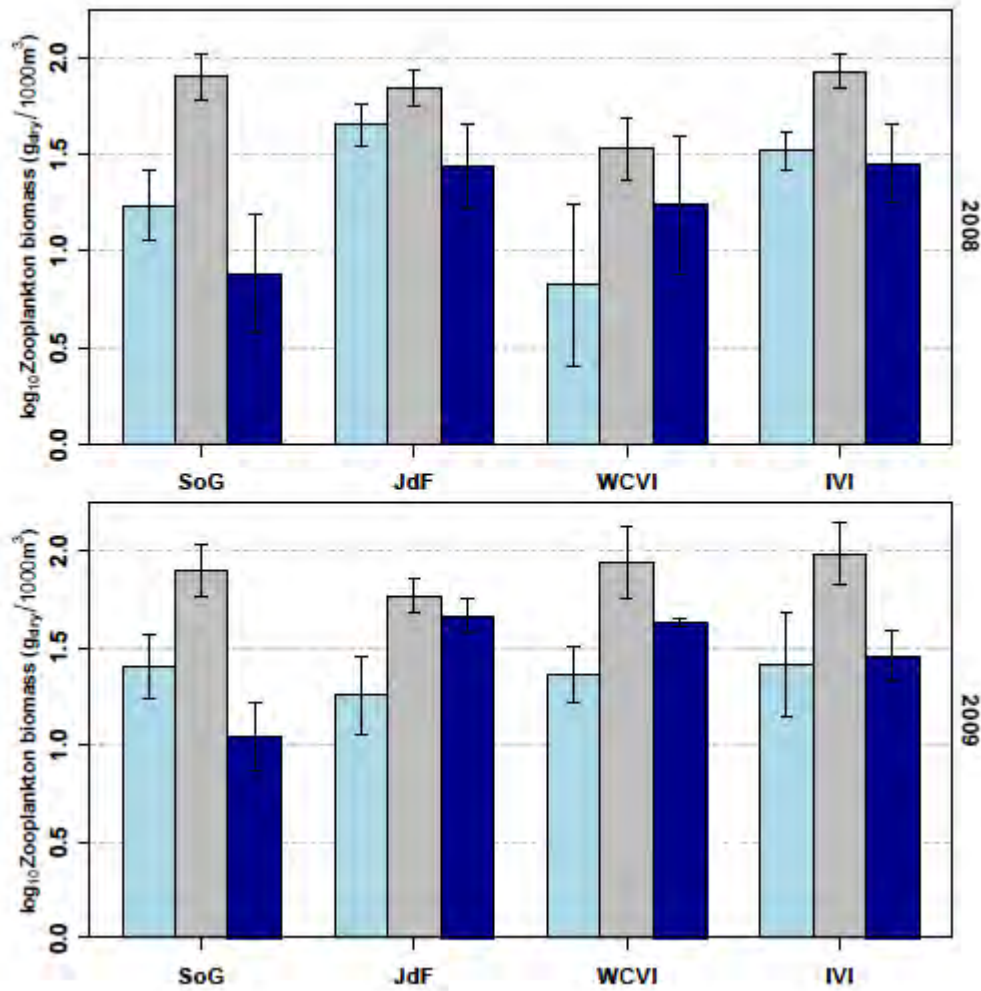


Figure 7. Zooplankton biomass ($\text{gdry} \cdot 1000\text{-}1\text{m}^3$) in surface waters (10 m) of the Strait of Georgia (SoG), Juan de Fuca Strait (JdF), off the west coast of Vancouver Island (VI), and in inlets of Vancouver Island (IVI) during winter (pale blue bars), summer (grey bars) and fall (dark blue bars) of 2008 and 2009. The error bars are 2-SE

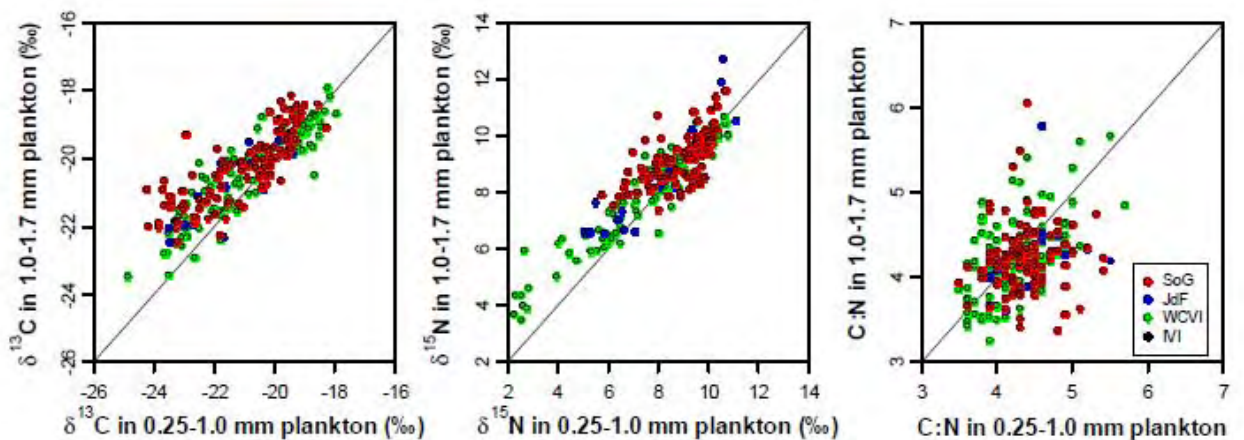
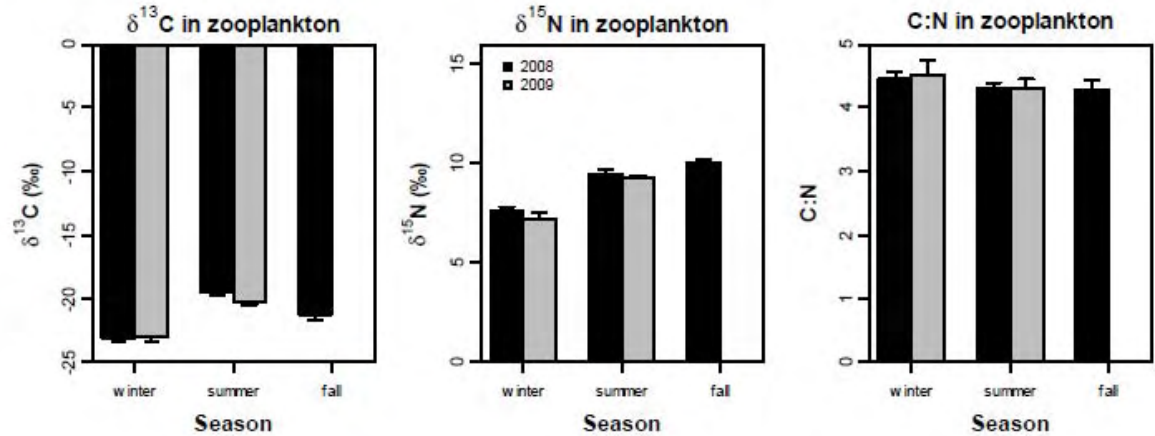


Figure 8. Relationship between the $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and C:N ratio in small-size zooplankton (0.25-1.0 mm) and medium size zooplankton (1.0-1.7 mm) in the Strait of Georgia (SoG), Juan deFuca Strait (JdF), off the west coast of Vancouver Island (WCVI), and in the inlets of the westcoast of Vancouver Island (IVI). The solid line represents the 1:1 line.

A) Zooplankton (0.25-1.0 mm)



B) Zooplankton (1.0-1.7 mm)

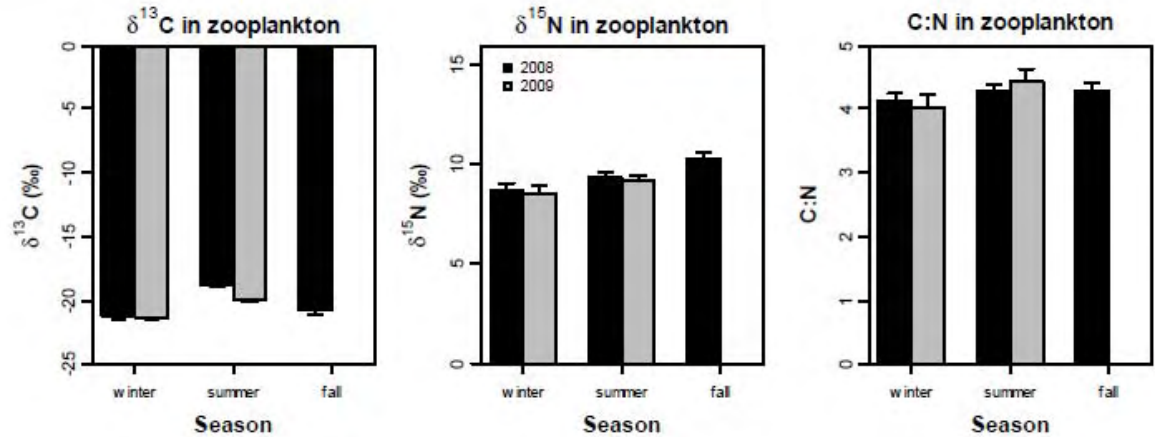


Figure 9. Stable isotopes ratios of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) and carbon to nitrogen ratio(C:N) in A) small size zooplankton (0.25-1.0 mm) and B) medium size zooplankton (1.0-1.7 mm) collected in the Strait of Georgia in 2008 (black bars) and 2009 (grey bars). The error bars are 2·SE.

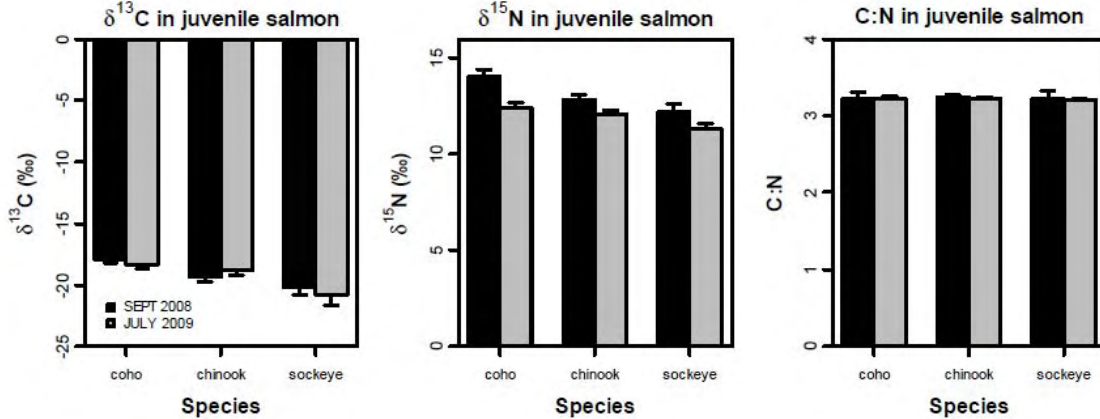


Figure 10. Stable isotopes ratios of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) and carbon to nitrogen ratio (C:N) in juvenile coho salmon, Chinook salmon, and sockeye salmon collected in the Strait of Georgia in September 2008 (black bars) and June-July 2009 (grey bars). The error bars are $2 \cdot \text{SE}$.

A10: TRENDS IN UPWELLING AND DOWNWELLING WINDS ALONG THE BRITISH COLUMBIA SHELF *Foreman*

Fifty-year time series of winds at six buoys near the British Columbia shelf break (Fig 1) have been examined for trends in the timing and cumulative intensity of upwelling- and downwelling-favourable winds. Cumulative upwelling intensities (CUIs) were computed by integrating daily offshore/onshore Ekman transports (Pickett and Schwing, 2006) and the spring and fall transitions were determined as the dates when the gradient of the CUIs changed sign from negative to positive (spring), and vice-versa (fall). At each buoy location, decadal means were computed by averaging the CUIs over ten consecutive years, and filtering with a fifteen-day running averages to remove any remaining high frequency variability. The total upwelling magnitude index (TUMI) was computed as the difference between CUI values at the end and start of the upwelling period while the total downwelling magnitude index (TDMI) was defined as the CUI value on December 31 minus the TUMI. (See Foreman *et al.* (2011) for more details.)

Unlike the similar analyses to the south (Bograd *et al.* 2009), the BC CUIs and upwelling season durations did not reveal consistent trends toward later spring transitions and shorter seasons (Foreman *et al.* 2011). While the buoys off southern Vancouver Island displayed progressively later onsets of upwelling over 1969-98, these trends reversed over 1999-2008. However at all buoys, trends were found in the TUMIs and TDMIs (Figure 2) indicating that although the season lengths were not changing appreciably, on average the alongshore winds have been intensifying. Upwelling favorable wind increases associated with the TUMI trends ranged between 0 and 21.2% at the six buoys, while analogous downwelling favorable wind increases ranged between 12.8% and 51.4%.

These intensifying TDMIs are consistent with trends in winter atmospheric pressure computed by Gillett *et al.* (2003) over the second half of the 20th century. Though a comparison with analogous summer trends (Gillett and Stott 2009) is less conclusive, Gillett *et al.* (2003) showed that anthropogenic greenhouse gases and sulphate aerosols

have had a detectable influence on atmospheric pressures over the same time period. Analyses of global and regional climate model forecasts that seek to determine if these trends persist in the future are continuing.

References

- Bograd, S.J., I. Schroeder, N. Sarkar, X. Qiu, W.J. Sydeman, and F.B. Schwing (2009), Phenology of coastal upwelling in the California Current, *Geophys. Res. Lett.*, 36, L01602, doi:10.1029/2008GL035933.
- Foreman, M.G.G., W.J. Merryfield, and B. Pal (2011), Trends in upwelling and downwelling winds off the British Columbia coast, soon to be submitted to Geophysical Research Letters.
- Gillett, N.P., F.W. Zwiers, A.J. Weaver, and P.A. Stott (2003), Detection of human influence on sea-level pressure, *Nature*, 422, 292-294.
- Gillett, N.P. and P.A. Stott (2009), Attribution of anthropogenic influence on seasonal sea level pressure, *Geophysical Research Letters*, 36, L23709, doi:10.1029/2009GL041269.
- Pickett, M.H., and F.B. Schwing (2006), Evaluating upwelling estimates off the west coasts of North and South America, *Fisheries Oceanography*, 15:3, 256-269.

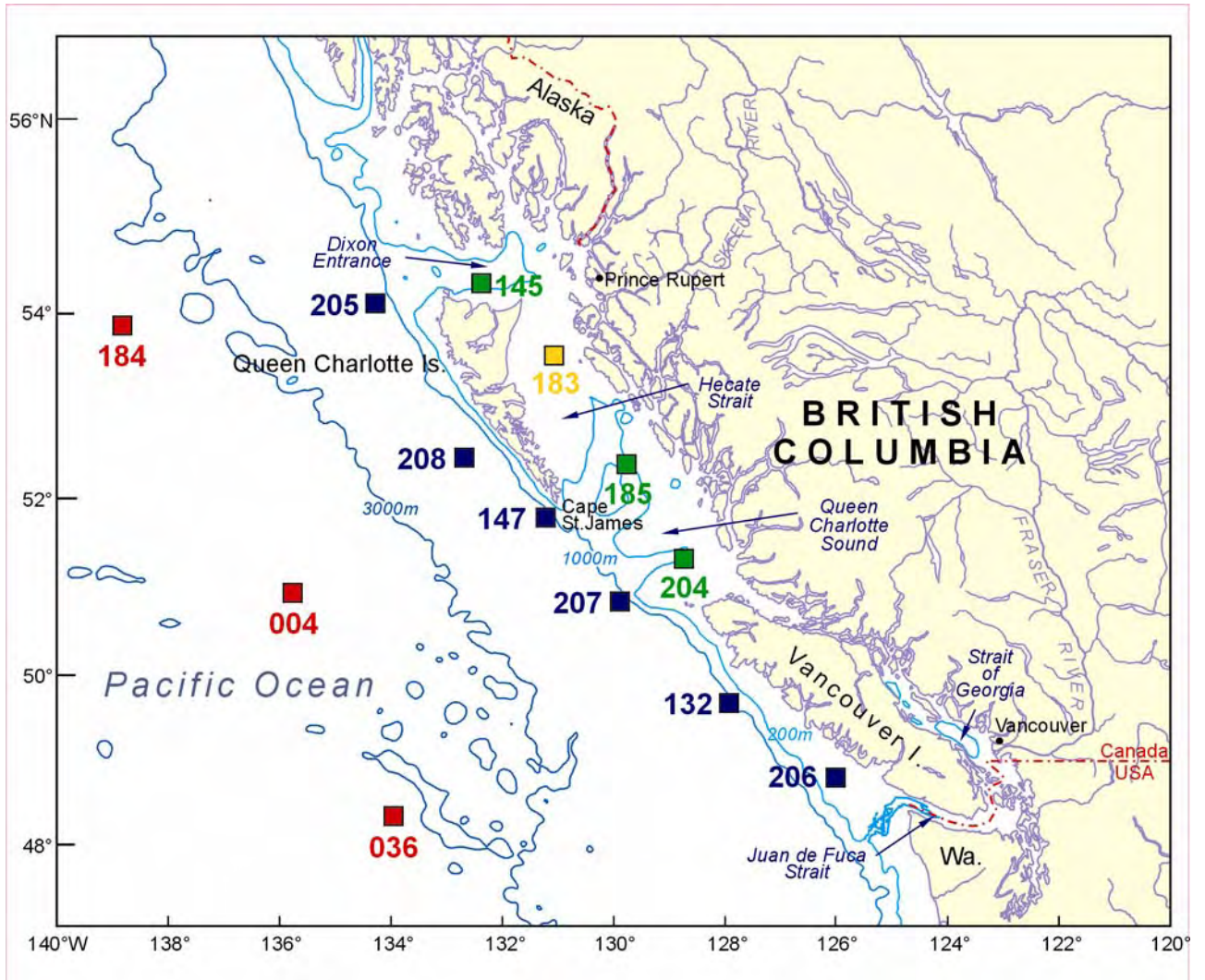


Figure 1. Weather buoys off the BC coast. Winds from only those shown in dark blue were included in this analysis. Depth contours are 200, 1000, and 3000m.

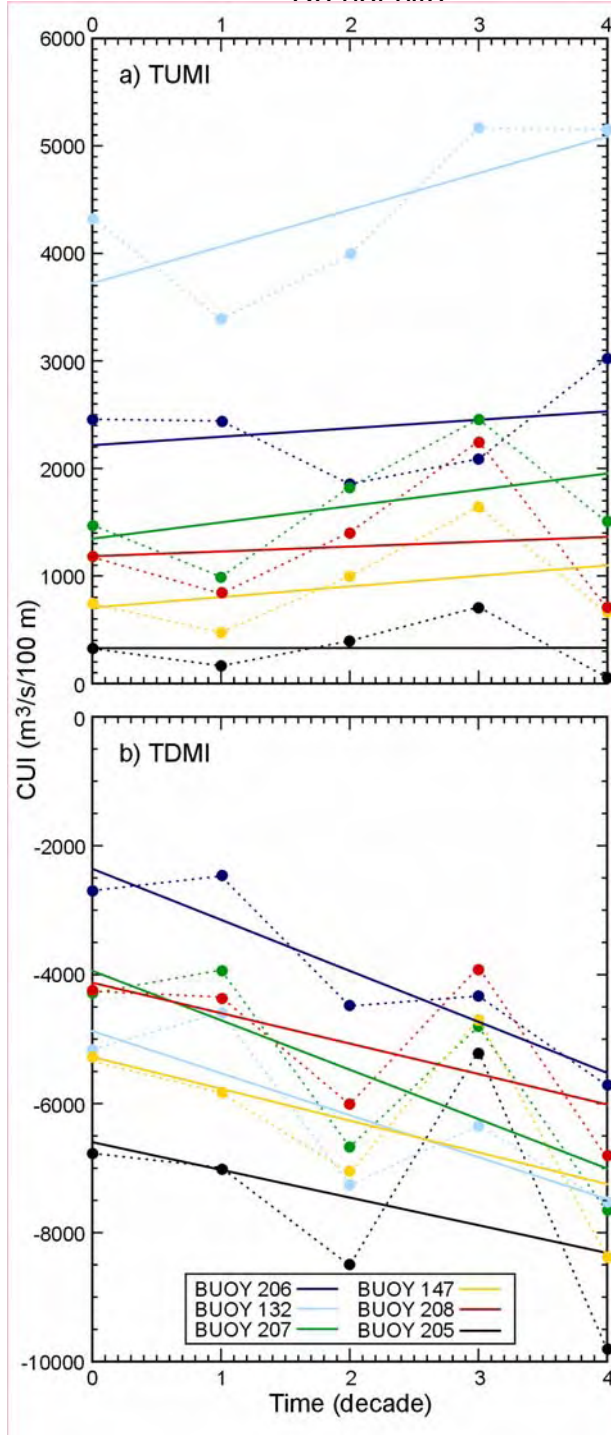


Figure 2. a) TUMI and b) TDMI values (dots) and linear trends at the six weather buoys. Decades 0-4 are 1959-1968, 1969-78, 1979-88, 1989-98, and 1999-2008, respectively

A11: INTERACTIONS BETWEEN THE STRAIT OF GEORGIA'S PREDOMINANT APEX PREDATOR (HARBOUR SEALS) AND THEIR PRINCIPLE PREY (HAKE AND HERRING): TOP-DOWN FORCING OR BOTTOM-UP LIMITATION

Peter Olesiuk and Jake Schweigert (with contributions from Jaclyn Cleary and Ron Tanasichuk)

The two main objectives of the study are:

- 1) Synthesize and model information on the abundance, population dynamics, bioenergetics and diet of harbour seals in the Strait of Georgia with information from hake and herring stock assessments to develop a better understanding of the interactions between these dominant apex predators and key prey species.
- 2) As a pre-requisite to the first objective, abundance surveys will be updated and telemetry instruments will be deployed on harbour seals to monitor their daily foraging and haulout patterns. Data from instrument deployments will be used to update activity levels in the bioenergetic model and to correct survey counts for animals that were at sea and missed during surveys (previous bioenergetic models and correction factors were developed when the seal population was still rapidly increasing, and may not be applicable to a population that has now stabilized).

In 2009-10 the project was allocated \$21K to continue deployment of telemetry instruments. Seven satellite-linked tags were deployed on seals at haulout sites in the central Strait of Georgia. Instruments performed as expected and collected detailed data over periods ranging from 100-144 (mean 123) days. All 7 tags were recovered after they were moulted by animals, and 2 new tags have been acquired, which we plan on redeploying in 2010. The behavioural data will be used to update bioenergetics models (based on activity budgets) and survey correction factors (based on the proportion of seals hauled out during surveys), both of which had been developed in the 1990s when the seal population was still increasing. Preliminary analysis of data from recent instrument deployments indicate that seals are now making more extensive movements and spending more time foraging than they were in the 1990s.

We also continued to explore the interactions between seals and their prey. Based on harbour seal population trends and bioenergetics models, it is estimated that seals in the Strait of Georgia currently consume about 8,100 tonnes of prey annually, compared with about 500 tonnes in 1970. Based on the proportion of herring in the diet (Olesiuk 1993) and herring stock assessment models (Schweigert et al. 2009; Cleary et al. 2010), it is estimated that seals consumed 1.3% to 19.3% of the herring spawning biomass annually (Figure 1). Predation levels increased during the 1970s, 1980s and early 1990s as seal populations grew, but predation levels also fluctuated due to changes in herring abundance levels. The lowest predation rates occurred in the early-1970s when seal abundance was low and herring were abundant. The highest predation levels have occurred in recent years when seal abundance has been high, and herring stocks were at low levels. There appears to be an inverse relation between herring survival rates and seal predation levels, especially for older age-classes of herring (Figure 2). This suggests that seals have a greater impact on older age-classes, presumably because they are targeting larger fish. Selective predation on larger fish may also be contributing to an observed decline in the mean weight at age of herring over time. The decline in weight-at-age of herring started in the early 1970s when seal populations

began to recover for their lowest levels, and the decline in size of herring are most pronounced in the older age-classes targeted by seals (Figure 3).

Stock assessment data for Pacific hake in the Strait of Georgia are less extensive. A series of hake biomass estimates are available for the 1980s and 1990s from acoustic surveys. Based on the proportion of hake in the diet (Olesiuk 1993) and the hake biomass surveys (Kieser et al. 1999), it is estimated that seals consumed 3% to 31% of the hake biomass annually. Predation levels appear to have increased sharply over this period due to the rapid growth of seal populations as well as a slight decline in hake biomass (Figure 4). There has also been a decline in the size-at-age of hake over time similar to that observed in herring (Figure 5), again suggesting that seals might be selectively targeting larger hake. Hake less than 40cm feed primarily on euphasids, whereas hake larger than 40cm include fish in their diet. As a result of the decline in size of Strait of Georgia hake, there has also been a shift in their diet from fish to euphasids (Figure 6). The reduced predation of hake on juvenile hake and herring appears to have resulted in improved recruitment levels to these stocks, which to some degree offsets the increased predation on larger hake and herring by seals. These interactions are being modelled to assess the extent to which seals have displaced hake as the main fish predator in the Strait of Georgia, and the consequences of reduced predation on smaller fish by hake and increased predation on larger fish by seals.

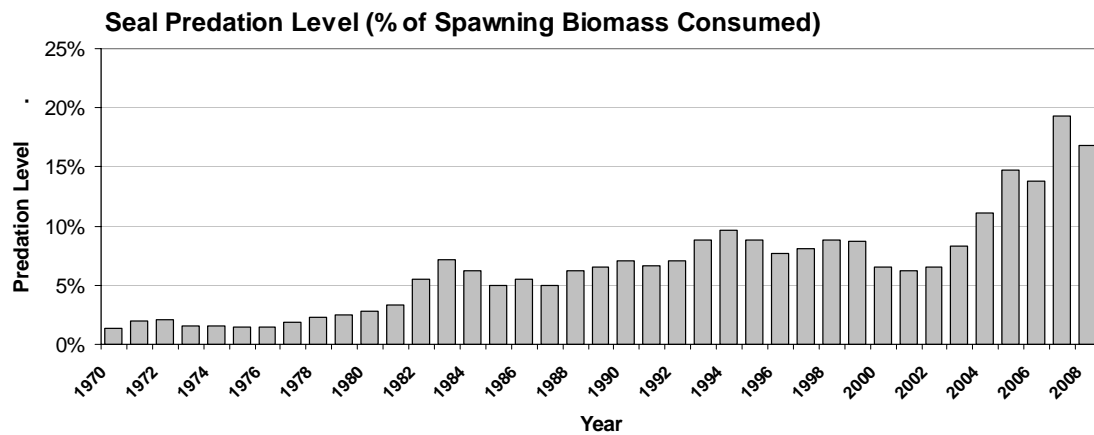


Figure 1. Seal predation levels on herring (% of the spawning biomass consumed annually) have ranged from 1.3 to 19.3% in the Strait of Georgia since 1970.

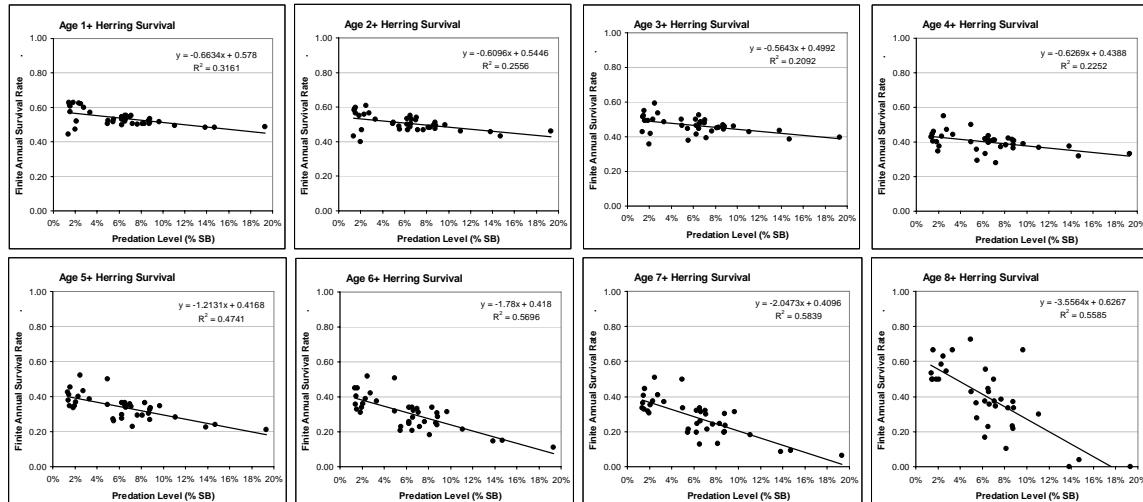


Figure 2. Annual survival rates of herring by age-class as a function of seal predation levels.

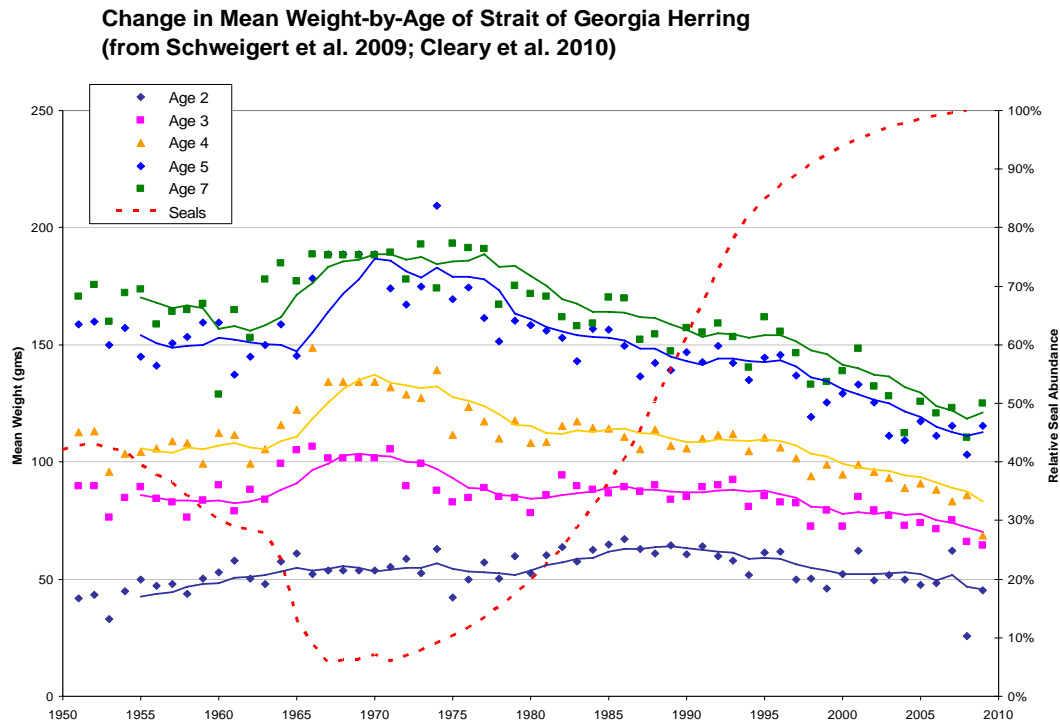


Figure 3. Declines in size-at-age of Strait of Georgia herring (solid lines) compared with temporal trends in abundance of harbour seals in B.C. (dashed red line).

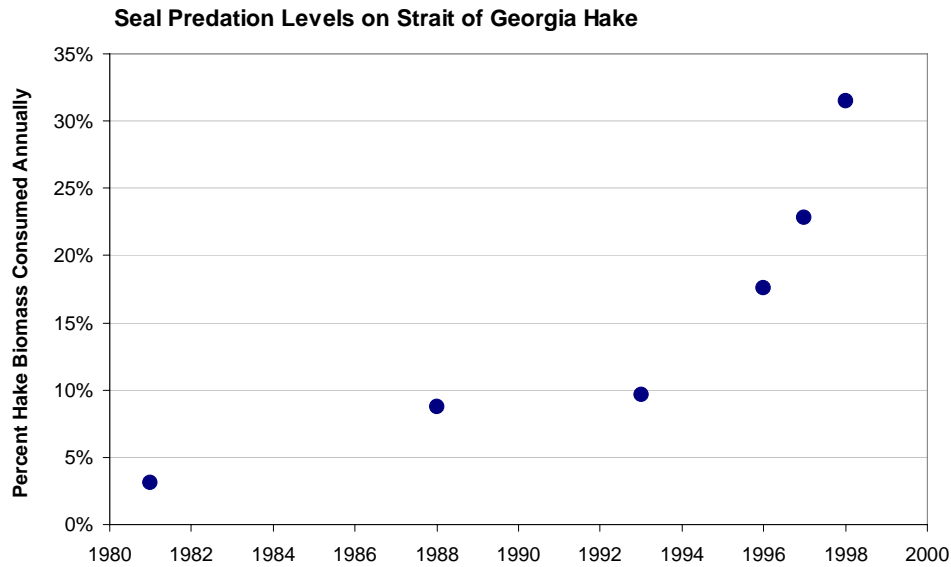


Figure 4. Seal predation levels on hake (% of biomass consumed annually) are estimated to have increased from roughly 3% to 33% the Strait of Georgia during the 1980s and 1990s.

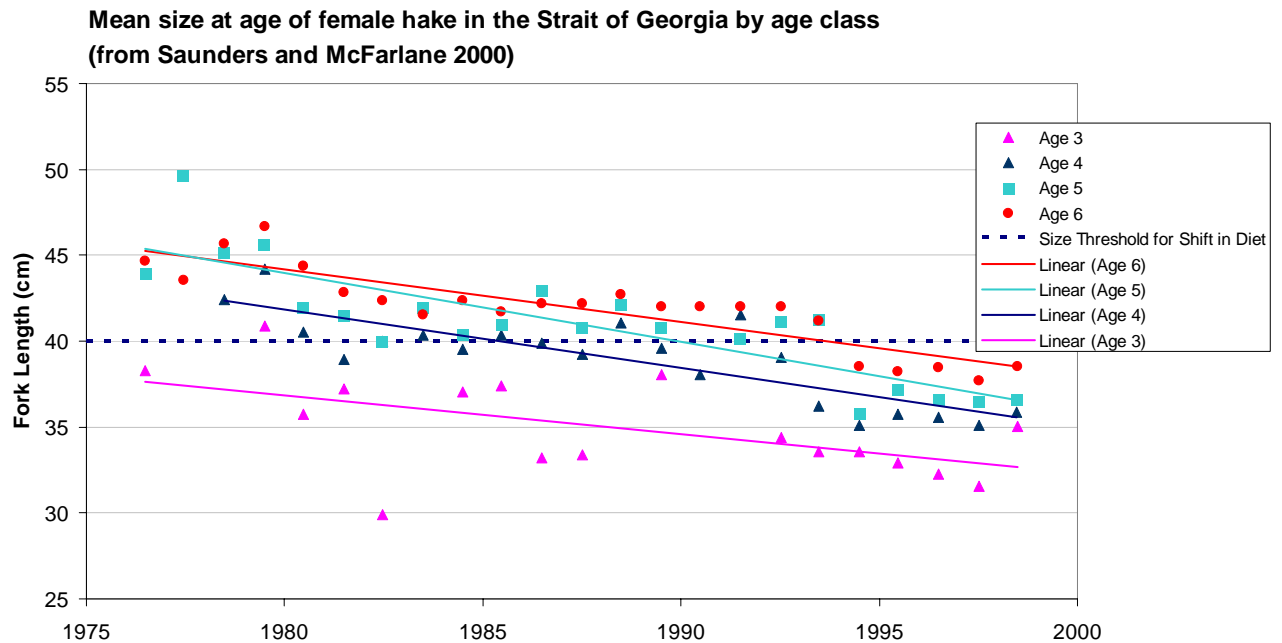


Figure 5. Decline in size-at-age of hake in the Strait of Georgia when seal populations were rapidly increasing during the 1980s and 1990s. Due to the decline in size over time, there have been a shift from hake being greater than 40 cm that tend to include fish in diet, to hake less than 40 cm that tend to feed exclusively on euphasids (dashed blue line).

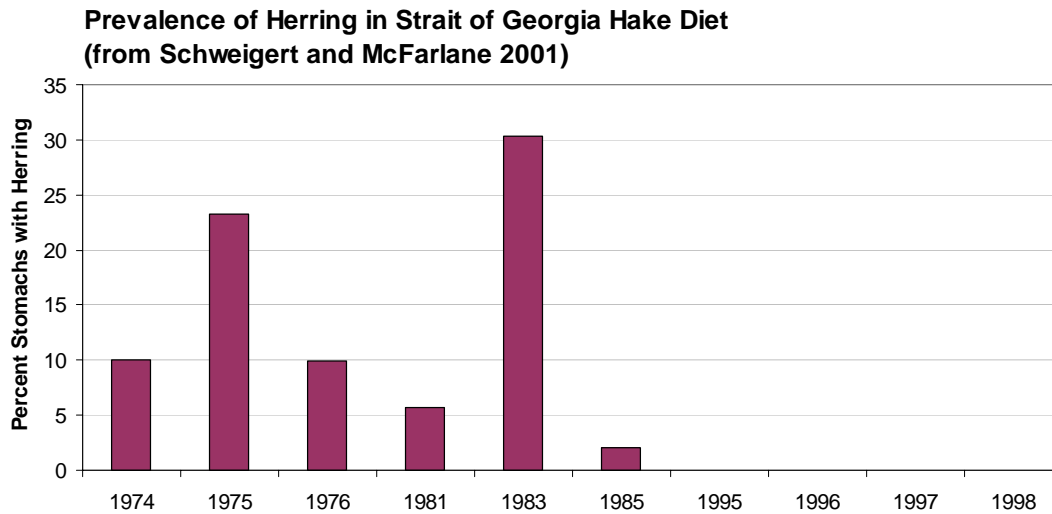


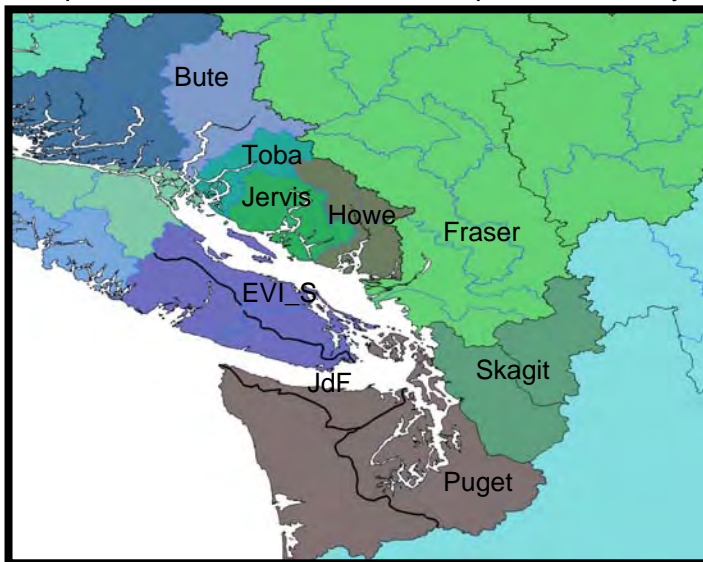
Figure 6. Change in prevalence of herring in the diet of hake in the Strait of Georgia (percent of stomachs containing herring). The absence of herring in the diet in the 1990s coincides with the decline in size of hake such that few attain the 40 cm in length at which point hake begin to prey on fish.

A12: RIVERINE FLOWS INTO THE SALISH SEA

John Morrison

Background

The Salish Sea drainage basin covers an area of approximately 300,000 km². Rivers flowing into the Salish Sea originate in a variety of climatic zones resulting in a variety of flow patterns. Rivers in coastal plains have hydrograph profiles that match the precipitation profiles with minimal flow in the summer and peak flows in late fall or early winter. Rivers originating in the coastal mountains follow the same pattern in the warm months but store precipitation as snow cover over the winter months. Coastal mountain rivers have peaks in both the early fall and early spring. However, the majority of the drainage basin (217,000 km²) is located above Hope on the Fraser River. This means that



precipitation profiles with minimal flow in the summer and peak flows in late fall or early winter. Rivers originating in the coastal mountains follow the same pattern in the warm months but store precipitation as snow cover over the winter months. Coastal mountain rivers have peaks in both the early fall and early spring. However, the majority of the drainage basin (217,000 km²) is located above Hope on the Fraser River. This means that

the fresh water inflows are dominated by climate zones that are remote from what is normally considered as the Georgia Basin. Here the flow pattern is dominated by winter storage with minimal impact from fall precipitation. Peak flow occurs in late May or early June.

Runoff estimation

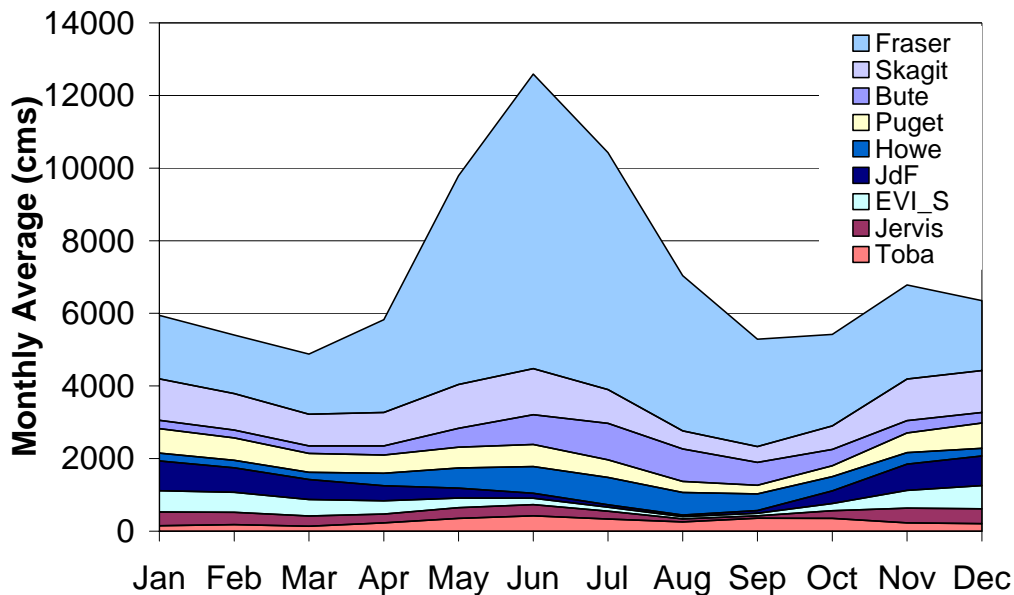
River flow is estimated gauging stations by measuring the river height and calculating the flow based on corresponding cross sectional areas and water velocities. Unfortunately there are large areas of the drainage basin that are ungauged. In order to calculate the total runoff for the basin it is necessary to provide estimates for the ungauged areas.

The classic water balance equation is $Runoff = Precipitation - Evaporation$ which can be rewritten as $1 = \frac{R}{P} + \frac{E}{P}$. With observations of runoff and precipitation we calculate the R/P ratio at the gauges. If we assume that in a local area that E and R/P are constant then we can use the R/P ratio to estimate runoff for the ungauged portion of the area.

$$R_u = Area_u \cdot P_u \cdot \frac{R}{P}$$

We define the local areas to be in the same Water Survey of Canada drainage basin. We further divide the drainage basins into “coastal” i.e. elevation less than 1000m and less than 100km from the coast. Areas above 1000m or more than 100km from the coast are considered to be “inland”. At present it is estimated that British Columbia glaciers are declining in volume by about 22 km³ per year (Schiefer et al 2007). Approximately 7 km³ of that loss will be flowing into the Strait of Georgia in the June through September time frame. The peak flow in July and August will reach the level of 870 cms which is roughly 10% of the flow for that period.

Monthly Runoff by Drainage Basin



The graph shows contribution of each drainage basin to the Salish Sea fresh water inflow. It is dominated by the Fraser River with its prominent spring freshet that is due to the melting on the snow accumulation from the provinces interior. Also apparent is the summer dry period depicted by the thinning of the bands representing Jervis, East Vancouver Island and Juan de Fuca. On the other hand the thickening of the bands for Bute and Howe in the June through September time period indicates that these watersheds are highly influenced by glacier runoff.

Schiefer E., B.Menounos, and R. Wheate (2007), *Geophys. Res. Lett.*, 34, L16503, doi:10.1029/2007GL030780

A13 KILLER WHALES IN THE STRAIT OF GEORGIA: DISTRIBUTION AND ABUNDANCE TRENDS IN THREE ECOTYPES OF APEX PREDATORS.

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The killer whale (*Orcinus orca*) is the world's apex marine predator. It has an extremely diverse diet over its cosmopolitan range, with more than 150 prey species documented, including marine mammals, seabirds, turtles, fishes, and invertebrates. Although as a species it can be considered a generalist predator, different populations of killer whales often have very distinct foraging specializations that appear to be culturally determined (Ford 2009). In cold temperate coastal waters of the northeastern Pacific, three genetically and socially distinct ecotypes of killer whales exist, the so-called 'resident', 'transient', and 'offshore' killer whales. Here, we summarize trends in the occurrence

and population dynamics of these three ecotypes in the Strait of Georgia with respect to the status of their primary prey species.

Resident killer whales

Resident killer whales are salmonid specialists, with a strong preference for Chinook salmon and, secondarily, chum salmon. Coho salmon are sometimes taken but smaller pink and sockeye salmon are not significant prey despite their seasonal abundance. Despite their name, resident killer whales are common only seasonally in the Strait of Georgia. A population of 87 whales (2009 census) known as the 'southern residents' are found in the Strait of Georgia region mostly during June through November. The occurrence of the three pods J, K and L, which comprise this population, coincides with the migratory timing and routes taken by Chinook salmon en route to the Fraser River, which is the source of most of the Chinook stocks taken by the whales in the area (Ford et al. 2009). The whales are most often found in Juan de Fuca Strait, Haro Strait and the various passes connecting these straits to the southern Strait of Georgia. In the past, J pod spent the majority of the year in the Strait of Georgia region, but in recent years it appears to have adopted the pattern typical of K and L pods and leaves the area for outer coastal waters during winter and spring.

Long-term field studies of resident killer whales using photo-identification of individuals have allowed precise annual monitoring of population trends and dynamics (see Figure 1). Analyses of annual indices of mortality in both northern and southern resident killer whales during 1979-2008 have revealed a strong correlation between survival and coast-wide Chinook salmon abundance (Ford et al. 2005, 2009). In particular, a prolonged decline in Chinook abundance during the late 1990s was associated with unprecedented mortality rates of resident killer whales, which led to a decline in both northern and southern populations. This decline ended after 2001, which coincided with an increase in coast-wide Chinook abundance, but the southern population has failed to maintain an increasing abundance trend as seen in the northern population. This difference may be related to the low abundance of Chinook salmon in the Strait of Georgia and other parts of the southern residents' range over the past decade.

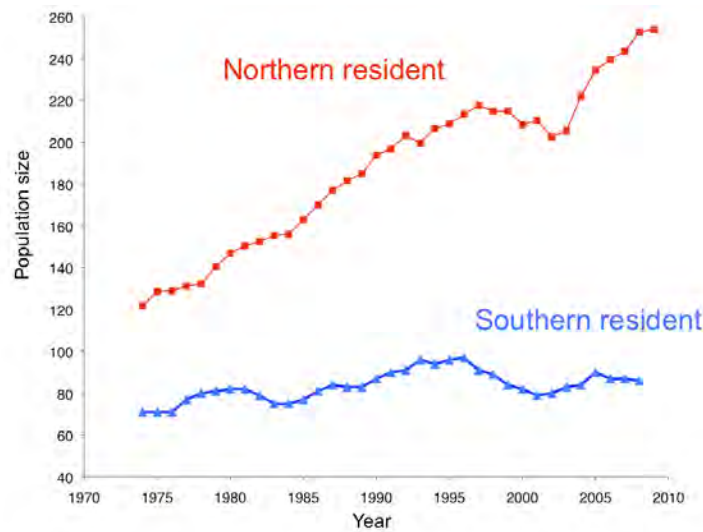


Figure 1. Abundance of northern and southern resident killer whales, 1974-2008 (from Ford et al. 2009).

Offshore killer whales

Offshore killer whales are a poorly known population of at least 300 whales that is found primarily in outer coast waters and ranges from southern California to the Aleutians. They were not observed in the Strait of Georgia until 1992 despite considerable killer whale survey effort in the area since 1973, and have only made occasional appearances in the Strait since then. It is not clear what prey resources have attracted offshore killer whales to the Strait of Georgia, but they appear to be fish feeders and may specialize on sharks (Ford and Ellis, unpubl. data).

Transient killer whales

Transient killer whales are mammal-hunting specialists that feed on pinnipeds and small cetacean species found in their coastal range. By far the most important prey species, however, is the harbour seal, which comprises over one-half of their kills (Ford et al. 1998). The abundance of harbour seals in the Strait of Georgia has fluctuated widely over the past century as a result of human harvests and culls (DFO 2009), and this likely had a major impact on the abundance and distribution of transient killer whales. These sources of mortality largely ended around 1970, and harbour seal abundance has increased dramatically since then. In the Strait of Georgia, harbour seals have increased 10-fold, from an estimated 3,900 in 1973 to 39,000 in 1994-2008 (Fig. 2A). To evaluate the potential effects of this change in primary prey base, we assessed trends in the population dynamics of transient killer whales over the same time period. For this analysis, we developed a Bayesian capture-recapture model using our long-term database of individual photo-identifications in order to estimate abundance and demographic parameters. This model showed that transient killer whale abundance throughout our coast-wide study area increased markedly over the time series, from a low of about 23 whales in 1975 to about 222 in 2006 (Fig. 2B). This trend closely matches the increase in harbour seal abundance in the Strait of Georgia, which can be considered an index of abundance for the BC coast generally. The increase in abundance of transients results from high survival and recruitment rates as well as immigration from outside the study area. Population growth appears to have slowed in

recent years due to a decrease in survival, suggesting density dependence as carrying capacity of the habitat is approached.

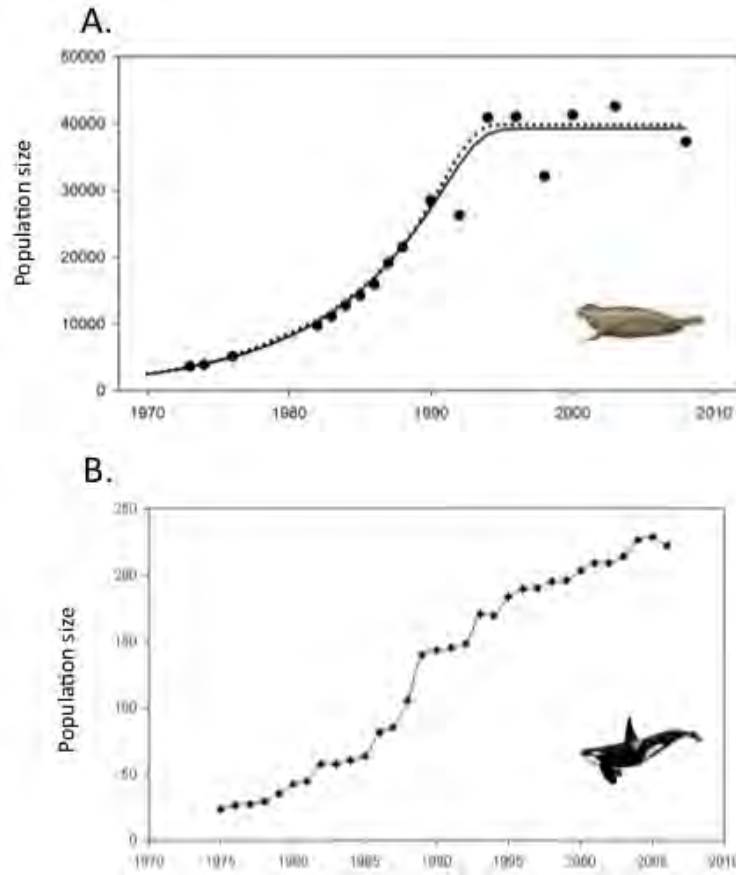


Figure 2. Estimated abundance of harbour seals in the Strait of Georgia (A) and killer whales *throughout their coastal range (B). (Harbour seal graph from DFO 2010)

Summary

Killer whales are a high profile, iconic species in the waters of the Strait of Georgia. The three ecotypes found in the area have distinct diets based on fixed behavioural traditions that are highly resistant to change. The occurrence and survival of each ecotype in the Strait is thus influenced by different ecological factors, and these should be taken into consideration in conservation and management decisions to promote recovery of these species at risk.

References

- DFO. 2010. Population Assessment Pacific Harbour Seal (*Phoca vitulina richardsi*). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2009/011.
- Ford, J.K.B. 2009. Killer whale *Orcinus orca*. In: Perrin, W.F., Wursig, B., and Thewissen, H.G.M. (eds.), The Encyclopedia of Marine Mammals Second Edition. Elsevier, New York, NY.

- Ford, J.K.B., Ellis, G.M., Barrett-Lennard, L., Morton, A, Palm, R., and Balcomb, K.C. 1998. Dietary specialization in two sympatric populations of killer whales (*Orcinus orca*) in coastal British Columbia and adjacent waters. *Canadian Journal of Zoology*, 76:1456-1471.
- Ford, J.K.B., Ellis, G.E., and Olesiuk, P.F. 2005. Linking prey and population dynamics: did food limitation cause recent declines of 'resident' killer whales (*Orcinus orca*) in British Columbia? Research Document 2005/042. Canadian Science Advisory Secretariat, Fisheries & Oceans Canada, Ottawa, ON.
- Ford, J.K.B., Wright, B.M., Ellis, G.M., and Candy, J.R. 2009. Chinook salmon predation by resident killer whales: seasonal and regional selectivity, stock identity of prey, and consumption rates. Canadian Science Advisory Secretariat, Res. Doc 2009/101. Fisheries and Oceans Canada, Ottawa, ON.

A14: ECOSYSTEM MODELING FOR THE STRAIT OF GEORGIA USING OSMOSE Fu

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What is the approach

In this ERI project led by Caihong Fu, an individual-based ecosystem model (OSMOSE: Object-oriented Simulator of Marine Ecosystems Exploitation, Shin and Cury 2001, 2004) has been applied to the Strait of Georgia (SoG) ecosystem and has been extensively upgraded to address various ecosystem research issues related to impacts of fishing and climate change, ecosystem indicators, and fisheries management. In OSMOSE, all fish within the same year class (or cohort) of a certain species are divided into a number of schools and these fish schools are treated as super-individuals. OSMOSE keeps track of the fate of all fish schools of each species through their life cycle and simulates species interactions through predation in a dynamic and spatially-explicit way. The biological processes simulated in OSMOSE include reproduction, growth, spatial movement (including migration), and death due to predation, starvation, and fishing, as well as death due to other uncounted causes represented by additional mortality. Predation in OSMOSE is a size-based opportunistic process so that trophic interactions are fundamentally dynamic with no pre-established links between species. This assumption may be unrealistic in some cases, e.g. when species do not co-exist in the water column, or when for any reason certain species are never encountered in predators' stomach contents. In order to allow deliberate selection/exclusion of certain food items, a simple binary diet preference matrix is imposed based on crude trophic knowledge, and which is still compatible with opportunistic predation. A fish school is subject to starvation mortality if the food ration is too low to provide the basic fish maintenance requirements. Fishing mortality is assumed to be knife-edged, i.e., all fish schools become vulnerable to fishing when they reach the age of recruitment to the fishery. The movement of fish schools within the modeled area as well as migration out of the modeled area is represented explicitly in OSMOSE. Spatial distribution of each

species at the initial time step is determined by distribution maps provided as input to the model. At each of the subsequent time steps, the spatial distribution is updated in a random fashion but within the grid cells defined by the distribution maps. If fish schools of a migratory species are out of the area at a certain time step, they are subject to average growth and natural mortality only. All processes are updated at each time step, which can be set as one year, half year, or a finer scale of every two weeks, depending on the purpose of the study.

OSMOSE species configuration for the Strait of Georgia ecosystem

The number of species that can be included in OSMOSE is conceptually unlimited. Each species follows its own dynamics and can be independent of each other species given its own food and lack of predation interactions with other modeled species. In the SoG OSMOSE model configuration, six currently or historically important commercial fish species are included: Pacific herring (*Clupea pallasii*), Pacific hake (*Merluccius productus*), walleye pollock (*Theragra chalcogramma*), spiny dogfish (*Squalus acanthias*), Pacific cod (*Gadus macrocephalus*), and lingcod (*Ophiodon elongates*), which comprised an average of 91% of total commercial catches since 1954. For simplicity, Pacific herring, Pacific hake, walleye pollock, and spiny dogfish will be called as herring, hake, pollock, and dogfish hereafter. In addition to the six commercial fish species, harbour seal (*Phoca vitulina*) is included in the model as a major predator. Harbour seal is the most important marine mammal species in the SoG, consuming an annual average of 27324 tons of prey since 1999, four times more than what California Sea lion (*Zalophus californianus*) and Steller sea lion (*Eumetopias jubatus*) consumed annually in the SoG (Peter Olesiuk, Pacific Biological Station, Nanaimo, 2009, pers. comm.). The diet of harbour seal is dominated by herring and hake, comprising 75% of its annual consumption (Olesiuk 1993). Spotted ratfish (*Hydrolagus collieri*), a non-commercial species, is included in the SoG model because of its high abundance, being 58 – 68% of total biomass obtained during bottom trawl surveys conducted in May and June 2001 in the southern SoG (Palsson et al. 2003). The SoG model also simulates the dynamics of euphausiids that serve as major food sources for herring (Stout et al. 2001), hake (McFarlane and Beamish 1985), pollock (Shaw and McFarlane 1986), and dogfish (Ware and McFarlane 1995). For benthos, the SoG OSMOSE model simulates the dynamics of Pandalid shrimp which serves as an important prey for lingcod (Cass et al. 1990), Pacific cod and pollock (Yang 1993). Except for euphausiids, Pandalid shrimp, dogfish, and harbour seal, all other species are divided into juvenile and mature categories based on pre-defined sizes (herring: 15 cm, hake and pollock: 30 cm, Pacific cod: 60 cm, lingcod: 65 cm, spotted ratfish: 30 cm) in order to construct the diet preference matrix. Pacific cod and lingcod juveniles are further separated into two groups because their young-of-the-year (< 25 cm) are in different locations from other age classes (e.g. in eel grass beds, Cass et al. 1990). The dividing size of dogfish is set at 60 cm corresponding to 15 years old to reflect the fact that spiny dogfish younger than 15 form pelagic groups (Beamish and Sweeting 2009).

Ecosystem research issues and brief results

1. Exploring climate and fishing impacts in an ecosystem framework

* Manuscript has been submitted for publication in November 2010)

Commercial fisheries directly affect the dynamics of targeted species, their predator and prey species, as well as all other species in the ecosystem that have indirect connections through the food web. Interannual and interdecadal climatic variations also

strongly affect the dynamics of each species as well as the structure and function of marine ecosystems (McGowan *et al.* 1998). Thus, it becomes imperative to develop tools to understand how harvested populations and entire ecosystems respond to climate variations (McGowan *et al.* 1998). In all, the combined effects of ecological processes through trophic interactions, environmental disturbances, and fishing need to be understood to help move toward ecosystem-based approaches to fisheries management. This understanding has been hampered by the lack of modeling tools that can include ecological considerations (Gamble and Link 2009). By developing models that take account of these ecological processes explicitly, we may be able to move progressively towards ecosystem-based fisheries management (Link 2002, Pikitch *et al.* 2004).

The objective of this study is to examine how climate change and fishing may affect species in this ecosystem that are connected through the food web. We use OSMOSE as our modeling platform, to simulate ecological interactions produced by fishing, climate change, and their interactions. We approximated the climate effect indirectly by imposing changes in phytoplankton or copepod biomass, because changes in phytoplankton abundance have been related to changes in water temperatures (e.g. in the NE Atlantic; Richardson and Schoeman 2004) and because phytoplankton biomass has been correlated with fish production along the B.C. coast (Ware and Thomson 2005; Perry and Schweigert 2008). We included copepods because they are directly consumed by many fish species. We modelled changes in phytoplankton or copepod biomass over time along with various fishing scenarios in order to understand the potential combined effects of ecological processes acting through trophic interactions, environmental disturbances, and fishing.

All simulations were run for 100 years with the last 30 years being used for manipulating scenarios of fishing mortality (F) and plankton biomass. Keeping phytoplankton and copepod biomass at the constant level of 2005 (Li *et al.* 2010), we simulated six contrasted fishing scenarios: $F = 0$ for herring and hake, and intensive removals of herring, hake, dogfish, and harbour seal. The annual F was arbitrarily set at 1.0 to achieve the fishing down effects. We also simulated temporal changes in phytoplankton and copepod biomass in a decadal fashion while assuming spatial homogeneity across all grid cells: phytoplankton “high-low-high” and copepod “high-low-high” scenarios. Under each plankton scenario, we tested concomitant fishing scenarios in which F is set at natural mortality (M) in addition to a scenario with the initial F levels (herring $F = 0.2$, and hake $F = 0.1$).

As an illustration, we give the results for the phytoplankton biomass “high-low-high” scenarios. With the changes in phytoplankton biomass, euphausiids responded quickly by either increasing or decreasing their biomass (Figure 1a). The changes in euphausiid biomass tended to have greater impact on pollock and hake than on herring likely because herring of age 2 and above spent half the year outside the SoG and thus consumed less euphausiids in the system than did hake and pollock. With the rise and fall of euphausiids, each species peaked and dipped at different times as a result of different longevity and predation pressures. Herring biomass peaked the earliest in the 9th year and decreased afterwards likely due to increased predation by its predators whose biomasses rose with the euphausiids. On the other hand, herring biomass started to increase at the end of the low euphausiid regime in the 18th year as herring predator biomass continued to decline. Dogfish, because of its long life-span, did not exhibit biomass oscillations like the relatively short-lived species. Fishing herring at $F = M = 0.435$ caused its population to decline even during the first decade of high euphausiid biomass and resulted in higher biomasses for hake and pollock (Figure 1b). Herring only

showed slight increases in biomass during the last decade with high euphausiid biomass. The reduction of herring biomass had negative impacts on Pacific cod, lingcod, and harbour seal populations (Figure 1b). With higher F on hake, pollock became more prevalent (Figure 1c). Hake was able to sustain a lower biomass level and recover during the last decade of high euphausiid biomass. When dogfish was fished at $F = M = 0.043$, its biomass steadily declined, which caused harbour seal (Figure 1d) and spotted ratfish (not shown) to increase. In addition, the biomasses of pollock, hake, Pacific cod and lingcod also increased.

We conclude from the simulations that research should consider the pathways through which environmental disturbances enter the ecosystem and interact with predator-prey dynamics and species life history in order to understand species' responses to environmental changes and management actions. As one example, in the simulations herring was more sensitive to changes in copepod biomass than changes in phytoplankton biomass, and intensive fishing on herring decreased the overall fish production from the ecosystem. This study demonstrates the importance of using a model such as OSMOSE to explore scenarios which combine species interactions, fisheries management, and climate change.

2. An ecosystem framework for incorporating climate regime shifts into fisheries management

* Manuscript is near ready for submission (January 15, 2010)

Ecosystem-based fisheries management (EBFM) attempts to account for ecosystem processes when formulating fisheries management advice (Sissenwine and Murawski 2004). Accounting for either fishing or climate variability (or both processes), in conjunction with species interactions, falls within the framework of EBFM (King and McFarlane 2006). Numerous studies have illustrated that climate-ocean regimes are associated with fluctuations in the abundance of fish populations and in the species composition (e.g., Mantua *et al.* 1997, McFarlane *et al.* 2000). However, few attempts have been made to incorporate the dynamics of regimes into fisheries management, particularly in an ecosystem context. Using a single-species age-structured model, King and McFarlane (2006) incorporated climate regime impacts, by varying productivity parameters in the Beverton-Holt spawner-recruitment relationship, into marine resource management using two theoretical fish populations of different life history strategies: short-lived and long-lived. They concluded that regime-specific harvest rates produced the best balance between benefits (high yield) and trade-offs (fishery closures). However, within an ecosystem, how a fish population responds to climate variability and fishing pressure can be more complicated than what King and McFarlane (2006) portrayed due to complex species interactions. This study was designed to demonstrate how species at different trophic levels and of different life history types respond to climate regimes and how well single- or multi-species fisheries at different fishing levels perform in terms of benefits (total yield over time), trade-offs (number of fishery closure years), and the magnitude of changes in biomass with climate regime shifts. In addition, simulation analyses are used to facilitate a performance evaluation of different ecological indicators under varying fishing strategies (targeting different species), fishing intensities (varying fishing levels), and climate regimes and help inform management decisions given changes in climate.

The SoG OSMOSE model was run 20 times for 200 years with only the last 60 years being used for manipulating climate regimes through plankton dynamics as well as fishing strategies. The 60-year period is divided into three equal-length climate regimes. During the first 20-year climate regime, phytoplankton and copepod biomass are kept at

the levels of 2005. During the second 20-year climate regime, these plankton biomasses are reduced to a quarter of the 2005 levels and during the last 20-year climate regime, plankton biomasses increase and remain at half of the 2005 levels. Six fisheries are simulated during the last 60 years including one single-species fishery (herring), three 2-species fishery (herring along with hake, pollock, and dogfish, respectively), one 3-species fishery (herring + hake + pollock), and one 4-species fishery (herring + hake + pollock + dogfish). For each fishery, five different fishing scenarios are simulated with fishing mortality (F) being set at 25% of its natural mortality ($0.25M$), 50% of its M ($0.5M$), M , regime-specific F ($F = M$ for years 1 – 20, $F = 0.25M$ for years 21 – 40, and $F = 0.5M$ for years 41 – 60), or regime-specific F with 3-year lag ($F = M$ for years 1 – 23, $F = 0.25M$ for years 24 – 43, and $F = 0.5M$ for years 44 – 60) to account for the fact that regime detection was always delayed. Altogether, 30 fishing scenarios are modeled. Each fishing scenario is subject to the harvest control rule that fishery is closed for this year and this species, if the species biomass (B) is below 25% of the original B (B_0).

Under no fishing throughout the 60 years, each species responds to the changes in plankton biomass differently due to different life history traits and different trophic interactions (Figure 2a). The short-lived euphausiid responds quickly to the decline of plankton biomass. However, with the decline of its predators, euphausiid biomass rebounds slightly during the low plankton regime. As plankton biomass increases during the 3rd regime, euphausiid remains at higher level around 0.5 of the original biomass. The biomass changes for herring follow similar pattern except that both decline and recovery following plankton dynamics lag behind euphausiid by seven years. The decline in hake biomass during the low plankton regime appears to be most dramatic. In contrast, the decline of pollock biomass is less dramatic. Harbour seal declined throughout the last two regimes due to declined food availability. However, dogfish increased slightly during the last four years of the 3rd regime. Lingcod recovers to about the original level during the last 12 years and Pacific cod experiences nearly linear increasing during the 3rd regime. Under the 4-species fishery (herring + hake + pollock + dogfish) at $F = M$, hake and pollock biomass remain at low levels around 20% of the original biomass (B_0) after the first six years (Figure 2b). Herring on the other hand increases to 65% of B_0 during the 1st regime even under high $F = M$. The decline of herring predators (hake and pollock) under $F = M$ caused herring to be more robust to fishing pressure. As plankton biomass reduces during 2nd regime, herring biomass bounces around 20% of B_0 under fishing pressure or fishery closure. As plankton biomass increases during the 3rd regime, herring biomass is able to increase and sustain around 25% of B_0 . Dogfish biomass decreases steadily during the first two regimes but biomass stabilizes during the last 12 years.

When herring alone is fished (scenarios 1 – 5), yield over the 60 years increases as F increases from $0.25M$, $0.5M$, to M ; however, the number of years when the fishery is closed due to low B ($B \leq 0.25B_0$) also increases (Figure 3). Applying regime-specific F reduces total yield compared to fishing at M level, but the number of fishery closure also reduces. Regime-specific F with 3-year lag slightly increases yield as well as the number of fishery closure years compared with the regime-specific F without time lag. Fishing herring along with hake (fishing scenarios 6 – 10) results in similar pattern in yield and number of fishery closure years. With hake being fished, herring yield increases yet the number of fishery closure years decreases for all fishing scenarios (6 – 10) in comparison with scenarios 1 – 5. Similar results occur when herring is fished along with pollock (scenarios 11 – 15) or with dogfish (scenarios 16 – 20). Compared with the 3-species fishery (herring + hake + pollock), the 4-species fishery (herring + hake + pollock + dogfish) results in higher yield but lower number of fishery closure years under

four fishing scenarios (scenarios 27 – 30 vs. scenarios 22 – 25). When $F = 0.25M$ (scenarios 21 and 26), the 4-species fishery does not to be advantageous. Compared with constant $F = 0.5M$, the regime-specific F results in higher yield but lower number of fishery closure years for fishing herring alone, fishing herring and dogfish, and the 4-species fishery.

The development and the monitoring of ecological indicators play a prominent role for supporting the implementation of ecosystem-based fisheries management by assessing ecosystem status and the effectiveness of management strategies (Shin *et al.* 2010). Our simulations of 30 fishing scenarios indicate that how ecological indicators vary depends not only on the fishing configuration (species targeted, fishing intensity) but also on the different environmental configuration (high, low and median plankton biomass in the system). Overall, the ecological indicators respond to the 30 different fishing scenarios in a most consistent and predictable manner during the 1st climate regime with lower F resulting in higher biomass (B), biomass and yield ratio (B/Y), “1- Y/B ”, the inverse of total biomass coefficient of variation ($1/CVB$), the inverse of CV of species biomass ($1/CVBs$), and the inverse of the summed CV of species biomass and yield ($1/CVBsY$) (Figure 4 and 5). These indicators measure the ability either to maintain ecosystem resource potential (B , B/Y , “1- Y/B ”) or to maintain ecosystem and fishery stability ($1/CVB$, $1/CVBs$, $1/CVBsY$). On the other hand, the indicators $1/CVB$, $1/CVBs$, and $1/CVBsY$ that have strikingly different patterns during the 3rd regime under the 3- or 4-species fishery (Figure 4), i.e., the higher F tends to have higher indicator values. During the 1st and 3rd climate regimes when fishery closure does not happen frequently, the indicators B , B/Y and “1- Y/B ” are grouped into one cluster while the indicators $1/CVB$, $1/CVBs$, and $1/CVBsY$ are grouped into another (Figure 6). However, these two clusters are closer during the 1st regime but farther apart during the 3rd regime indicating these two groups of indicators behave more similarly in relation to the different fishing scenarios during the 1st than during the 3rd regime. During the 2nd regime with extensive fishery closure, the indicator groupings observed during the other two regimes no longer hold true, i.e., indicators with the yield component such as $1/CVBsY$, B/Y , and “1- Y/B ” are no longer grouped together with those without the yield component such as B and $1/CVBs$.

In conclusion, comparing among the different ecological indicators across all fishing scenarios and climate regimes enables us to identify ecological indicators that help indicate fish community changes in response to fishing and climate regimes. We conclude that B , B/Y , and “1- Y/B ” are the most favorable ones with predictable properties that have most consistent patterns across the different fishing intensities and climate regimes. The fish community and fishery stability indicators ($1/CVB$, $1/CVBs$, and $1/CVBsY$) behave counter-intuitively during the 2nd and 3rd regimes for the 3- or 4-species fishery.

Future research proposals

Through modifying the OSMOSE model, we would like to undertake a number of potential research projects in the near future. Some major ones are listed below.

a. Exploring minimum ecologically viable populations in an ecosystem framework

A necessary first step in preserving any species is to identify a minimum viable population size that would allow the population to endure the calamities of various perturbations within a set time frame (Shaffer 1981). The intricate interdependencies of living organisms dictate that conservation efforts be focused on the community and ecosystem level (Shaffer 1981). Both theoretical and empirical studies have shown that

direct and indirect species interactions can lead to unexpected outcomes in the dynamics of populations and ecosystems (Enberg et al. 2006, Bruno and O'Connor 2005). However, identifying minimum viable populations through population viability analyses seldom addresses species interactivity from a community or ecosystem perspective (Sabo 2008). As such conservative recovery goals for single species populations are an inadequate regulatory context for strongly interacting species (Soulé et al. 2005) and lack biological realism at the community level (Sabo 2008). We therefore advocate OSMOSE to help answer questions posed by Soulé et al. (2005), such as: does the absence or decrease in abundance of species lead directly or indirectly to a reduction in local species diversity, a reduction of reproduction or recruitment of other species, a change in composition of ecosystems, a change in ecosystem productivity, in order to determine whether there are grounds to warrant the creation of appropriate management prescriptions and actions to guarantee its ecological effectiveness. In addition, simulations in OSMOSE will enable the exploration of minimum ecologically viable populations in an ecosystem context where each species is exposed to predation, competition, starvation, and environmental disturbances.

b. Linking oceanography to fish population dynamics

Ecopath with Ecosim (EwE) is a dynamic model representing a range of marine organisms across several trophic levels aggregated in boxes (Walters et al. 1997). EwE simulates the temporal dynamics of the biomass of ecosystem components linked through trophic interactions. Using EwE, Preikshot (2007) estimated phytoplankton biomass time series for the Strait of Georgia by fitting estimated fish species biomass to observed biomass time series. He found stronger association between phytoplankton biomass and oceanographic processes on a decadal scale than on an annual scale (Preikshot, 2007). However, because the early life history of fish species is not explicitly modelled in EwE, the delayed feedback loop from phytoplankton production to fish production may not be reflected. In this study, we will modify the current OSMOSE version to fit estimated fish species biomass to observed biomass time series by tuning phytoplankton biomass as what was done in Preikshot (2007). With fish life cycles being explicitly followed, OSMOSE is expected to reveal a more representative link between phytoplankton and larval fish survival and subsequently fish production. The OSMOSE model can be used in a predictive mode of future dynamic simulations to provide fishery managers with a framework within which to devise management strategies for single species as well as at ecosystem level under various climate scenarios.

c. Modelling bycatch impacts using an ecosystem model

It has been recognized that overfishing one species can have effects on the whole food web through direct and indirect species interactions (Goñi 1998). The direct impact of a fishery on bycatch species, particularly those of long-lived and at top trophic levels, can be more pronounced than that through food web effects. Reducing fishing impact by avoiding bycatch of non-targeted species is an important management measure for protecting biodiversity and maintaining ecosystem health. There have been empirical estimations of bycatch in the British Columbia shrimp fisheries (e.g., Olsen et al. 2000), but bycatch impact has not been modelled in an ecosystem context. Ignoring the bycatch impact in an ecosystem model can greatly underestimate fishing impact on non-target species. This study aims to 1) compare fishing impacts on all non-target species based on two ecosystem model configurations: OSMOSE without bycatch and OSMOSE with by-catch; 2) develop various fishing zones or alternatively develop MPAs that would mitigate bycatch of various species of concern. The effectiveness of different MPAs of different sizes and locations can also be evaluated through this modelling approach.

d. Linking dynamics of fish populations with plankton seasonal cycles

The fluctuations in annual fish recruitment are related to both the timing and intensity of spring blooms of phytoplankton (Platt *et al.* 2003, Winder and Cloern 2010) as well as species composition of phytoplankton and zooplankton. Using plankton output scenarios from an NPZD model forced by ROMS model, we would like to see how different seasonal cycles of plankton dynamics affect the dynamics of fish populations, which helps link oceanographic measurements with the dynamics and management of fish populations.

References

- Beamish, R.J and R.M. Sweeting. 2009. Spiny dogfish in the pelagic waters of the Strait of Georgia and Puget Sound. In: V. Gallucci, G.A. McFarlane and G.C. Bargmann (eds.), *Biology and Management of Dogfish Sharks*. American Fisheries Society, Bethesda, Maryland, pp. 101-119.
- Bruno, J. F. & O'Connor, M. I. 2005 Cascading effects of predator diversity and omnivory in a marine food web. *Ecol. Lett.* 8, 1048–1056. (doi:10.1111/j.1461-0248.2005.00808.x).
- Cass, A.J., R.J. Beamish, and G.A. McFarlane. 1990. Lingcod (*Ophiodon elongatus*). Canadian Special Publication of Fisheries and Aquatic Sciences 109, Fisheries and Oceans, Ottawa.
- Enberg, K., M.S. Fowler, and Ranta, E. 2006. The impacts of different management strategies and environmental forcing in ecological communities. *Proc. R. Soc. B.* 273:2491-2499. doi: 10.1098/rspb.2006.3611
- Gamble, R.J., and J.S. Link. 2009. Analyzing the tradeoffs among ecological and fishing effects on an example fish community: A multispecies (fisheries) production model. *Ecol. Modell.* 220:2570–2582.
- Goni, R., 1998. Ecosystem effects of marine fisheries: an overview. *Ocean & Coastal Management* 40, 37–64.
- King, J.R., and G.A. McFarlane. 2006. A framework for incorporating climate regime shifts into the management of marine resources. *Fisheries management and Ecology* 13: 93-102.
- Li, L., C. Ainsworth, and T. Pitcher. 2010. Presence of harbour seals (*Phoca vitulina*) may increase exploitable fish biomass in the Strait of Georgia. *Prog. Oceanogr.* doi:10.1016/j.pocean.2010.09.006
- Link, J.S. 2002. Ecological considerations in fisheries management: when does it matter? *Fisheries* 27 (4):10–17.
- Mantua, N.J., S.R. Hare, Y. Zhang, J.M. Wallace, and R.C. Francis. 1997. A pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society* 78:1069-1079.
- McFarlane, G.A., and R.J. Beamish. 1985. Biology and Fishery of Pacific hake (*Merluccius productus*) in the Strait of Georgia. *Mar. Fish. Rev.* 47(2):23-34.

- McFarlane, G.A., King, J.R., and Beamish, R. J. 2000. Have there been recent changes in climate? Ask the fish. *Progress in Oceanography* 47: 147 - 169.
- McGowan, J.A., D.R. Cayan, and L.M. Dorman. 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific. *Science* 281:210-217.
- Olesiuk, P.F. 1993. Annual prey consumption by harbor seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. *Fish. Bull.* 91:491-515.
- Olsen, N., J.A. Boutillier, and L. Conver. 2000. Estimated bycatch in the British Columbia shrimp trawl fishery. Canadian Stock Assessment Secretariat, Research Document 2000/168.
- Palsson, W.A., S. Hoffmann, P. Clarke, and J. Beam. 2003. Results from the 2001 transboundary Trawl survey of the southern Strait of Georgia, San Juan Archipelago and adjacent waters. Wash. Dept. Fish and Wildlife Report No. FPT 03-09. 109 pp.
- Perry, R.I., and J.F. Schweigert. 2008. Primary productivity and the carrying capacity for herring in NE Pacific marine ecosystems. *Progress in Oceanography* 77: 241-251.
- Pikitch, E.K., C. Santora, E.A. Babcock, A. Bakun, R. Bonfil, D.O. Conover, P. Dayton, P. Doukakis, D. Fluharty, B. Heneman, E.D. Houde, J. Link, P. Livingston, M. Mangel, M. McAllister, J. Pope, and K.J. Sainsbury. 2004. Ecosystem-based fishery management. *Science* 305:346–347.
- Platt, T., Fuentes-Yaco, C. & Frank, K. T. 2003 Spring algal bloom and larval fish survival. *Nature* 423, 398–399. (doi:10.1038/423398b).
- Preikshot, D.B. 2007. The influence of geographic scale, climate and trophic dynamics upon North Pacific oceanic ecosystem models. Ph. D. Thesis. The University of British Columbia, Vancouver.
- Richardson, A.J., and D.S. Schoeman. 2004. Climate impact on plankton ecosystems in the Northeast Atlantic. *Science* 305:1609-1612.
- Sabo, J. L. (2008). Population viability and species interactions: Life outside the single-species vacuum. *Biol.Conserv.*, 141, 276-286.
- Shaffer, M.L. 1981. Minimum population sizes for species conservation. *Bioscience* 31, 131–134.
- Shaw, W., and G.A. McFarlane. 1986. Biology, distribution and abundance of walleye pollock (*Theragra chalcogramma*) off the west coast of Canada. *Int. North Pac. Fish. Comm. Bull.* 45:262-283.
- Shin, Y.-J., and P. Cury. 2001. Exploring fish community dynamics through size-dependent trophic interactions using a spatialized individual-based model. *Aquat. Living Resour.* 14:65-80.

- Shin, Y.-J., and P. Cury. 2004. Using an individual-based model of fish assemblages to study the response of size spectra to changes in fishing. *Can. J. Fish. Aquat. Sci.* 61:414-431.
- Shin, Y.-J., Shannon, L. J., Bundy, A., Coll, M., Aydin, K., Bez, N., Blanchard, J. L., Borges, M. F., Diallo, I., Diaz, E., Heymans, J. J., Hill, L., Johannesen, E., Jouffre, D., Kifani, S., Labrosse, P., Link, J. S., Mackinson, S., Masski, H., Möllmann, C., Neira, S., Ojaveer, H., Ould Mohammed Abdallahi, K., Perry, I., Thiao, D., Yemane, D., and Cury, P. M. 2010. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2. Setting the scene. *ICES Journal of Marine Science*, 67: 692–716.
- Sissenwine, M. and S. Murawski. 2004. Moving beyond 'intelligent tinkering': advancing an Ecosystem Approach to Fisheries. In: perspectives on Ecosystem-based Approaches to the management of Marine Resources. *Marine Ecology Progress Series* 274: 269-303.
- Soulé, M.E., J.A. Estes, B. Miller, and D.L. Honnold. 2005. Strongly Interacting Species: Conservation Policy, Management, and Ethics. *BioScience* 55 (2): 168-176.
- Stout, H.A., R.G. Gustafson, W.H. Lenarz, B.B. McCain, D.M. VanDoornik, T.L. Builder, and R.D. Methot. 2001. Status review of Pacific herring in Puget Sound, Washington. NOAA Tech. Memo. NMFS-NWFSC- 45. 175 pp.
- Walters, C., Christensen, V., Pauly, D., 1997. Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. *Reviews in Fish Biology and Fisheries* 7, 139–172.
- Ware, D.M., and G.A. McFarlane. 1995. Climate-induced changes in Pacific hake (*Merluccius productus*) abundance and pelagic community interactions in the Vancouver Island upwelling system. In: R.J. Beamish [ed.] *Climate change and northern fish populations*. Canadian Special Publication of Fisheries and Aquatic Sciences 121, Fisheries and Oceans, Ottawa, pp. 509-521.
- Ware, D.M., and R.E. Thomson. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Science* 308:1280-1284.
- Winder, M., and Cloern, J.E. 2010. The annual cycles of phytoplankton biomass. *Phil. Trans. R. Soc. B.* 365: 3215–3226. doi:10.1098/rstb.2010.0125
- Yang, M-S. 1993. Food habits of the commercially important groundfishes in the Gulf of Alaska in 1990. NOAA Tech. Memo. NMFS-AFSC-22. 150 pp.

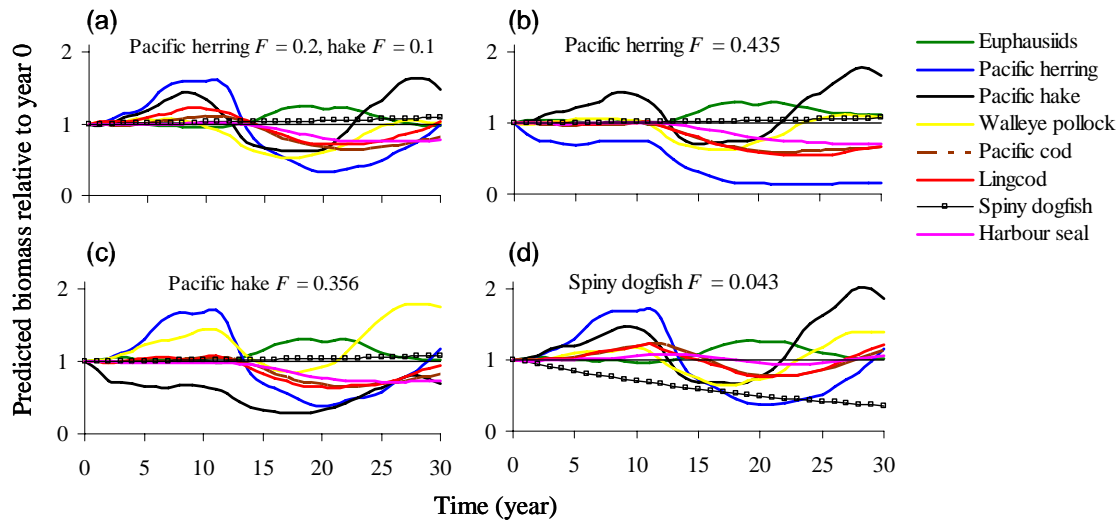


Figure 1. Predicted biomass of main species under decadal changes in phytoplankton biomass (high-low-high) relative to year 0 prior to the 30-year period (a) at equilibrium condition of 2005, (b) increasing Pacific herring fishing mortality F to 0.435, (c) increasing Pacific hake F to 0.356, and (d) fishing spiny dogfish at $F = 0.043$.

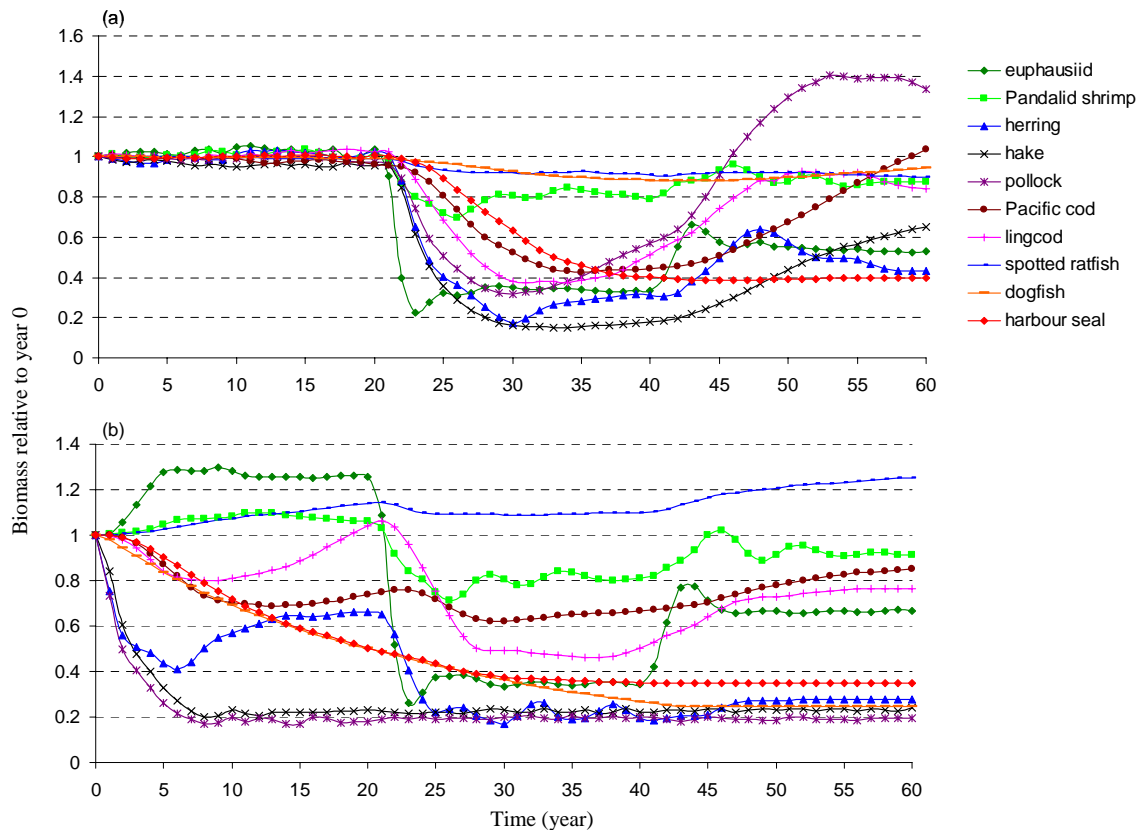


Figure 2. Biomass relative to year 0 under (a) no fishing on any species, (b) fishing herring, hake, pollock, and dogfish at natural mortality levels

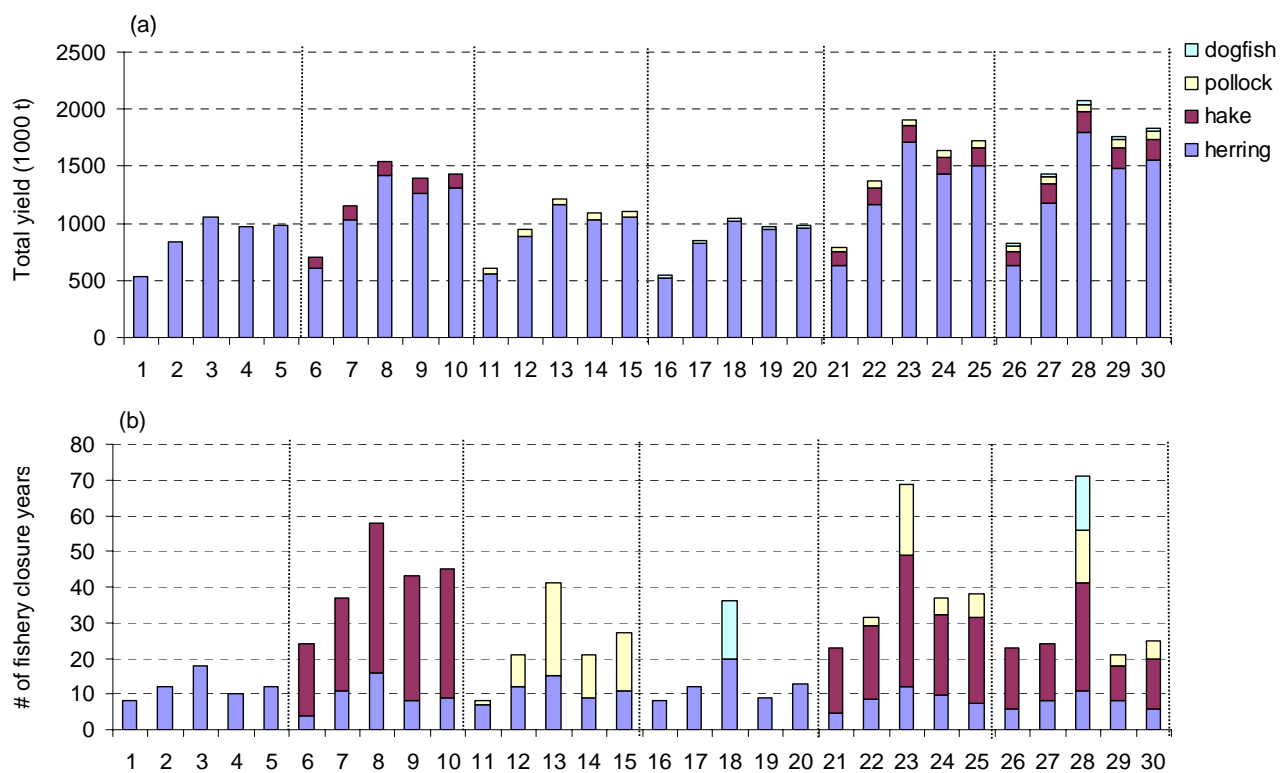


Figure 3. Total yield (a) and number of years with fishery closure (b) under 30 different fishing scenarios

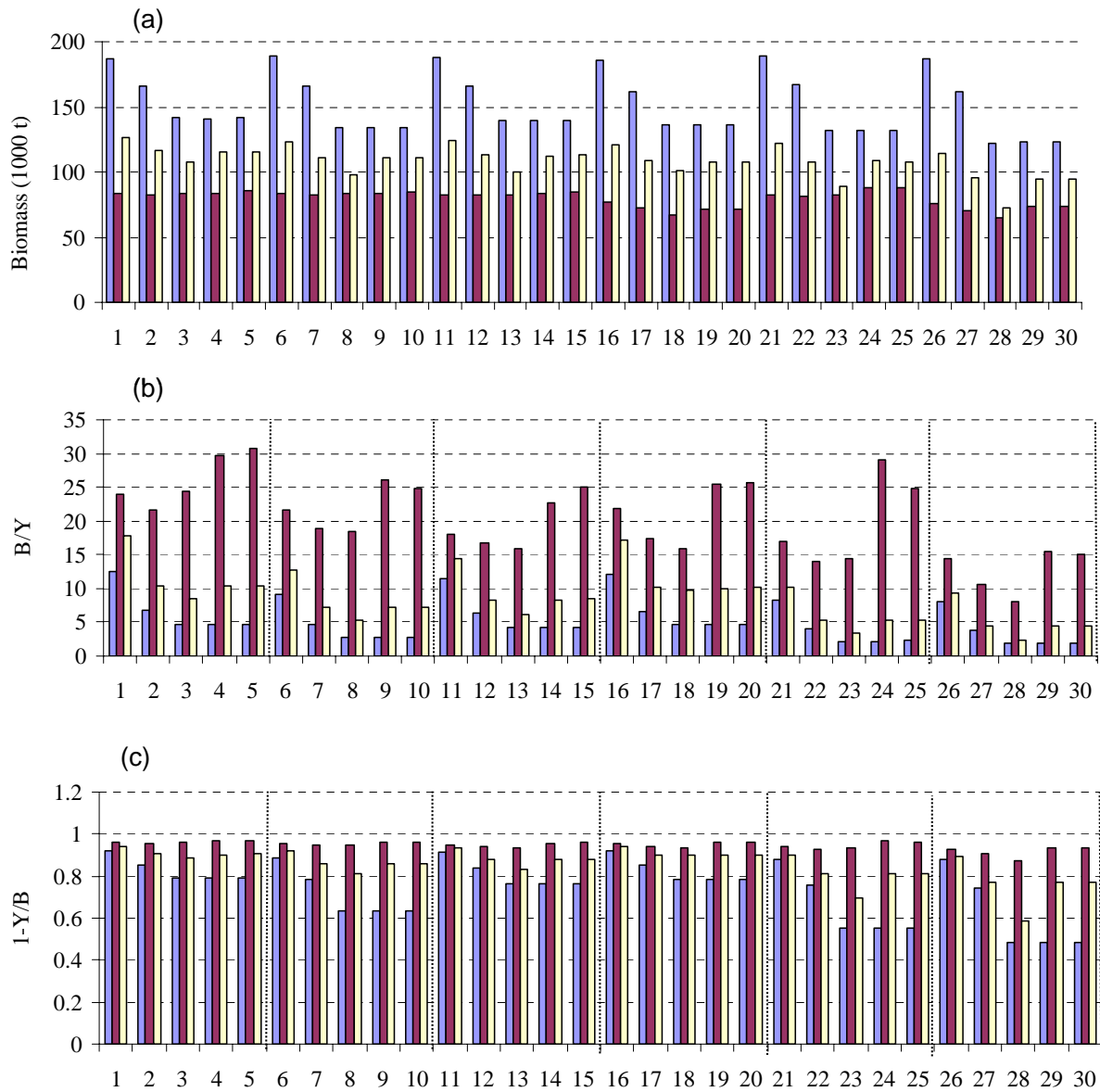


Figure 4. Ecological indicators under 30 fishing scenarios that are averaged over the latter 10 years of each 20-year climate regime: (a) total biomass (B), (b) total biomass and yield ratio (B/Y), and (c) 1-yield/biomass ($1-Y/B$).

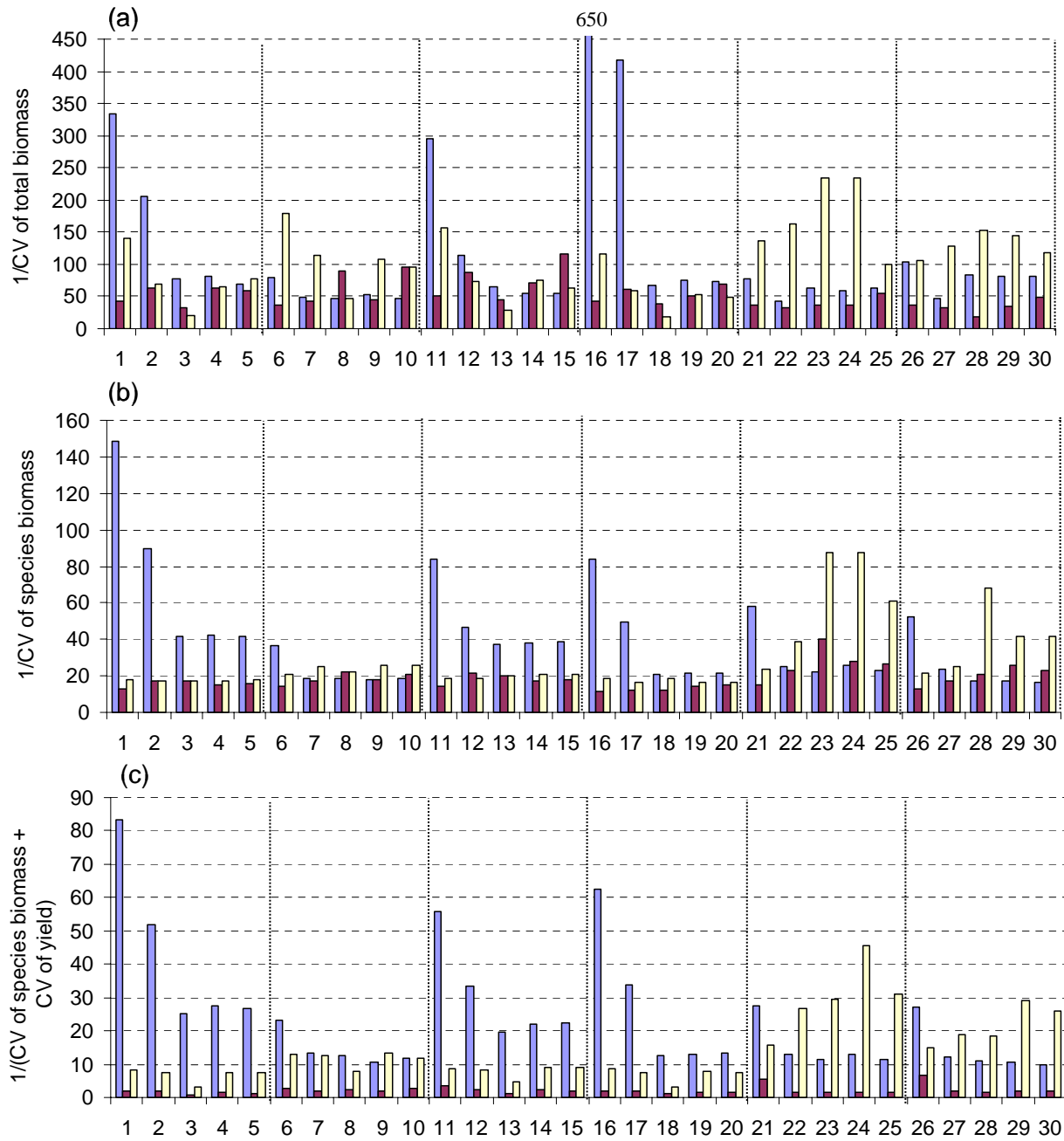


Figure 5. Ecological indicators under 30 fishing scenarios: (a) 1/CV of total biomass (1/CVB), (b) 1/CV of species biomass (1/CVBs), and (c) 1 over the sum of CV of species biomass and CV of yield (1/CVBsY).

A15: GIS SUPPORT FOR SOG ERI – DIGITAL BATHYMETRY & BENTHIC VIDEO

Bodo de Lange Boom & James Galloway, CHS Pacific, IOS

Objectives:

The objectives this year were scaled back to fit the available resources while still enhancing the previous work. The resulting objectives were to extend the existing GIS layers developed in previous years:

- to include new 2010 high resolution bathymetry,
- expand the coverage area with digital field sheet data, and
- digitising field sheets where no digital data exist.

No benthic composition data was acquired this year aside from raw benthic backscatter data:

This work would continue support of models of the physical oceanography of the Strait of Georgia, benthic morphology and to be fully expandable as new data were acquired. The data products would become an expanded foundation for SoG ERI that would enable modeling procedures, the generation of input data, easy visualization and analysis of model results, and decision making.

Approach

The bathymetry portion of the project used the same methodology as previously (see previous project reports). To accomplish our project goals, we used Co-Op Program and casual workers to assemble the bathymetry data, contracted digitising of fieldsheets (FS) to fill data gaps and co-ordinated the work with other CHS projects, in order to achieve synergy. All work was done with commercial off-the-shelf software tools used in regular CHS data acquisition, processing and data management tasks.

Progress**Digital Bathymetry**

High resolution (10 m grid) bathymetry tiles have been added or updated for the greater part of the SoG from Juan de Fuca Strait and the southern Gulf Islands to the Bute and Toba inlets area. Eight existing tiles were updated and one new tile was created with 2010 data. Low resolution bathymetry and bottom type data sets have also been enhanced through the digitizing of three FS in the Okisollo Channel – Bute Inlet area.

Strait of Georgia Seabed Video Database

The CHS bottom grab video database was previously compiled and converted into a standard format conforming to the VideoBank archiving project underway in Maritimes (Pierre Clement). No further video data were acquired this year.

Video clips are currently stored in the CHS Data Warehouse (contact Terry Curran for access) and the metadata were uploaded to GeoPortal to facilitate geographic or other searches.

Bathymetry Changes

Bathymetry changes are happening in the SoG – both natural and man made changes. Natural bathymetry change drivers include isostatic rebound and crustal deformation, subsidence, deposition and slumping, earthquakes, tsunamis, landslides (terrestrial and marine), sea level changes (thermal, salinity, wind regime, El Nino/La Nina). Examples of man-made bathymetry change drivers are dredging, in-filling and dumping, landslides

(terrestrial and marine), construction of structures (e.g. training walls => changing sedimentation/erosion), climate change => sea level change (various drivers).

These changes occur at various time and spatial scales but for most of the area, the changes are generally undetectable within the time frame of the measurements. An exception is sea level change, which in the SoG area is an increase of the order of +10 cm/century. However, the next Cascadia Subduction Zone earthquake will drop the land in the SoG area by an amount that is likely to be < 1 m.

There are localised, very dynamic areas such as the Fraser River and Squamish River deltas (Fig. 1), observed from the results of repeated MB surveys over several years. The morphology of the heads of Bute and Toba Inlets (and to a lesser extent Jervis Inlet) suggests that these are also active areas. In addition to the more gradual deposition of sediments, rapid catastrophic slope failures have been observed resulting in bathymetry changes of about -20 m and +10 m (Fig. 2a, 2b). Active processes are also maintaining the pock marks in English Bay and at other sites.

Accomplishments

- The high resolution bathymetry tiles for the SoG coverage were updated to include 2010 data.
- Low resolution bathymetry is also extended to fill gaps in high resolution data.
- Three FS were digitized to fill data gaps in the Okisollo Channel – Bute Inlet area.
- Metadata records for the benthic video clips were uploaded to GeoPortal.

Next Steps

With the termination of the ERI project, work will continue by building on the accomplishments to date as resources permit.

- Continue to enhance non-navigation, high resolution bathymetry data in SoG ERI area, as new data becomes available and extending coverage to rest of BC coast where MB coverage is available
- Enhance low resolution digital data sets (to fill gaps in MB coverage) by digitizing data sets
- Update and create other thematic data sets
- Enhance the gridded data product of the Chart Datum – Mean Sea Level separation surface
- Create a bathymetry data product for modellers by shifting bathymetric data from Chart Datum (LNT) to Geodetic Datum (MSL)
- Integrate the benthic video clips into VideoBank to permit nationwide DFO access on line.
- Classify backscatter data to expand the coverage of classified benthic substrate maps in the SoG area.

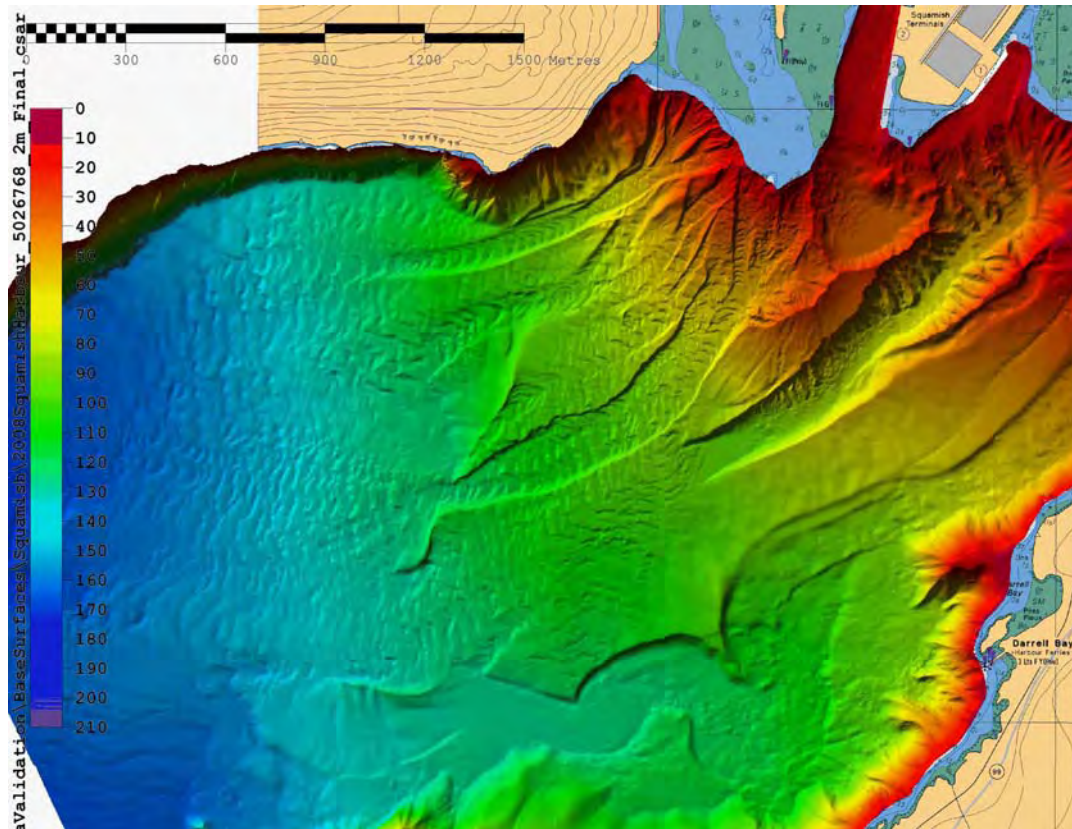
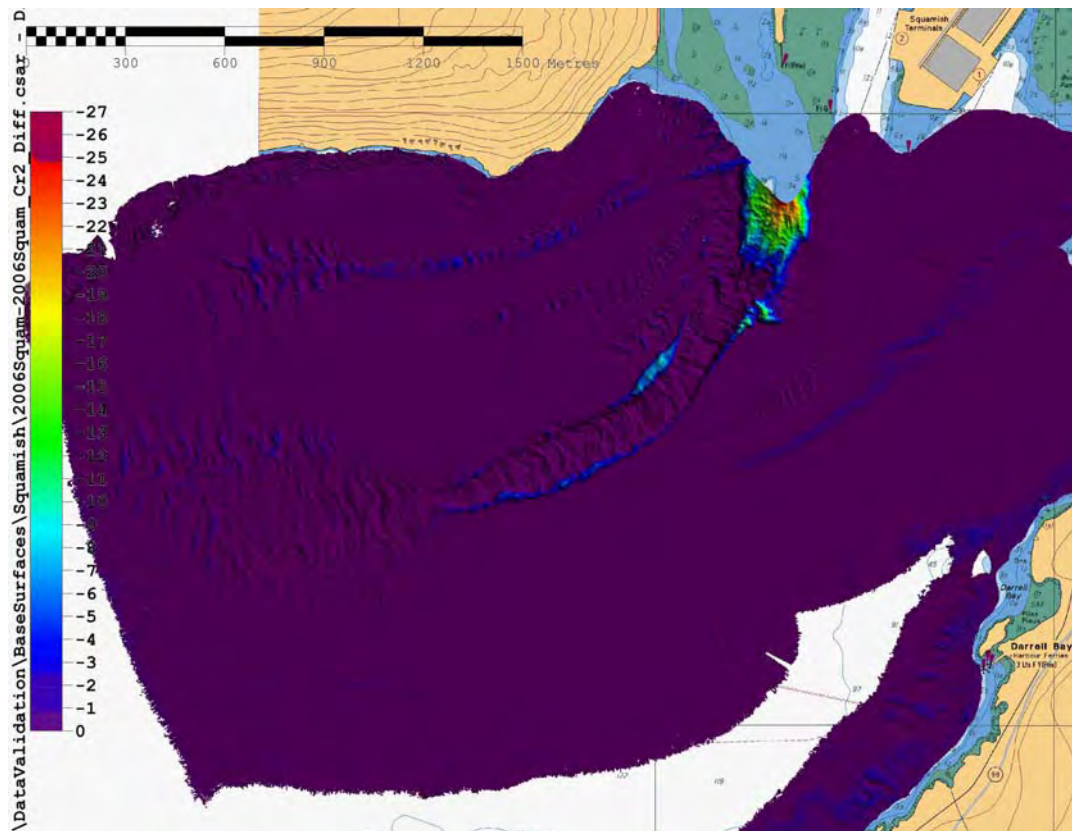


Fig. 1. Squamish River underwater delta morphology (2008).



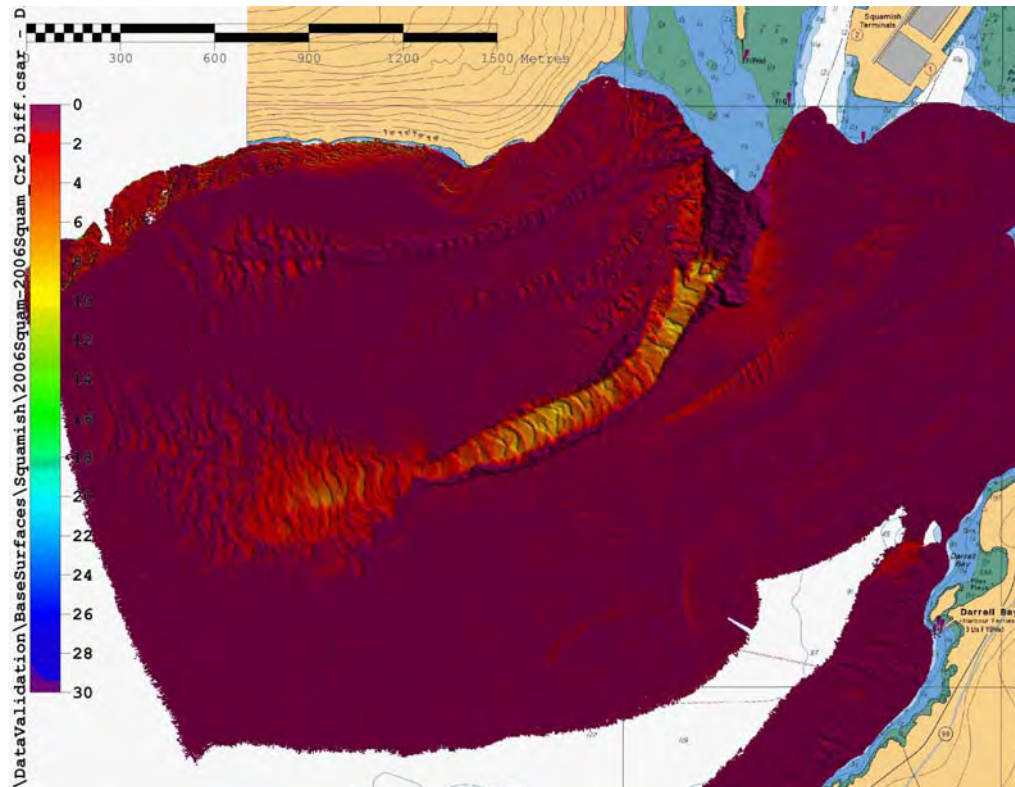


Fig. 2. Squamish 2006 event: (a) with slump emphasized, (b) with deposition emphasized.

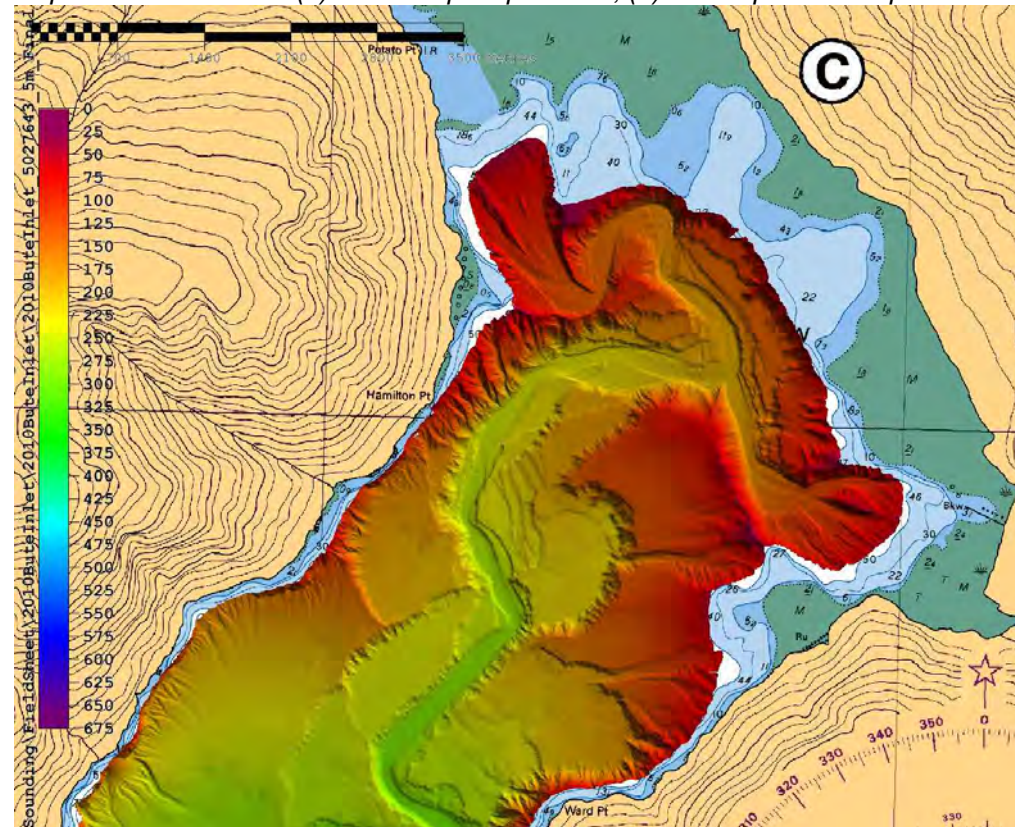


Fig. 3. Bute Inlet (Waddington Harbour) underwater delta morphology (2010).

A16: LOWER TROPHIC LEVEL ECOSYSTEM MODELING OF THE STRAIT OF GEORGIA

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Objectives

The overall objective of this project is to develop an ecosystem-biogeochemical model for the Strait of Georgia coupled to ROMS (Regional Ocean Modeling System) circulation model to identify and understand key factors responsible for temporal and geographical changes in plankton productivity. For 2009/2010 the plan was to continue developing the coupled circulation / plankton ecosystem model (ROMS-NPZD model) of the Strait of Georgia by working towards simulating the mean seasonal cycle and long term (annual/interannual) realistic simulations of the region.

Accomplishments

1. Continued the development of the lower trophic level ecosystem model (NPZD – Nitrate, Phytoplankton, Zooplankton and Detritus) to incorporate observations from the field program and to increase model complexity to better represent conditions in the Strait of Georgia. In particular, the ecosystem model was modified to include chlorophyll compartments for large and small phytoplankton to facilitate comparison of model output with observations.
2. Assembled relevant nutrient data for the Straits of Georgia and Juan de Fuca from existing databases (NODC, IOS, etc) and prepared seasonal climatologies of the region. Prepared initial conditions of nutrients (nitrate and silicate) from these seasonal climatologies
3. Prepare more realistic daily solar radiation forcing fields using the output of MM5 atmospheric model
4. The ROMS-NPZD model was configured to simulate the 2007 annual cycle. The model was initiated with seasonal climatological nutrient (nitrate and silicate) fields and was forced using daily surface irradiance and winds fields from 2007 output of UW mesoscale atmospheric model (MM5) with 4 km resolution. The model simulates winter and spring conditions reasonable well but so far it is not able to run for the full year. Work is in progress to fix the problem.
5. Meet with scientists developing the OSMOSE upper trophic level model to discuss best ways to provide the output of the ROMS-NPZD model to feed their model.

A17: RELATIVE INFLUENCE OF CLIMATE AND HATCHERY PRODUCTION ON THE EARLY MARINE SURVIVAL OF COHO SALMON *ONCORHYNCHUS KISUTCH* DURING ITS RESIDENCE IN THE STRAIT OF GEORGIA

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Introduction

The Strait of Georgia is an important rearing area for coho salmon, *Oncorhynchus kisutch*, of southern British Columbia. Historically, the Strait has been a biologically productive area supporting many commercial and non-commercial aquatic species. Current findings indicate that the Strait of Georgia is undergoing a rapid physical transformation noticeable from the mid 1980s, likely due to global climate change and the impact of local human activities (Johannessen and McCarter, 2010). Studies also link the physical and biological changes of the Strait with poor early marine survival of juvenile coho salmon (Beamish et al., 2008, Beamish et al. 2010). These studies indicate that coho salmon declined 10-fold over the past 25 years to a level that threatens the persistence of the population. Beamish et al. (2008) suggest that early marine mortality of coho salmon during their residence in the Strait is an important determinant of their overall marine survival.

Of special interest are the roles of several climatic variables that have been shown to have a direct or indirect effect on the early marine survival for coho salmon in the Strait. Water temperature has been increasing over the past two decades at all depths due to estuarine circulation (Masson and Cummins, 2007). The timing of peak discharge of the Fraser River has been more variable over the last two decades compared to recorded historical levels with a tendency to occur earlier. The consequences of these changes on aquatic biota remain poorly understood (Morrison et al. 2002), but may affect the productivity in the Strait. The number of days with wind speeds below 25 km.h⁻¹ during May to July is positively correlated with the total marine survival of coho salmon, with an apparent regime shift in 2000 associated with more than 58.5 windy days every year in the May-July period (Beamish et al. 2010). Wind strength may play an important role driving primary productivity (Collins et al. 2009), and hence prey availability for coho salmon. Reduced prey availability may in turn result in reductions in salmon growth and survival during the first months at sea (Yin et al. 1997; Bertram et al. 2001). The timing of the phytoplankton and zooplankton spring bloom has occurred earlier in recent years, possibly resulting in a mismatch between the timing of ocean entry of juvenile coho salmon and that of prey availability. Other species such as harbour seals (*Phoca vitulina*) and pink salmon (*O. gorbuscha*) may compete with or prey on coho salmon, and these species have increased over the past decades (Olesiuk, 1999; King and Beamish, 2000; Beamish et al. 2004). Given uncertainty in the relative magnitude of mechanisms driving declines in the early marine survival of coho salmon, we explore responses of coho salmon to alternative environmental and management scenarios in a probabilistic framework. Complex relationships such as the ones described above can be represented in simple heuristic models that focus on the main ecological and abiotic drivers of coho marine survival, while explicitly considering uncertainty associated with those processes.

In addition to the possible effects of the physical environment and inter-specific competition on the early marine survival of coho salmon, wild stocks may compete with hatchery fish for prey resources, and scarcity of food during periods of poor environmental conditions may enhance intra-specific competition (King and Beamish, 2000; Orr et al. 2002). A hatchery supplementation program was implemented in the 1970s with the purpose of maximizing total adult returns by improving freshwater survival (DFO, 2010). Evidence suggests that hatchery-reared fish tend to have lower marine survival than their wild counterparts (Beamish et al. 2008), and interactions among wild and hatchery-origin fish may reduce fitness of wild stocks through genetic interactions, competition, predation, and pathogen exchanges (Gardner et al. 2004).

Such potential consequences generate controversy surrounding the long-term benefits of the supplementation approach.

Here we used a Bayesian belief network (BBN) to represent multiple ecological processes and independent information sources in a probabilistic framework (Pearl, 1988). Bayesian belief networks (BBN) are a powerful decision-support framework that can accommodate multiple research and management objectives, performance criteria, and uncertainties in parameters and model structure. BBNs are based on establishing probabilistic links among variables, and allow us to evaluate relative degrees of support for alternative hypotheses, validate predictions, identify the value of reducing uncertainty of climate impacts, detect cost-effective indicator variables, and inform decisions about prioritizing resources among research and management activities.

The first objective of this project was to evaluate the probability of further changes in the early marine survival of coho salmon under various climate change scenarios during their residence in the Strait of Georgia. Second, we evaluated the probability that hatchery production could mitigate those reductions. Probabilities were estimated for different hypothesized states of key physical and biological variables that compose the ecosystem represented in the Bayesian belief network. Using existing information on climatic and biological processes that drive the marine survival of juvenile coho salmon, we provide a quantitative methodology that integrates relationships among influential variables into a single analytical framework.

Methods

Data sources

We employed yearly time series data adjusted for lag effects for all variables included in the network (Table 1). Variables were selected according to their known importance in driving physical and biological processes in the Strait and on the basis of data availability. Additional variables were hypothesized to drive biological processes in the Strait but were not included because of a lack of apparent statistical relationships with other variables in the network (seal abundance or pink salmon abundance). The absence of statistical relationships does not mean these variables do not play an important biological role in biophysical processes in the Strait; indeed there may be insufficient information to characterize a relationship, if it exists. Another possible reason for observing unclear trends in some biological variables is changing environmental and biological conditions in the Strait; variables with dynamics that may have been causally linked in the past may no longer be correlated, e.g., shifts in ecosystem structure associated with prey switching behaviour in predator-prey relationships.

Model structure

A BBN is a representation of joint probability distributions over a group of statistical variables (nodes) using a directed acyclic graph, a graph with arrows among nodes that flow in a single direction (Pearl, 1988; Jensen, 1996; Korb and Nicholson, 2004). Arrows, commonly known as arcs, represent causal dependencies among variables based on underlying probabilistic relationships between parent and child nodes. A parent node is any variable that has a causal effect on another variable (a child node). Every child node contains a conditional probability table (CPT), which includes the probabilities of several hypothesized states given every possible combination of states of its parent nodes. A marginal probability table (MPT) contains the probability of each hypothesized state in a parent node.

By manipulating an observed (climate) or controlled (hatchery production) variable, it is possible to examine the probabilistic effects on the whole network or on one or more target variables (top-down inference). We can also observe the overall conditions in the set of observable variables necessary to achieve a certain state of a target variable or outcome of interest (bottom-up inference). For more details on BBNs and Bayesian inference, see Pearl (1988), Jensen (1996), Needham (2007), and Uusitalo (2007).

Candidate variables and model structures were explored based on a review of primary literature and government reports on the Strait of Georgia as well as interviews with experts on the biophysical processes in the Strait. Statistical relationships among variables were then identified to further narrow the subset of those which could inform probabilistic relationships in the BBN. In this sense, this component of the network structure is based on expert opinion but strongly supported by the statistical relationships observed in the data. When exploring intra-species interactions (e.g. competition between hatchery and wild fish), a similar procedure was undertaken but with a stronger reliance on expert opinion, because of a dearth of biological data on the topic. Thus, this component of the network structure represents hypothesized dynamics.

Model parameterization

After designing the initial ecological causal web, (a structure containing nodes in the BBN without filling in the CPTs), we assigned a number of hypothesized states in each node, striving for the minimum necessary to represent a probability distribution for the each variable while ensuring precision in the probability estimates, which is reduced with numerous states. The number of states required for each variable depends on the type of distribution observed in the data (Prairie 1996) and the known biological or physical thresholds of interest for the researchers (as shown in Table 1). We computed marginal and conditional probability tables (MPTs and CPTs, respectively) for each node from the probabilities assigned to each hypothesized state. We parameterized the CPTs based entirely on ecological data, but expert opinion could be included in future iterations of the BBN. Given the large data requirements to compute probability distributions in the CPTs we employed a Monte Carlo approach to simulate data that was missing from the historical time-series but could be interpolated based on underlying relationships among variables.

First, we fit linear models among variables using QR decomposition (R Development Core Team, 2009), and extracted model parameters and the residual standard errors. Second, we selected values of the predictor variables (parent nodes) that covered the range of the hypothesized states, and simulated values for the child node by applying the fitted model with random variability, thus creating a hypothesized predicted distribution. The simulation was iterated over 1000 samples, with a different random sample for the residual standard error at each time. Third, we compiled all observations belonging to a state of the predicted variable (child node) for each state of the predictor variable(s) (parent nodes), extracting their probability density function. Finally, the values of a discretized probability density function in the child node for each state for the parent node(s) were used to populate the CPTs

Results

After performing an initial exploratory data analysis and detecting statistical relationships, we found that 6 of 23 variables considered had statistically significant relationships ($p < 0.1$) with early marine survival of coho salmon in the Strait of Georgia, or with other variables that were related to coho survival (Fig. 1, squares). Two

additional variables were highly correlated to the early marine survival of coho salmon: herring biomass prior to the fishery and biomass of *Neocalanus plumchrus* (life-history stage 5).

When performing bottom-up inference, we found that low early marine survival for hatchery fish (less than 10%) is associated with increasing probability of El Niño (>39% ENSO index > 1.3), relatively high probability of observing early Fraser River maximum discharge prior June 1st (>51%), relatively low probability of observing high zooplankton abundance (<19%), and high probability of warm water temperatures from the time the juveniles enter the Strait until late September (> 65%). Given the highly correlated total marine survival of hatchery and wild coho salmon ($r^2 = 0.90$) and that both groups are subject to the same climatic forces, the same trend is expected for the early marine survival of wild coho salmon.

The hypothesized relationships between hatchery and wild salmon indicate that intra-specific competition affects the early marine survival of both groups under extreme scarcity of prey (negative zooplankton anomaly), which in turn is triggered by positive El Niño indexes correlated with warmer water temperatures. In addition, the hatchery supplementation approach was only beneficial (e.g. reflected in increased probability of high returns) when climatic factors were optimal such as during colder water temperatures and high prey availability, associated with high probabilities of a negative El Niño index. Poor climatic conditions resulted in markedly increased probabilities of low returns of both hatchery and wild fish. Further investigations will quantify the probabilistic relationships described here.

Discussion

Our findings suggest that worsening of the current climatic conditions will result in high probabilities of further declines in early marine survival for coho juveniles rearing in the Strait. Early marine survival is most strongly determined by El Niño, mediated by its effect on zooplankton abundance and water temperature. The impacts of PDO and timing of Fraser River peak discharge on early marine survival are weaker than those from El Niño. Other atmospheric or biological forces that we have not incorporated in this study may also play an important role in determining the early marine survival of coho salmon (e.g. nutrient availability, or solar irradiance) but because of data limitations these could not be explicitly included but are implicitly accounted for in the random variation associated with models predicting coho survival.

Recent climate change research indicates that there is a trend to experience warmer water temperatures and earlier timing of the phytoplankton and zooplankton spring bloom in the Strait (Johannessen and McCarter, 2010). In addition, with warmer temperatures the zooplankton composition tends to shift towards a less nutritious assemblage (El-Sabaawi *et al.* 2009). Under these circumstances, the early marine survival of coho salmon in the Strait is likely to remain very low. A recent review of the biological processes operating in the Strait observed that populations of many piscivorous species such as chinook and coho salmon are experiencing strong declines, while species of planktivorous fish such as hake, and chum and pink salmon seem to be more stable or within the ranges of historical variability (Crawford and Irvine, 2010). These changes could be a result of warming temperatures in the Strait and variability in the timing of peak river discharge, resulting in changes in zooplankton composition, changes in food web structure, and a mismatch in the timing of predators and prey in the Strait (Yin *et al.* 1997).

Our findings on the role of hatchery supplementation agree with similar studies (e.g., Pearsons, 2010) indicating that hatchery fish will improve the total adult returns only under favorable ocean conditions. Because of the lack of information on the interactions between hatchery and wild fish, our results simply reflect the expert opinion on which network relationships are based. Ongoing work will include more information on wild and hatchery-origin fish dynamics possibly including information from other case studies (e.g. Nickelson, 2003; Reese *et al.* 2009). These results highlight the need for further research on biological interactions between hatchery and wild fish in the Strait of Georgia in order to have a better understanding of the outcomes from the supplementation approach. Interactions between wild and hatchery fish remain a wide research gap not only in the Strait but in most places where supplementation is practiced (Naish *et al.* 2007).

In our study, most CPTs of the BBN are based on data while the network structure is based on expert opinion that takes into account statistical relationships among variables. Whether or not these relationships imply causation or correlation is still a matter of debate requiring further ecosystem-level research. Because of the highly dynamic environment in the Strait, it is possible that the probabilistic relationships among variables have changed over time. Although we assumed that the relationships among variables remained constant, temporal variability in model parameters will result in increased residual error in the relationships among variables, which is implicitly accounted for in our network.

Conclusion

The network presented here is based on the physical and biological variables that affect the early marine survival of coho salmon in the Strait of Georgia. Our findings suggest that increased probabilities of El Niño events and warm surface temperatures will likely result in further declines in early marine survival while possible benefits of hatchery supplementation are perhaps limited to periods of favorable ocean conditions. Climatic forces such as El Niño and the PDO seem to have a strong effect on physical and biological variables such as the zooplankton abundance, the timing of the Fraser River peak discharge, and the average spring and summer water temperature. Our results emphasize the need to promote research on the interactions between hatchery and wild fish in the Strait in order to improve our understanding of the benefits or shortcomings of the supplementation program. This project provides an example of a quantitative tool for ecosystem-based management in the Strait of Georgia, which can be applied to other species and management contexts.

References

- Beamish, R. J., Sweeting, R. M., Lange, K. L., Noakes, Preikshot D., and Neville, C. M. 2010. Early marine survival of coho salmon in the Strait of Georgia declines to very low levels. *Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science* **2**: 424-439 doi: 10.1577/C09-040.1
- Beamish, R.J., Mahnken, C. and Neville, C.M. 2004. Evidence that reduced early marine growth is associated with lower marine survival of coho salmon. *Transactions of the American Fisheries Society*, **133**:26-33.

- Beamish, R.J., Sweeting, R.M. Lange, K.L. and Neville, C.M. 2008. Changes in the population ecology of hatchery and wild coho salmon in the Strait of Georgia. *Trans. Am. Fish. Soc.* **137**: 503–520.
- Bertram, D.F., Mackas, D.L. and McKinnell, S.M. 2001. The seasonal cycle revisited: interannual variations and ecosystem consequences. *Progress in Oceanography*, **49**:283-307.
- Collins, A.K., Allen, S.E. Pawlowicz R. 2009. The role of wind in determining the timing of the spring bloom in the Strait of Georgia. *Can. J. Fish. Aquat. Sci.* **66**: 1597–1616.
- Crawford, W.R., and Irvine, J.R. 2010. State of physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2009. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/053. viii + 137 p.
- DFO, Salmonid Enhancement program 2010. Available at <http://www.pac.dfo-mpo.gc.ca/sep-pmvs/about-sujet-eng.htm>. Accessed Nov 25, 2010
- DFO, BC lighthouse data. 2010. Available at <http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.htm>. Accessed Nov 2, 2010.
- El-Sabaawi, R., Dower, J.F., Kainz, M., and Mazumder, A. 2009. Interannual variability in fatty acid composition of the copepod *Neocalanus plumchrus* in the Strait of Georgia, British Columbia. *Mar. Ecol. Prog. Ser.* **382**: 151–161. doi:10.3354/meps07915.
- Gardner, J., Peterson, D.L., Wood, A., and V. Maloney. 2004. Making sense of the debate about hatchery impacts: Interactions between enhanced and wild salmon on Canada's pacific coast. Prepared for the Pacific Fisheries Resource Conservation Council.
- Jensen, F. V. 1996. An introduction to Bayesian networks. UCL Press, London, UK.
- Johannessen, S. C. and McCarter, B. 2010. Ecosystem Status and Trends Report for the Strait of Georgia Ecozone. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/010. vi + 45 p
- King, J.R. and Beamish, R.J. 2000. Diet comparisons indicate a competitive interaction between ocean age-0 chum and coho salmon. *North Pacific Anadromous Fisheries Commission Bulletin*. **2**:65-74.
- Marcot, B. G., Steventon, J. D., Sutherland, G.D., and McCann R.K. 2006. Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. *Canadian Journal of Forest Research*. **36**: 3063-3074.
- Masson, D. and Cummins, P.F. 2007. Temperature trends and inter-annual variability in the Strait of Georgia, British Columbia. *Continental Shelf Research* **27**:634- 649.

- Morrison, J., Quick, M.C. and Foreman, M.G.G. 2002. Climate change in the Fraser River Watershed: flow and temperature projections. *Journal of Hydrology*, **263**:230-244
- Naish, K. A., Taylor, J. E., Levin, P. S., Quinn, T. P., Winton, J. R. Huppert, D., and Hilborn, R. 2007. An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. *Advances in Marine Biology* **53**:61–194.
- Needham, C.J, Bradford, J.R., Bulpitt, A.J. and Westhead, D.R. 2007. A primer on learning in Bayesian networks for computational biology. *PLoS Computational Biology*, **3** (8). e129. ISSN 1553-7358
- Nickelson, T. 2003. The influence of hatchery coho salmon (*Oncorhynchus kisutch*) on the productivity of wild coho salmon populations in Oregon coastal basins. *Canadian Journal Of Fisheries And Aquatic Sciences*: **60** (9): 1050-1056
- Nyberg, J. B., Marcot, B. G., and Sulyma R. 2006. Using Bayesian belief networks in adaptive management. *Canadian Journal of Forest Research* **36**:3104-3116
- Olesiuk, P. 1999. An assessment of the status of harbour seals (*Phoca vitulina*) in British Columbia. DFO Can. Stock. Assess. Sec. Res. Doc. 1999/33. 130 pp.
- Orr, C., Gallagher, P. and Penikett, J. 2002. Hatcheries and the protection of wild salmon. Simon Fraser University, Burnaby.
- Pearl, J., 1988. Probabilistic reasoning in intelligent systems. Morgan Kaufmann, San Mateo, CA.
- Pearsons, T. 2010. Operating hatcheries within an ecosystem context using the adaptive stocking concept. *Fisheries* **35** (1),: 23-31
- Prairie, Y.T. 1996. Evaluating the predictive power of regression models. *Canadian Journal of Fisheries and Aquatic Sciences* **53**: 490-492.
- R Development Core Team. 2009. A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. Available at <http://www.R-project.org>.
- Reese, C., Hillgruber, N., Sturdevant, M., Wertheimer, A. Smoker, W., Focht, R. 2009. Spatial and temporal distribution and the potential for estuarine interactions between wild and hatchery chum salmon (*Oncorhynchus keta*) in Taku Inlet, Alaska. *Fishery Bulletin*. **107** (4): 433-450
- Uusitalo, L. 2007. Advantages and challenges of Bayesian networks in environmental modelling. *Ecological Modelling*. **203**(3-4), 312-318.
- Yin, K., Harrison, P.J., Goldblatt, R.H., St. John, M.A., and Beamish R.J. 1997. Factors controlling the timing of the spring bloom in the Strait of Georgia estuary, British Columbia, Canada. *Can. J. Fish. Aquat. Sci.* 54: 1985–1995. doi:10.1139/cjfas-54-9-1985.

Figures and Tables

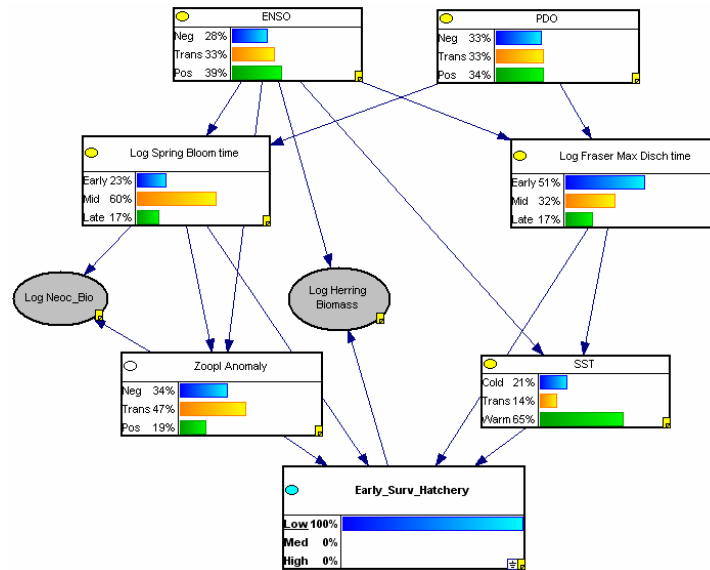


Figure 1. Network structure showing bottom-up inference, which is done by setting evidence on a state (or states) of the target variable(s) (in this case early marine survival for hatchery fish) with the purpose of inferring the probabilities of the states in the observable nodes (e.g. ENSO, PDO, zooplankton anomaly, SST, etc). Round nodes can potentially act as ecosystem indicators because, although not mechanistic causes of early marine survival, their trends are highly correlated with it.

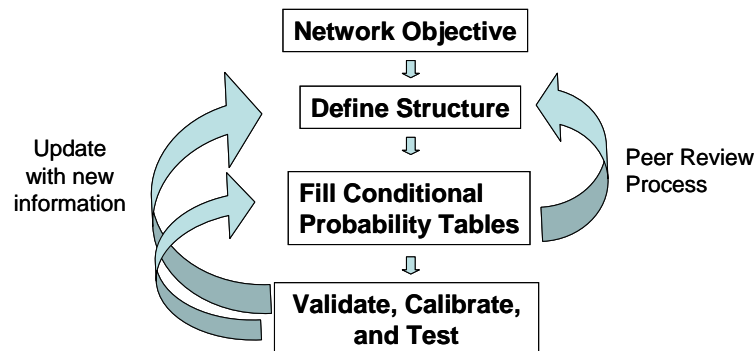


Figure 2. Diagram of the process of designing and implementing a Bayesian Belief Network

Name	Definition	States	Source	Time period
ENSO	El Niño Index.	Neg < -1.3 Trans $\geq -1.3 \leq +1.3$ Pos > 1.3	NOAA (US National Oceanic and Atmospheric Administration)	1960-2008
PDO	Pacific Decadal Oscillation Index.	Neg < -1.13 Trans $\geq -1.13 \leq 1.13$ Pos > 1.13	NOAA(US National Oceanic and Atmospheric Administration)	1960-2008
Log Spring	Day of the year (Julian day) in log	Early < .2	Susan Allen	1992-2008

Bloom time	scale where the spring phytoplankton bloom has historically occurred (log scale).	Mid $\geq 4.2 \leq 4.5$ Late > 4.5	(UBC) Unpublished data	
Log Fraser Maximum Discharge time	Day of the year (Julian day) in log scale where the maximum historical Fraser river discharge occurred.	Early < 5 Mid $\geq 5 \leq 5.5$ Late > 5.5	Water Survey of Canada	1960-2008
Log Neocalanus Biomass	Biomass of <i>Neocalanus plumchrus</i> stage 5, measured in mg/m ³ .	Low < -3.8 Med $\geq -3.8 \leq -2.5$ High > -2.5	Moir Galbraith (Institute of Ocean Sciences)	2001-2008
Log Herring Biomass (Pre-Fishery)	Pre-Fishery Biomass in 1000's of tonnes (in Log scale)	Low < 4.2 med $\geq 4.2 \leq 5$ high > 5	J. Schweigert, (Pacific Biological Station)	1960-2008
Zooplankton Anomaly	Index of total taxa combination of: crustacean carnivores, copepods, crustacean herbivores, other carnivores, other herbivores, and polychaetes.	Neg < -0.2 Trans $\geq -0.2 \leq +0.2$ Pos $> +0.2$	Dave Mackas (Institute of Ocean Sciences) Unpublished data	1990-2008
SST	Average Spring-Summer temperature (Apr, May, Jun, Jul, Aug, Sep) taken at entrance island (Celsius degrees).	Cold < 14 Trans $\geq 14 \leq 16$ Warm ≥ 16	DFO Lighthouse data.	1960-2008
Early Survival of Hatchery Fish	Percentage of hatchery Juveniles that survive from the entrance into the Strait around April until September each year. Estimated from survey CPUE data.	Low $< 10\%$ Med $\geq 11 \leq 20\%$ High $> 21\%$	Beamish et. al. 2008; Beamish et. al. 2010	1997-2008
Early Survival of Wild Fish	Percentage of wild Juveniles that survive from the entrance around April into the Strait until September each year. Estimated from survey CPUE data.	Low $< 10\%$ Med $\geq 11 \leq 20\%$ High $> 21\%$	Beamish et. al. 2008; Beamish et. al. 2010	1997-2008

Table .1 Selected Variables Used in the Bayesian Belief Network

A18: LARGE AND SMALL PELAGICS HOTSPOTS IN THE STRAIT OF GEORGIA

John Holmes, Tom Therriault, Ken Cooke, George Cronkite, Jake Schweigert - PBS/MEAD, Applied Technology and Pelagics

Pelagic species are an important linkage between lower and upper trophic levels in the Strait of Georgia (SoG). The goal of this project is to identify biological hotspots that may be key drivers of the productivity of pelagic fish stocks in the Strait of Georgia. Biological hotspots are locations where species concentrate regularly or where there is high biological activity. Operationally, a biological hotspot as an area with greater than average biomass. Research in 2009-10 focused on identifying hotspots using acoustic data collected in Feb-Mar 2009 and Oct 2009 and characterizing these hotspots based on fish backscatter (acoustic biomass - s_A) at 38 kHz and zooplankton backscatter at 120 kHz, i.e., "trophic levels". Sampling with trawls and Bioness provided information on fish and zooplankton species assemblages and key species at each trophic level. Acoustic backscatter data at each frequency were standardized to standard deviates with a mean of 0 ((observed s_A - mean survey s_A)/SD of survey s_A) and kriging was applied to these data to produce contour maps of biomass anomalies at 38- and 120-kHz.

Strong positive anomalies at 38-kHz (i.e., above average biomass - fish hotspots) in Malaspina Strait and the Quadra Basin/Lasqueti Ridge area on the west side of Texada Island, and a minor hotspot in the southern SoG off Saturna Island were identified in Feb-Mar 2009 (Fig. 1A). Positive plankton anomalies (120-kHz) were observed near Powell River and the Hernando Basin by Desolation Sound in the northern part of the

Strait, and the Balenas Basin, between Departure Bay and Halibut Bank in the central SoG during the winter (Fig. 1B). Fish and plankton abundance were below the survey average in most areas of the SoG during the winter.

Malaspina Strait and the west side of Texada Island were assessed in more detail in Feb 2009 using a 1 km grid. During the day, positive fish anomalies occurred in the mouth of Jervis Inlet and along the Lasqueti Ridge, west of Texada island (Fig. 2A). These hotspots differ in terms of key species and layering. The Jervis hotspot is primarily related to hake, *Merluccius productus*, which accounted for 73% of the catch weight, ranged in size from 10.0 to 71.0, and occupied a depth range of 160-420 m. Spiny dogfish (*Squalus acanthias*), pollock, and brown cat shark (*Apristurus brunneus*) were of secondary importance in Malaspina Strait fish assemblage. In contrast, hotspots on the west side of Texada Island were dominated by herring (*Clupea harengus pallasii*), which accounted for 55% of the catch weight and occupied a depth range of 60-160 m. Hake, spiny dogfish, rattfish (*Hydrolagus colliei*), and pollock (*Theragra chalcogramma*) were secondarily important accounting for about 45% of the catch weight combined and occupied a depth range of 200-400 m in the Quadra Basin. Two plankton hotspots were observed in Malaspina Strait adjacent to Northeast Bay during the day (Fig. 2B) and one positive fish anomaly occurred at the night, off the tip of Sinclair Bank in Malaspina Strait (Fig. 3). Plankton hotspots were dominated by euphausiids, chaetognaths, and glass shrimp.

A brief survey of Malaspina Strait in fall 2009 (23-24 Oct) revealed higher fish productivity than in the winter and a more consistent pattern of positive biomass anomalies primarily in the main trough, which is an extension of the Malaspina Basin in the main part of the SoG (Fig. 4A). These anomalies are dominated by spiny dogfish (*Squalus acanthias*) and hake at depths below 200 m and accounted for 85% of trawl samples by weight, and secondarily by schoolmaster squid (*Beryteuthis magister*) and brown cat shark. Herring were not detected acoustically nor in trawl samples. However, in contrast to the winter results, young-of-the-year hake were found sympatrically with older hake in the fall. Positive plankton biomass anomalies occurred on the east side of Malaspina Strait (Fig. 4B), over relatively shallow bottom depths and consistent with persistent northwesterly winds at the time of the survey.

Aquatic animal species at all trophic levels aggregate for a variety of reasons including reproduction, feeding, protection, and migration. Herring dominated hotspots along Lasqueti Ridge in Feb 2009 were likely the result of prespawning staging, while the Malaspina Strait hotspots may be feeding aggregations of hake, since the majority of mature hake (based on size distributions) were in Jervis Inlet in Feb. The spatial overlap between young-of-the-year hake and older hake in Malaspina Strait in October is unusual since older hake will cannibalize younger fish (Ressler et al. 2007). The water column was layered acoustically, with a top layer between 60 and 160 m dominated by herring, a bottom layer from 200-400+ m dominated by hake and dogfish, and an intermediate layer from 150-225 m dominated by zooplankton, particularly euphausiids, chaetognaths, and glass shrimp.

Fish and plankton hotspots identified in the winter and fall of 2009 occurred close to prominent habitat features such as shoals, ridges, shelf-breaks, and inlet sills. The identification of Malaspina Strait as a hotspot is consistent with previous acoustic surveys in the SoG, which began in 1975 and usually reported that during the winter the productivity of large pelagics (hake, pollock, dogfish) highest in Malaspina Strait and lower in the main areas of the SoG, particularly areas where the bottom is impacted by deposition from the Fraser River (Taylor and Barner 1976a, b; Shaw et al. 1990). From

this perspective, substantial change in the pattern of pelagic biomass distribution during the winter has not occurred over the past 30 years. The locations of the plankton and nighttime fish hotspots during the winter survey roughly correspond in time and space with the initial appearance of a surface phytoplankton bloom that developed in Jervis Inlet and proceeded through Malaspina Strait into the SoG and was captured by Meris satellite images (Jim Gower's presentation). We believe this finding is positive evidence that the biological hotspot approach to ecosystem observation and monitoring holds promise. We infer from these spatial overlaps of fish and plankton hotspots in both the winter and fall of 2009, that trophic interactions and predator-prey dynamics are probably the main drivers in the formation of these pelagic hotspots in late winter and fall. This hypothesis is supported by differences in the daytime and nighttime depth distributions of fish and plankton acoustic biomass (data not shown). The results reported here represent an initial attempt to develop an acoustically-based approach to ecosystem monitoring. Further research in different seasons, particularly spring and summer acoustic surveys, would supplement our findings and aid in the identification and characterization biological hotspots as a monitoring tool.

Figures

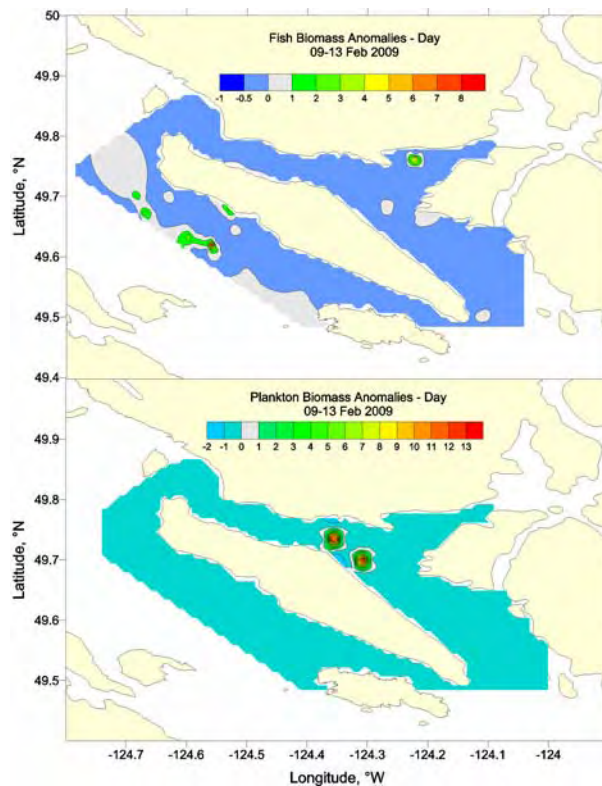


Figure 3. Fish (A) and plankton (B) biomass anomalies in the Strait of Georgia, winter 2009.

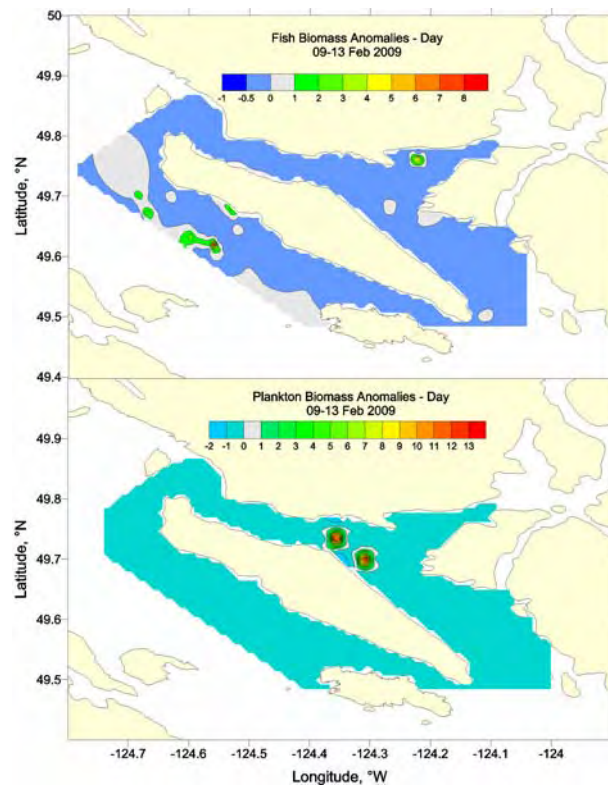


Figure 4. Fish (A) and plankton (B) biomass anomalies during the day, winter 2009, in Malaspina Strait and the west side of Texada Island.

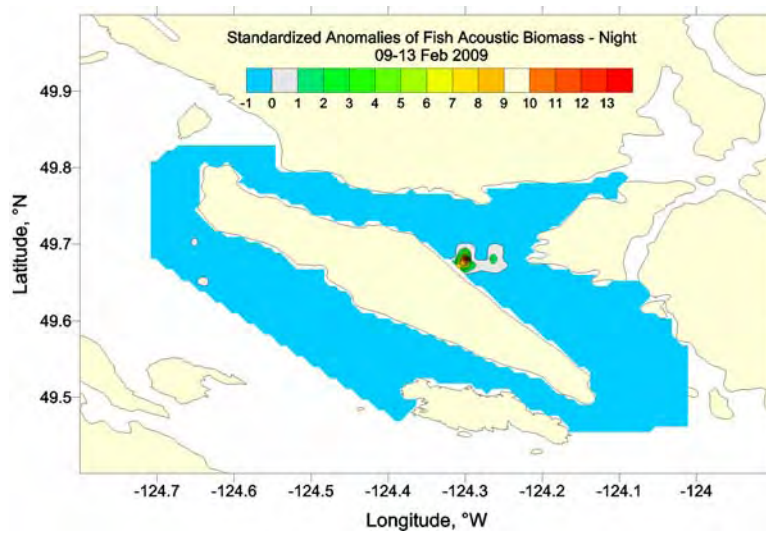


Figure 5. Fish biomass anomalies at night, 09-13 Feb 2009.

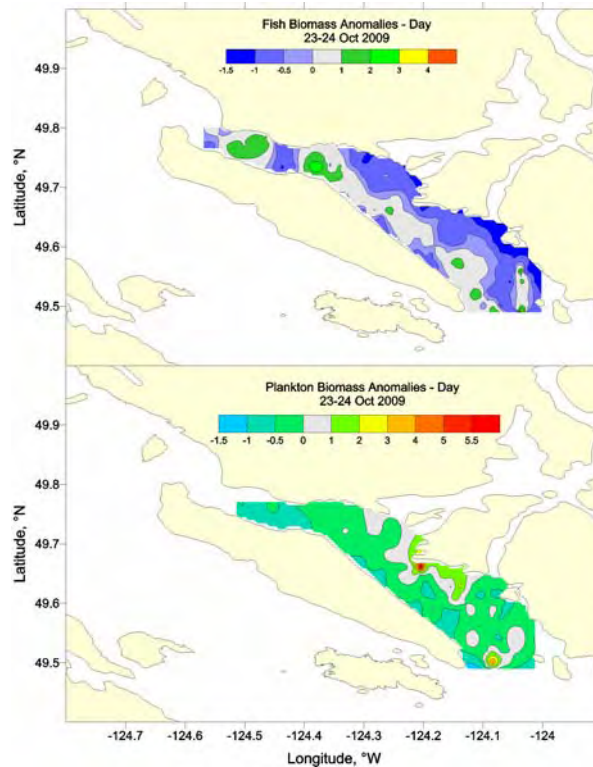


Figure 4. Fish and plankton biomass anomalies in Malaspina Strait, October 2009.

References

Ressler, P.H., J.A. Holmes, G.W. Fleischer, R.E. Thomas, and K.D. Cooke. 2007. Pacific hake, *Merluccius productus*, autecology: a timely review. *Marine Fisheries Review* 69: 1-24.

Taylor, F.H.C., and Barner, L.W. 1976a. The distribution and abundance of hake, pollock and dogfish in the Strait of Georgia in 1975 determined by digital echo-integration. *Fish. Res. Board Can. Man. Rep. Ser.* 1411: 51 p.

Taylor, F.H.C., and Barner, L.W. 1976b. The distribution and abundance of hake, walleye pollock and dogfish in the Strait of Georgia in 1976 determined by digital echo-integration. *Fish. Res. Board Can. Man. Rep. Ser.* 1410: 33 p.

Shaw, W., McFarlane, G.A., and Kieser, R. 1990. Distribution and abundance of the Pacific hake (*Merluccius productus*) spawning stocks in the Strait of Georgia, British Columbia, based on trawl and acoustic surveys in 1981 and 1988, pp. 121-134. *In* L.-I. Low (ed.) *Proceedings of the Symposium on Application of Stock Assessment Techniques to Gadids*. *Int. North Pac. Fish. Comm. Bull.* 50.

A19: CHARACTERIZING THE RESUSPENSION AND TRANSPORT OF NUTRIENTS AND TRACE-ELEMENT CONTAMINANTS IN THE STRAIT OF GEORGIA

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Background:

Accelerated sea level rise and intensified storminess brought on by climate change will lead to the resuspension of nutrients and trace-metals from bottom sediments to the overlying water column within the Strait of Georgia. These sediment constituents may have accumulated in the benthic environment over time due to the limited exchange with the open ocean and a net sedimentation flux within the Strait of Georgia (Macdonald et al. 1991; Johannessen et al. 2003). The mobilization of toxic metals (ie. mercury, cadmium and copper) may take place through both chronic and acute processes associated with gradual increases in water currents due to greater tidal flows and sea level rise as well as with the occurrence of episodic and high-intensity storms, respectively. Ecosystem health relates to transport pathways and rates at which contaminant metals and nutrients enter the food web and expose vulnerable biota within the benthic boundary layer (ie. groundfish and shellfish). Knowledge regarding the timing and location of these physical processes in association with critical biological events (spring bloom, salmon migration, shore-bird migration) will allow one to identify significant stresses and potential threats to the marine ecosystem.

Objective:

The objective of this study is three-fold:

- 1) To characterize benthic fluxes of nutrients and trace-metals associated with resuspension events to provide modeling inputs for hydrodynamic models and particulate budgets.
- 2) To assess sediment stability and characterize seafloor properties to provide a connection between bathymetry and oceanographic attributes.
- 3) To build on recent climate change and ecosystem programs within the Strait of Georgia.

Approach:

To date we have explored both shallow and deepwater environments within the Strait of Georgia to characterize benthic fluxes associated with varied topographic and oceanographic characteristics and valued ecosystem functions that will be influenced by climate change in different ways.

- Nearshore and shallow environments at Roberts Bank and Baynes Sound
 - Create tide- and storm-induced resuspension events.
 - Method: Sea Carousel – a benthic annular flume (Amos et al. 1998).
 - Site of Climate change sensitivity project – 2005 (NRCan, DFO, EC).
- Offshore and deepwater environments in Georgia Basin
 - Capture resuspension via deepwater renewal during neap tides.
 - Method: CTD-LISST profiles of the water column.
- North and south deepwater environments in the Strait of Georgia
 - Benthic-pelagic exchange processes in collaboration with Sophie Johannessen and Robie Macdonald (TIN station completed, SF stations).
 - Method: Lab Carousel Flume experiment
- Area-wide assessment of present-day distribution of benthic nutrients, metals, and infauna within the Strait of Georgia
 - Ongoing survey of benthic environments.

- Method: Grab sampling.

Accomplishments:

Resuspension fluxes of nutrients and trace-metals were characterized in the shallow-water environments using the Sea Carousel. Particulate material was analyzed for C:N ratios, stable carbon/nitrogen isotopes, and a suite of trace-elements. Since benthic microbial biofilms play a major role in sequestering contaminants (trace-elements), altering the erosion criteria of sediments, and providing a food source for primary and secondary consumers, groundfish, and shorebirds (Sutherland et al. 1998; Elner et al. 2005), benthic grab samples were also collected to measure biofilm and geotechnical properties. Erosion thresholds were determined by examining the relationship between suspended particulate matter and current velocity (Figure 1). Sediment stability coefficients and resuspension fluxes will be available as model inputs for particle transport models, deep-water renewal (Masson, 2002), and nutrient-contaminant budgets.

Water column profiles were carried out along a canyon-axis within the Georgia Basin using both a CTD and a LISST profiler. These profiles took place under neap-tide conditions which favour deepwater renewal events (pers. comm. Richard Dewey). Figure 2 shows a sharp increase in oxygen and turbidity levels along with a decrease in water temperature at depth, suggesting an association between benthic resuspension and deep-water renewal within the basin. Work has been ongoing to quantify shallow-water and deep-water resuspension fluxes and develop tracers to help characterize transport pathways of nutrients and trace-metals.

Next Steps:

To continue assessments and characterization of seafloor attributes and resuspension fluxes to close the information gap regarding the role of resuspension and nutrient-recycling in the Strait. Overall, a better understanding of both chronic and acute resuspension processes will help predict the fate of contaminants and their constraint on the productivity and abundance of higher trophic level species. Gaining knowledge of the resilience of the Strait of Georgia ecosystem will help formulate future management practices. The next phase of this project will be to 1) map and classify seafloor provinces (where seabed properties may be considered constant) and identify hotspots characterized by benthic organic enrichment and/or excess trace-elements (contaminants).

Rapid assessment:

A survey of the current and historical concentrations of benthic nutrients and contaminants in the Strait of Georgia. Time-series trends presented to identify ecosystem indicators. **Detailed assessment:** A detailed literature review pertaining to benthic nutrient and contaminant accumulation on a local and global-scale. Comparisons of similar ecosystems (e.g. North Sea - nutrient recycling study involving annular flume resuspension experiments). **Models:** Sediment stability coefficients and resuspension fluxes will be available as model inputs for particle transport models, deep-water renewal, and nutrient-contaminant budgets. **Identification of “hotspots”, ecosystem indicators, and decision support-tools:** Benthic habitat “provinces” will be classified and critical areas identified according to trends in nutrients/contaminants and their erodibility. The identification of “excess” contaminants (indicators) through applied geochemical normalization techniques (decision support-tool) will allow management to

highlight high-risk “hotspots” for “special management concern”. **Future scenarios and scientific legacy:** The resuspension results will fill a knowledge gap regarding transport pathways of contaminants. Sediment stability information will support predictions of future scenarios assessing climate change impacts.

References::

Amos, C.L., J. Grant, G.R. Daborn, and K. Black. 1992. Sea Carousel – a benthic annular flume. *Est. Coast. Shelf Sci.* 34: 557 – 577. Johannessen, S.C., R.W. Macdonald, D.W. Paton. 2003. A sediment and organic carbon budget for the greater Strait of Georgia. *Est. Coast. and Shelf Science*, 56: 845-860. Macdonald, R.W., and D.M. Macdonald, M.C. O'Brien, and C. Goeil. 1991. Accumulation of heavy metals (Pb, Zn, Cu, Cd), carbon and nitrogen in sediments from Strait of Georgia, B.C., Canada. Masson, D. 2002. Deep-water renewal in the Strait of Georgia. *Est. Coast. Shelf Science*, 54: 115 – 126. Sutherland, T.F., C.L. Amos, and J. Grant. 1998. The effect of buoyant biofilms on the erodibility of sublittoral sediments of a temperate microtidal estuary. *Limnol. Oceanogr.* 43(2), 225 – 235.

Figure 1:

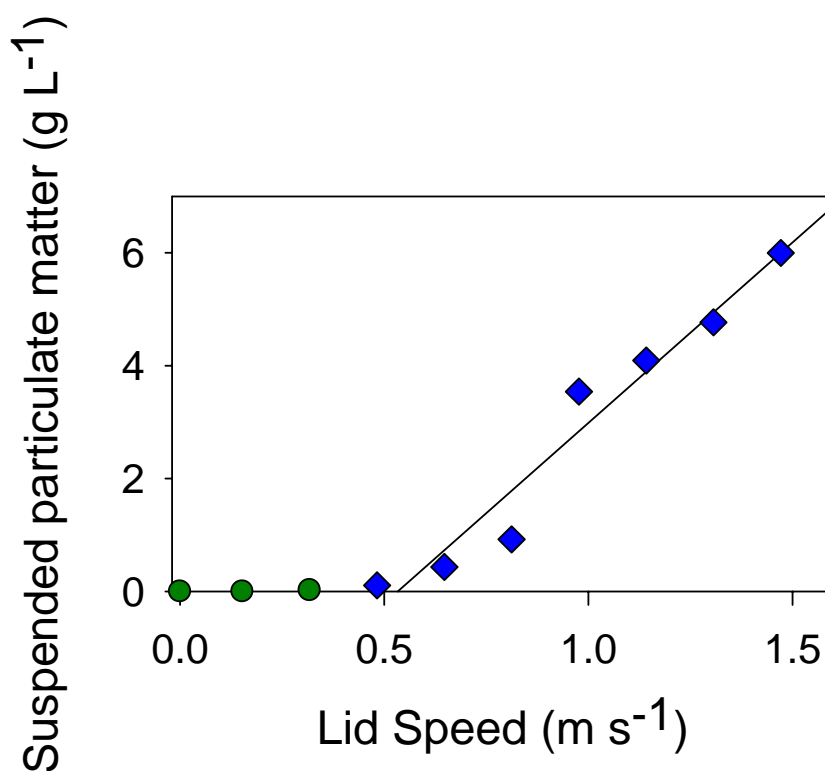
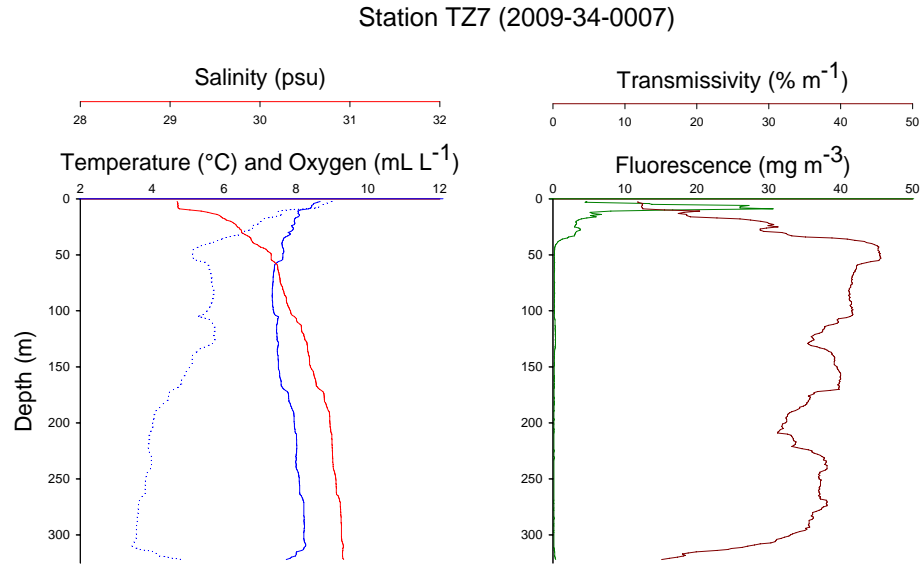


Figure 2:



A20: STRAIT OF GEORGIA ECOSYSTEM MODEL

D. Preikshot, R.J. Beamish, C.M. Neville, R.M. Sweeting

We have constructed a dynamic model of the Strait of Georgia Ecosystem that can be used to explore mechanisms influencing changes in chinook and coho salmon from 1960 to the present. The model represents the culmination of workshops and data assimilation with colleagues at the Pacific Biological Station and the Institute of Ocean Sciences. The model can simulate the timing and magnitude of changes in biomass, mortality and fishing yield of not only coho and chinook salmon but also other species like Pacific herring, resident orcas, harbour seals, lingcod, dogfish and marine birds. This model is now at a stage at which it can be used to explore research hypotheses as well as potential impacts of management policies, particularly trade-offs in the abundance of species and or species groups, and the related fisheries.

The first component of this work is the 1960 starting point Ecopath steady state model which outlines configurations of biomasses, growth, mortality, fisheries and diet compositions of the modeled species in 1960. The second component model is a dynamic Ecosim model emulating changes in biomass mortality and fisheries of Pacific salmon and other managed species from 1960 to the present. Many colleagues have made contributions to the parameterisation of both the Ecopath base model and helping assimilate time series for the dynamic Ecosim runs. The major contributors to our Strait of Georgia modelling work are;

- Dr. J. Schweigert and associates for Pacific herring
- Dr. Peter Olesiuk for harbour seals,
- Dr. John Ford and Mr Graeme Ellis for orcas, sea lions, and porpoises,
- Our own data for Pacific Salmon,

- Dr. Jackie King and Mr. Sandy MacFarlane for lingcod, dogfish, and Pacific hake and,
- Dr. David Mackas for zooplankton groups.

Significant portions of the model were derived from outside sources. The two chief examples of this are changes in dogfish biomass and fisheries from the PhD thesis work of Dr. Ian Taylor (2008) and changes in marine bird abundance derived from Strait of Georgia Christmas bird count data from the Audubon Society (2011).

Figure 1 Shows how the model can hindcast changes in the biomasses of several species of significant commercial social and ecological interest in the Strait of Georgia. Changes in predicted biomasses and mortalities are tuned to assessment data, *e.g.*, from colleagues as described above. Optimisation of predicted data to reference data was achieved by parameterising both top-down and bottom-up mechanisms. In the top-down case all species are linked by diet compositions. By altering how predator species may have been near or far from carrying capacity in 1960, we can manipulate their ability to both grow in biomass and increase mortality upon prey species. In the bottom-up case we use Ecosim to hindcast a time series of changes in primary production the forces changes in energy potentially available to the food web. Table 1 shows the status in 1960, relative to carrying capacity of species in our model. Table 1 shows how Ecosim can be used to help inform decisions on management policies like enhancement and fishing by examining how affected species may have biomass changes amplified or dampened.

The second way that hindcast data was optimised was to generate a historic time series of annual changes in primary production anomalies that introduces changes in energy available to the food web. Figure 2 shows the that the Strait of Georgia model suggests that the 1960s and early 21st century were periods of relatively low production which would have helped manifest low production in many fished species during those times. BY assessing how primary production changes may occur in the future and what the duration of these 'regimes' may be Ecosim can be used to examine which species are sensitive or robust to production regime and which may recover or collapse more easily.

Our model has matured to the stage that its parameterisation and results are ready for presentation in a peer-reviewed journal. We believe it can provide researchers and managers with a platform to examine hypotheses about ecosystem function, particularly in relation to changes in coho and chinook salmon. This work also shows that by pooling our institutional knowledge about the Strait of Georgia ecosystem we can develop a modelling tool that will help determine field research priorities. Finally, we believe the model can be a living resource, continually enriched by more accurate and precise data, or data on species not explicitly modelled at present.

References

- Audubon Society. 2011. Christmas Bird Count database available online at birds.audubon.org/Christmas-bird-count.
- Taylor, I. 2008. Modeling spiny dogfish population dynamics in the Northeast Pacific. Ph.D. dissertation. University of Washington. 188 pages.

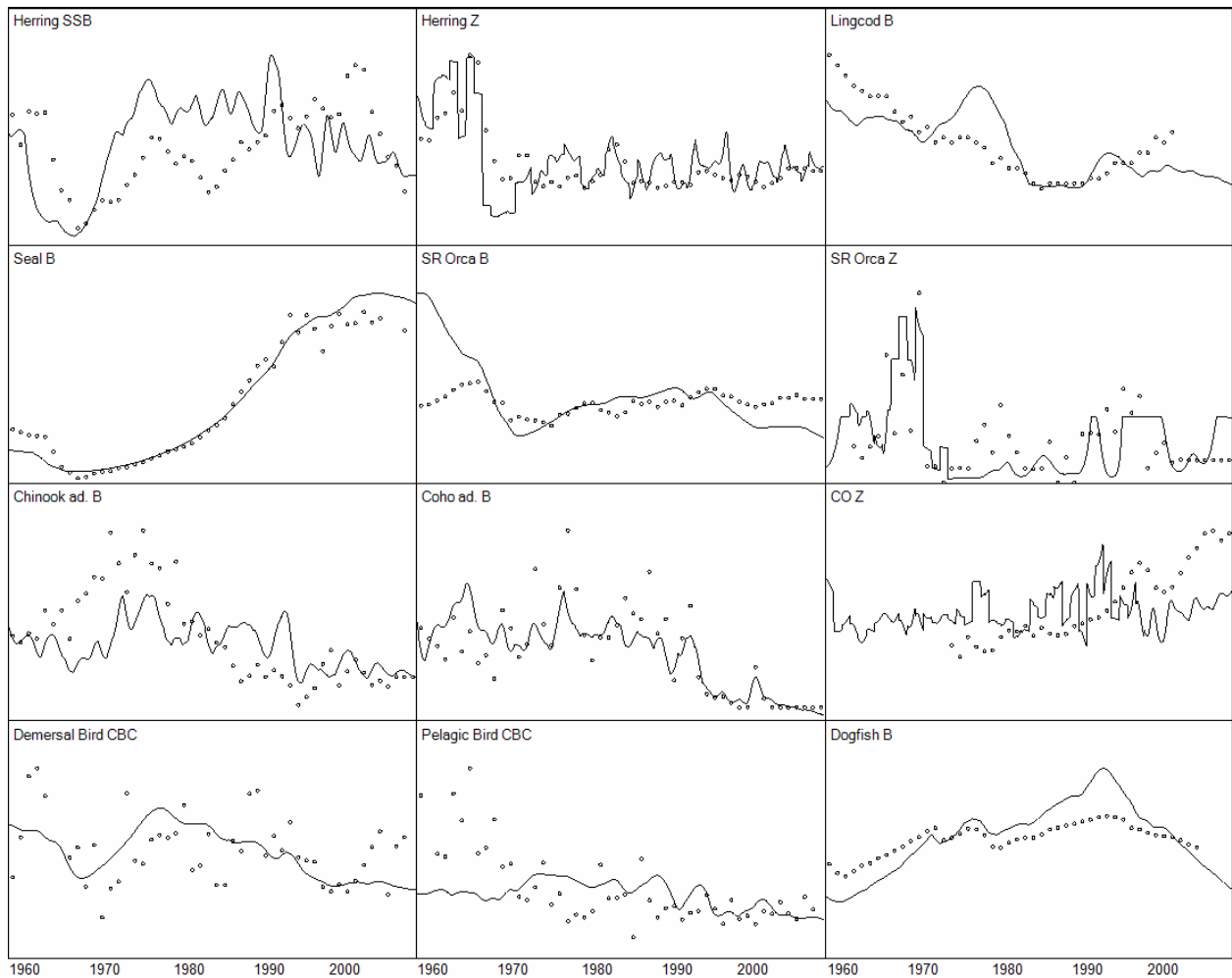


Figure 1: Relative changes in abundances and mortalities of species explicitly modelled in the Strait of Georgia dynamic simulations. Specific metrics were; Herring – spawning stock biomass, and total mortality, lingcod biomass, seal biomass, orca biomass and total mortality, adult chinook and coho biomass, coho adult total mortality, bird counts for marine bird groups and biomass of dogfish.

At carrying capacity	Pacific herring, marine birds, resident orcas, small demersal and small pelagic fishes, krill, carnivorous zooplankton
near carrying capacity	Pacific hake, lingcod, herbivorous zooplankton, chinook salmon
well below carrying capacity	harbour seals, dogfish, coho salmon

Table 1: Estimated, positions relative to carrying capacity, of species in the Strait of Georgia model used to optimise historic biomass and mortality changes.

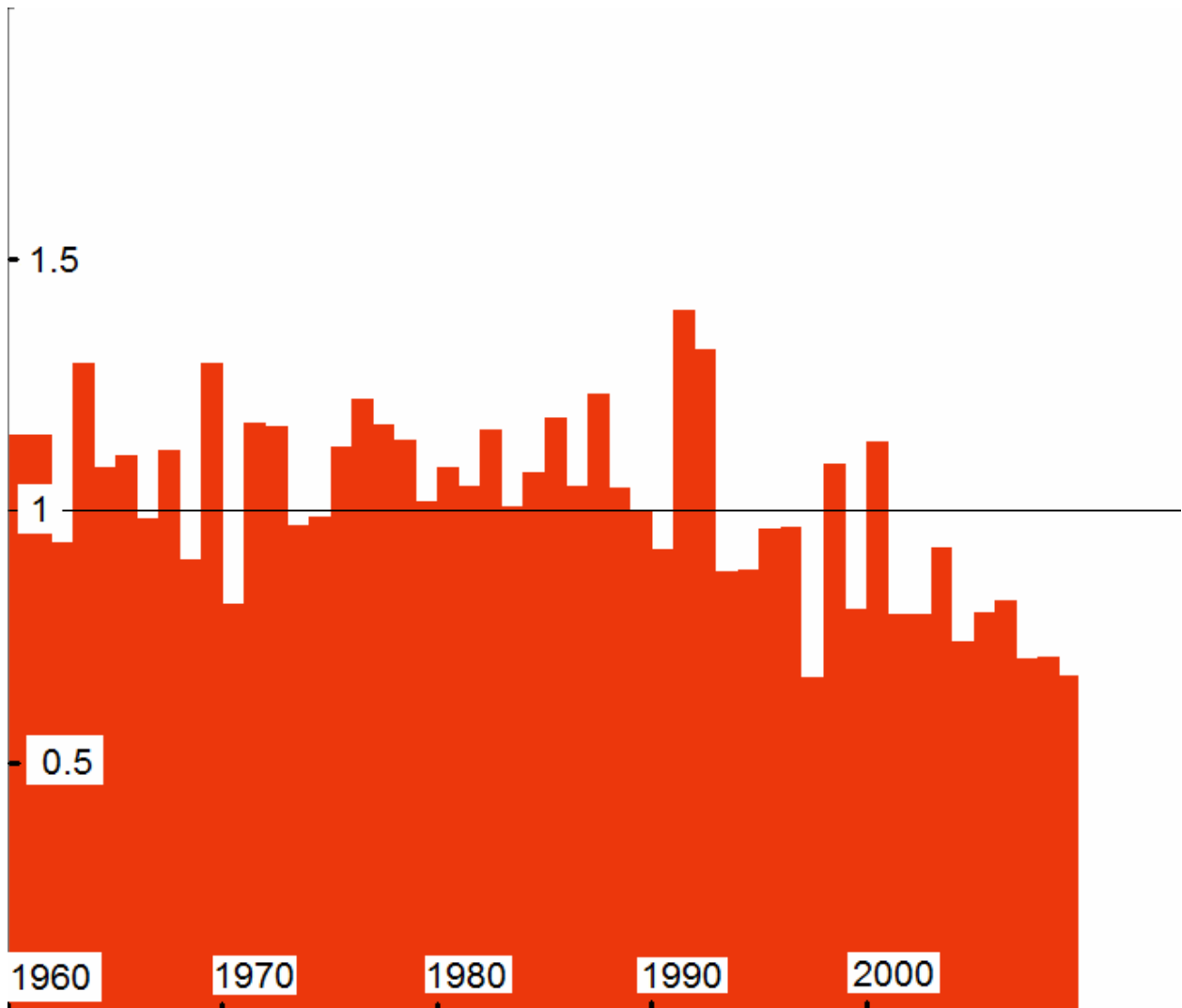


Figure 2: Hindcast annual primary production anomalies in the Strait of Georgia ecosim model to optimise fit of predicted to reference time series. The y-axis is scaled relative to the long term average of 1.

A21: THE INTERACTION OF JUVENILE PINK SALMON ON COHO SALMON IN THE STRAIT OF GEORGIA

R.J. Beamish, C.M. Neville, and R.M. Sweeting.

In even numbered years, large numbers of juvenile pink salmon enter the Strait of Georgia from the Fraser River. This results in juvenile pink salmon being one of the dominant juvenile salmon species in the Strait of Georgia in late spring/early summer. However, possible interactions or competition between this species and other species of Pacific salmon has largely been ignored. This project examined possible interactions between juvenile pink salmon and coho salmon including overlap in distribution and diet

and variation in coho survival and growth in years with (even years) and without (odd years) pink salmon.

The ERI provided funding over several years to assist in the collection of juvenile salmon from the Strait of Georgia in years with and without large abundances of juvenile pink salmon. This provided a natural control to examine the interaction between pink and coho salmon. This work was also supported from funding from the Pacific Salmon Commission (Chinook research) and Pacific Salmon Foundation.

Surveys of juvenile salmon in July and September indicate that in even numbered years the CPUE of pink salmon ranges from approximately 75-750 fish/hour in July and 26-80 fish/hour in September. In 2010 the CPUE in July was 753 fish per hour and was the highest recorded since the surveys began in 1998. In general, 80% of the juvenile pink salmon diet was amphipods, decapods and euphausiids although the ratio of these three prey group changed over the years of the surveys (Figure 1, Beamish et al. 2010). These diet items were also common in the diet of coho representing approximately 60-65% of their diet (Beamish et al. 2010).

In examining the potential interaction of pink salmon on coho salmon survival and growth, several patterns were apparent between pink years and non pink years. When pink salmon were present in the strait there was an increase in the percentage of empty stomachs observed in coho in September (Figure 2). This relationship was not apparent in July. In years when pink salmon were in the Strait of Georgia there was also a decrease in both the abundance and percentage of hatchery coho salmon in the Strait of Georgia in September (Figure 3). In addition, there has been a steady decline in the early marine survival of coho salmon over the past 15 years (Beamish et al. 2008). This decline has been greater in years when pink salmon were in the Strait of Georgia (Figure 4).

In general, our study demonstrates that there is a interaction between juvenile pink and coho salmon during their early marine period in the Strait of Georgia and that this interaction may impact the resulting marine survival of coho salmon (Beamish et al. 2010). The impact on hatchery and wild salmon is not consistent and appears greater for hatchery fish and should therefore be of concern to hatchery managers. Results of this study are presented in a more detailed report to NPAFC (Beamish et al. 2010).

Literature cited

- Beamish, R.J., Sweeting, R.M., Lange, K.L. and Neville, C.M. 2008. Changing trends in the population ecology of hatchery and wild coho salmon in the Strait of Georgia. *Trans. Am. Fish. Soc.* 137:503-520.
- Beamish, R.J., R.M. Sweeting, C.M. Neville, and K.L. Lange. 2010. Competitive interactions between pink salmon and other juvenile Pacific salmon in the Strait of Georgia. NPAFC Doc. 1284. 26 pp.

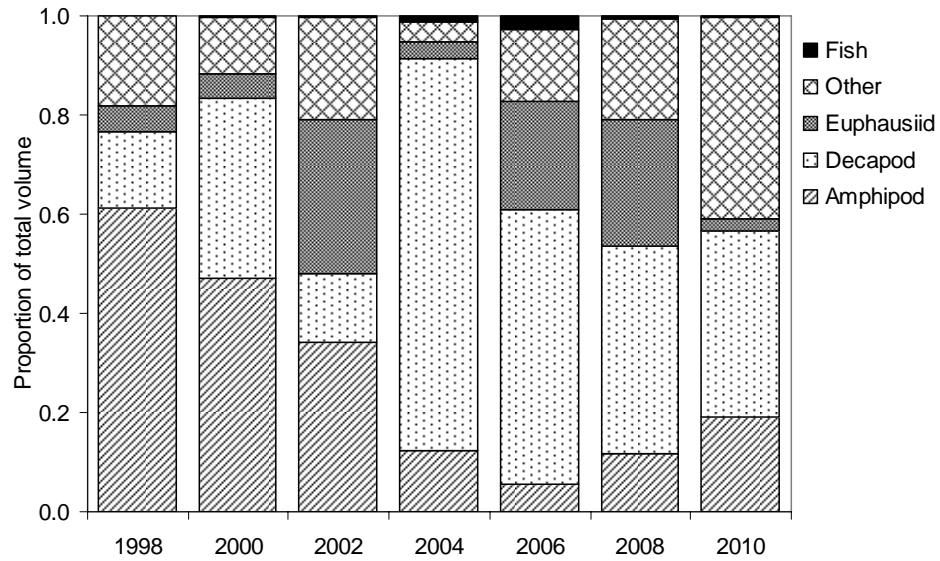


Figure 1. Juvenile pink salmon diet for the July surveys in the Strait of Georgia, 1998 to 2008 (from Beamish et al. 2010).

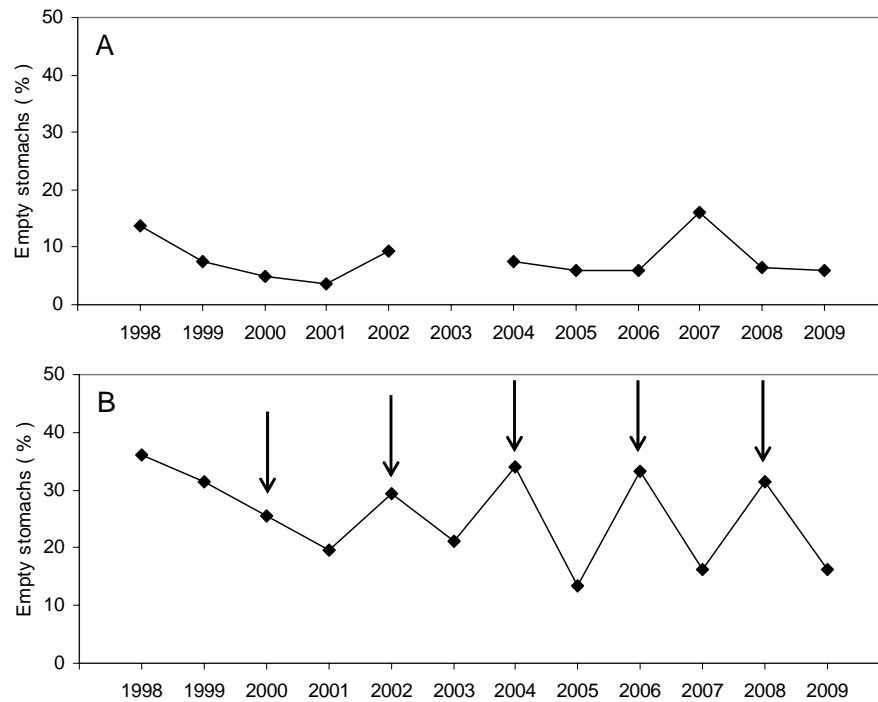


Figure 2. Percentage of empty stomachs for juvenile coho salmon examined in the A) July and B) September surveys in the Strait of Georgia, 1998 to 2009. Arrows indicate the years when juvenile pink were abundant in the Strait of Georgia. (from Beamish et al. 2010).

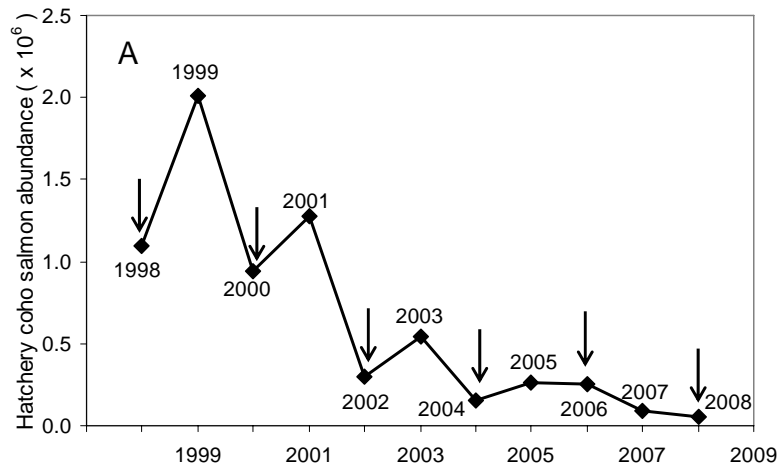


Figure 3. The abundance of hatchery coho in the September surveys (from Beamish et al. 2008, 2010) showing A) that the declines were greater in years where pink salmon were abundant (arrows) and C) the percentage of hatchery coho salmon in the September surveys, showing the reduced percentage in years of large pink salmon abundance (arrows). (modified from Beamish et al. 2010)

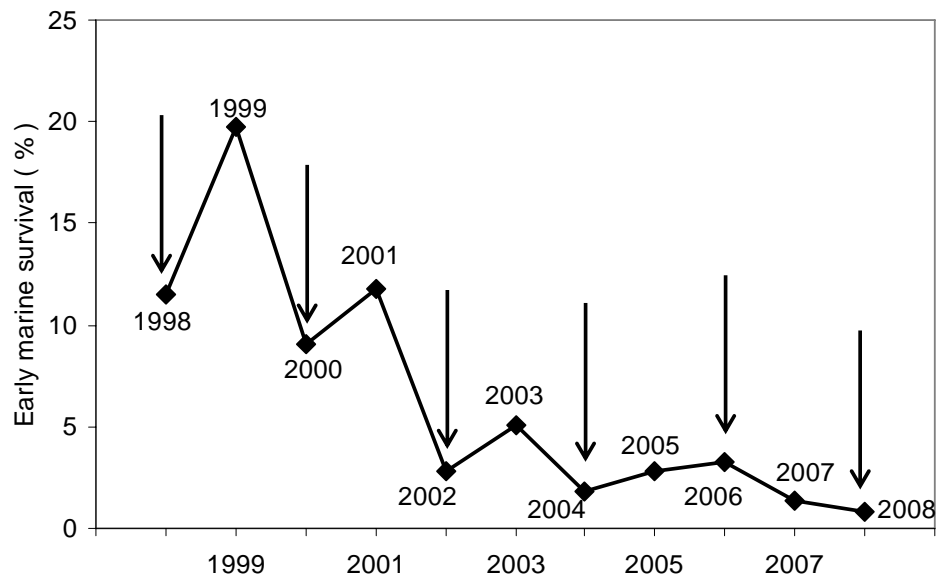
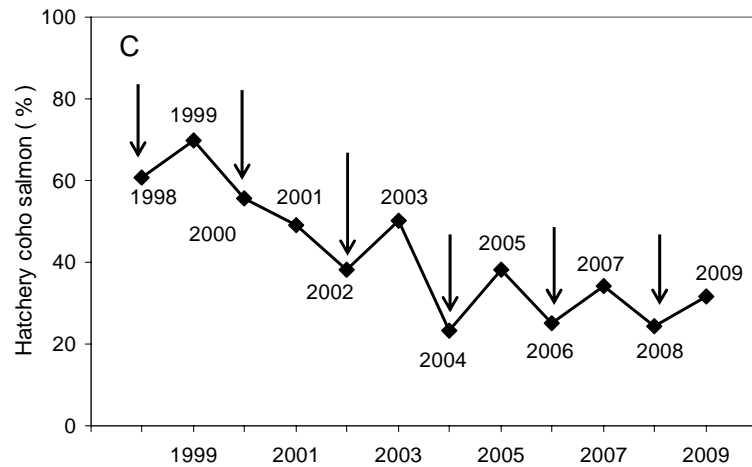


Figure 4. Marine survival from ocean entry until the September survey for coho salmon in the Strait of Georgia (Beamish et al. 2008). Arrows show that the declines are greater in years of juvenile pink salmon abundance.

A22 CHINOOK AND SOCKEYE SALMON DNA

R.J. Beamish, C. Neville and K. Lange

DNA analysis is a critical tool in understanding the early marine survival and distribution of juvenile Pacific salmon. The technology provides detailed information on distribution that was previously not available. Through DNA analysis we are improving our understanding of the changes in the juvenile Chinook and sockeye salmon population in the Strait of Georgia during their early marine life. This has provided information on important changes in the stock structure of both species between July and September. The ERI program provided funding for some of the DNA analysis in 2008, 2009 and 2010. This funding supplemented more extensive work funded by other agencies including the Pacific Salmon Foundation and the Pacific Salmon Foundation.

The request for funding from the ERI in 2010 was 41.5K however the ERI was only able to support 20K of the request. Therefore, we used the funding from the ERI to analyze approximately 1000 chinook salmon collected in the Gulf Islands purse seine survey and in the Strait of Georgia in Feb 2010, July 2010 and September 2010. We have an additional 3000 chinook DNA samples that were collected during surveys in the Strait of Georgia and Gulf Islands in 2010 that have not been analyzed. No sockeye were analyzed with ERI funds in 2010 although we have several thousand that could be analyzed.

DNA analysis is completed from approximately 1500 chinook salmon submitted in 2010. DNA analysis received to date for 2010 indicates that in 2010 Cowichan River Chinook salmon continue to be the dominant stock in the Gulf Islands in June and July. The residence of this stock in the Gulf Islands through the summer months has been a consistent observation for the past three years supporting our hypothesis that the Gulf Islands is a critical rearing habitat for this stock and that they remain and rear in this area for an extended period of time. This information was included in a paper on early marine survival of hatchery and wild chinook salmon (Beamish et al. 2011).

Interpretation of the results from other Chinook DNA analysis from the Strait of Georgia in 2010 is not complete. However, in general there were 69 distinct stocks identified between July and September with the majority of these (44) originating from the Fraser River. Other stocks identified included eight from the east coast of Vancouver Island, five from south coast mainland and eight from Washington State. Information on the change in Chinook salmon stock structure between July and September in the Strait of Georgia was included in a NPAFC publication (Beamish et al. (2010a).

Although no sockeye salmon were analyzed with ERI funds in 2010 there were samples in previous year analyzed. In the past two years the analysis indicated that Harrison River sockeye salmon appear in the Strait in July and are the dominant sockeye stock in the Strait of Georgia in September. This is important information as the Harrison River stock had increased marine survival in recent years whereas the marine survival of other (lake-type) Fraser River sockeye salmon stocks declined (Beamish et al., 2010b). To understand the mechanisms that may be regulating the marine survival of sockeye salmon in general, and this stock in particular, it is important that we understand the marine distribution patterns and if there are specific rearing areas within the strait for various stocks or if the distribution between years varies.

A complete analysis of the 2010 DNA results for Chinook and sockeye salmon will be completed over the this year. The DNA results will be included in several primary papers examining the factors regulating the early marine survival of Chinook and sockeye salmon in the Strait of Georgia expected to be completed over the next fiscal year.

Literature cited

Beamish, R.J., Sweeting, R.M., Neville, C.M., Lange, K.L., Beacham, T.D., and Preikshot, D. 2011. Wild chinook salmon survive better than hatchery salmon in a period of poor production. Environmental Biology of Fishes - Ecological Interactions Special Issue (accepted Jan 2011).

Beamish, R.J., R.M. Sweeting, T.D. Beacham, K.L. Lange, and C.M. Neville. 2010a. A late ocean entry life history strategy improves the marine survival of chinook salmon in the Strait of Georgia. NPAFC Doc. 1282. 14 pp.

Beamish, R.J., K.L. Lange, C.M. Neville, R.M. Sweeting, T.D. Beacham and D.Preikshot. 2010b. Late ocean entry of sea type sockeye salmon from the Harrison River in the Fraser River drainage results in improved productivity. NPAFC Doc. 1283.

Region	Population
Upper Fraser	Bowron Holmes Horsey James Kenneth_Cr Morkill Salmon@PG Slim Tete_Jaune Torpy Willow
Mid-upper Fraser	Baezaeko Chilko Cottonwood L_Cariboo L_Chilcoti Nazko Nechako Quesnel Stellako Taseko U_Cariboo
Lower Fraser	Chilliwac@Stav Harrison W_Chilliwack Upper_Pitt Maria_Slough
North Thompson	Barriere Blue Clearwater Lemieux_Cr N_Thom@Main

	Raft
South Thompson	Bessette Duteau_Cr Eagle L_Shuswap L_Thompson Little South_Thom
Lower Thompson	Deadman Nicola Spius U_Coldwat_SP

Table 1. Stocks of juvenile Chinook salmon from the Fraser River sampled in the Strait of Georgia (June-September) in 2010 based on DNA analysis

A23 COMPARISON OF COHO SALMON IN THE STRAIT OF GEORGIA AND PUGET SOUND

K.L. Lange, R.J. Beamish and R.M. Sweeting and C.M. Neville

The Strait of Georgia and Puget Sound are adjacent marine ecosystems however the early marine mortality of juvenile coho salmon is greater in the Strait of Georgia than in Puget Sound. The objectives of this project were to compare the physical and biological differences between coho salmon from these two adjacent basins. The mechanisms for reduced marine survival in coho salmon are poorly understood although some key factors have been hypothesized. Numerous researchers (Beamish and Mahnken 2001, Holtby et al. 1990, Mortensen et al. 2000, Neilson and Geen 1986) have identified the importance of early marine growth and its relationship to increased marine survival. Beamish and Mahken (2001) and Mahnken (1973) suggested that coho must achieve a critical size by the fall or risk increased mortality during the winter. Therefore, this project focuses on the early marine period between May and September. We examine some of the management and oceanographic factors that may be affecting this early marine growth and overall total marine survival.

Over the period of declining marine survival, the sea surface temperature (SST) has in both regions has increased although the increase in the Strait of Georgia has been greater than in Puget Sound. Since 1980 the increase in SST in the Strait of Georgia has been approximately 1.4°C compared to 0.6°C in Puget Sound (Figure 1). Overall, the sea surface temperature from May to September in Puget Sound is cooler than in the Strait of Georgia by approximately 2.4°C. This variation can be clearly seen in satellite images from May through August 2008 (Figure 2). The preferred temperature range of coho salmon is between 12 and 14°C (Brett 1952). The average SST in the Strait of Georgia during May to September 1980 to 2007 15.6°C compared to 13.2°C in Puget Sound. Thus, coho salmon in the Strait of Georgia over the past three decades have been rearing slightly outside of their preferred temperature range whereas those in Puget Sound have seen optimal temperatures. This variation in temperature between the regions is critical as higher temperatures can have great impacts on the bioenergetics of juvenile Pacific salmon, and these responses are more pronounced

when fish are at or near the marginal temperatures for optimal growth (Beauchamp et al. 2007).

Historical studies on optimal size and time of release provided recommendations for release size and time of hatchery raised coho salmon. These studies indicated that juvenile salmon that entered the ocean at a larger size had better survival rates than smaller fish (Healey 1982, Holtby et al. 1990, Parker 1971, Peterson and Wroblewski 1984, Ward et al. 1989, Henderson and Cass 1991). In addition, studies by Bilton et al. 1982 and Morley et al. 1988 suggested that coho salmon released from hatcheries in April to early-June had the highest survival rates. These historical studies provided the basis for the management practices in the hatchery system. However, changes in the aquatic environment may change the optimal migration time (Wedemeyer et al. 1980) and even optimal size of fish, suggesting that historical release strategies may not be appropriate. When we examine the release time of coho salmon smolts into the Strait of Georgia we see that there has been very little change in the past three decades (Figure 3a) with releases occurring in mid-May. The average release timing of coho into Puget Sound is similar, however, there is more variability in the range of release dates (Figure 3b). Releasing over a longer window of time allows for a greater chance that the coho will enter the ocean when feeding and growth conditions are favorable.

The average size of coho entering the ocean from hatcheries in the Strait of Georgia has also remained consistent over the past three decades (Figure 4a) with the average size at release 20g. In Puget Sound the average size at release is larger (28 g) and has greater variation or range in any brood year cohort (Figure 4b). These larger fish may be more equipped to feed, avoid predation and grow to the critical size required for increased survival over the first winter.

The marine migrations of coho salmon in their first year of ocean residence differ between the Strait of Georgia and Puget Sound. In the Strait of Georgia, coho salmon remain in inside waters until October/November (Chittenden et al. 2009), while in Puget Sound a majority of the juvenile coho salmon leave the inside waters before September. Coho salmon from the Strait of Georgia are therefore not only rearing in suboptimal conditions, they are doing so for a longer period of time, further increasing the potential for mortality in their first marine year.

Changes in climate may be responsible for declines in the early marine survival of juvenile coho salmon in the Strait of Georgia and Puget Sound, but survival may be able to be improved through optimal enhancement strategies. Coho salmon currently reared in hatcheries may not be physiologically able to adapt to the changes in the marine conditions although it is clear that marine survival of coho from Puget Sound is greater than the Strait of Georgia. Hatchery release strategies should be based on environmental indicators. This will be possible as we improve our understanding of the linkages between climate and early marine survival.

References

- Beamish, R.J. and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. *Progress in Oceanography*. 49: 423-437.
- Beauchamp et al. 2007
- Bilton, H.J., D.F. Alderdice, and J.T. Schnute. 1982. Influence of time and size at release of juvenile coho salmon (*Oncorhynchus kisutch*) on returns at maturity. *Canadian Journal of Fisheries and Aquatic Sciences*. 39: 426-447.

- Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, Genus *Oncorhynchus*. Journal of the Fisheries Research Board of Canada. 9: 265-323.
- Chittenden, C.M., R.J. Beamish, C.M. Neville, R.M. Sweeting and R.S. McKinley. 2009. The use of acoustic tags to determine the timing and location of the juvenile coho salmon migration out of the Strait of Georgia, Canada. Transactions of American Fisheries Society 138:1220-1225.
- Healey, M.C. 1982. Timing and relative intensity of size-selective mortality of juvenile chum salmon (*Oncorhynchus keta*) during early sea life. Canadian Journal of Fisheries and Aquatic Sciences. 39: 952-957.
- Henderson, M.A. and A.J. Cass. 1991. Effect of smolt size on smolt-to-adult survival for Chilko Lake sockeye salmon (*Oncorhynchus nerka*). Canadian Journal of Fisheries and Aquatic Sciences. 48: 988-994.
- Holtby, L.B., B.C. Andersen, and R.K. Kadowaki. 1990. Importance of smolt size and early ocean growth to interannual variability in marine survival of coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences. 47: 2181-2194.
- Mahnken, C.V.W. 1973. The size of coho salmon and time of entry into sea water: Part 1 Effects on growth and condition index. 24th Annual Northwest Fish Culture Conference. p. 30-31.
- Morley, R.B., H.T. Bilton, A.S. Coburn, D. Brouwer, J. Van Tyne, and W.C. Clarke. 1988. The influence of time and size of release of juvenile coho salmon (*Oncorhynchus kisutch*) on returns at maturity: results of studies on three brood years at Quinsam Hatchery. B.C. Can. Tech. Rep. Fish. Aquat. Sci. 1620. 120p.
- Mortensen, D., A. Wertheimer, S. Taylor and J. Landingham. 2000. The relation between early marine growth of pink salmon, *Oncorhynchus gorbuscha*, and marine water temperature, secondary production, and survival to adulthood. Fishery Bulletin. 98: 319-335.
- Neilson, J. D. and G. H. Geen. 1986. First-year growth rate of Sixes River chinook salmon as inferred from otoliths: effects on mortality and age at maturity. Transactions of the American Fisheries Society 115: 28-33.
- Parker, R.R. 1971. Size selective predation among juvenile salmonid fishes in a British Columbia inlet. Journal of the Fisheries Research Board of Canada 28: 1503-1510.
- Peterson, I. and J.S. Wroblewski. 1984. Mortality rate of fishes in the pelagic ecosystem. Canadian Journal of Fisheries and Aquatic Sciences. 41: 1117-1120.
- Ward, B.R., P.A. Slaney, A.R. Facchin, and R.W. Land. 1989. Size-biased survival in steelhead trout (*Oncorhynchus mykiss*): Back-calculated lengths from adults' scales compared to migrating smolts at the Keogh River, British Columbia. Canadian Journal of Fisheries and Aquatic Sciences. 46: 1853-1858.
- Wedemeyer, G.A., R.L. Saunders, and W.C. Clarke. 1980. Environmental factors affecting smoltification and early marine survival of anadromous salmonids. Marine Fisheries Review. 42: 1-14.

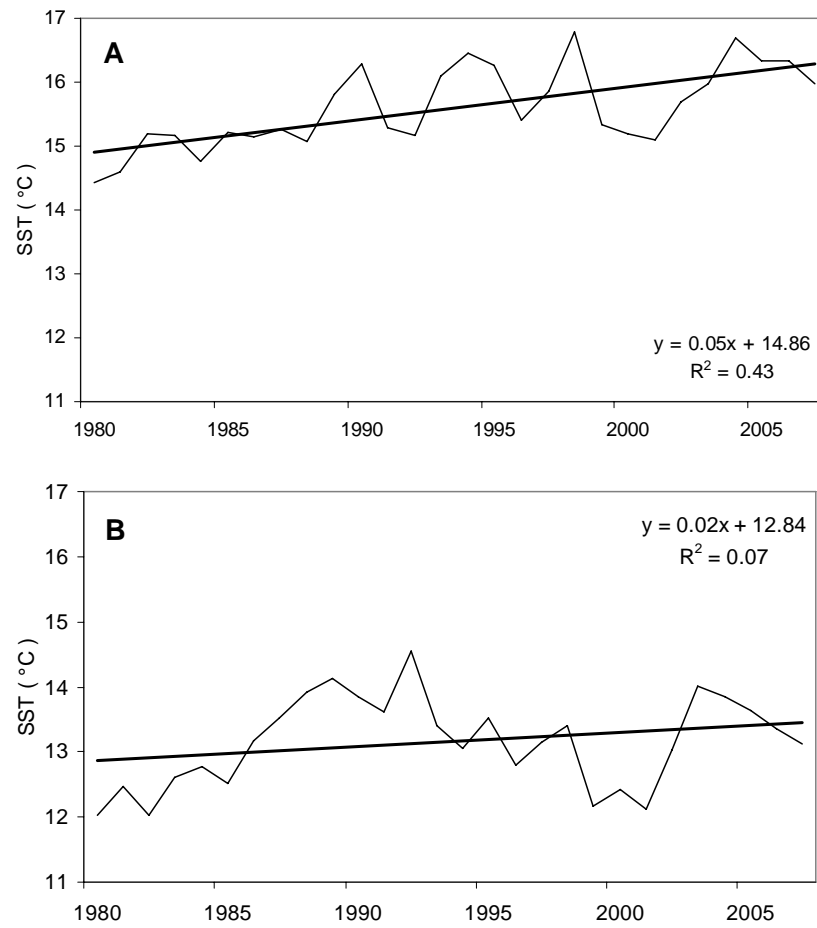


Figure 1. Sea surface temperature (SST) in the Strait of Georgia (A) and Puget Sound (B) from May to September.

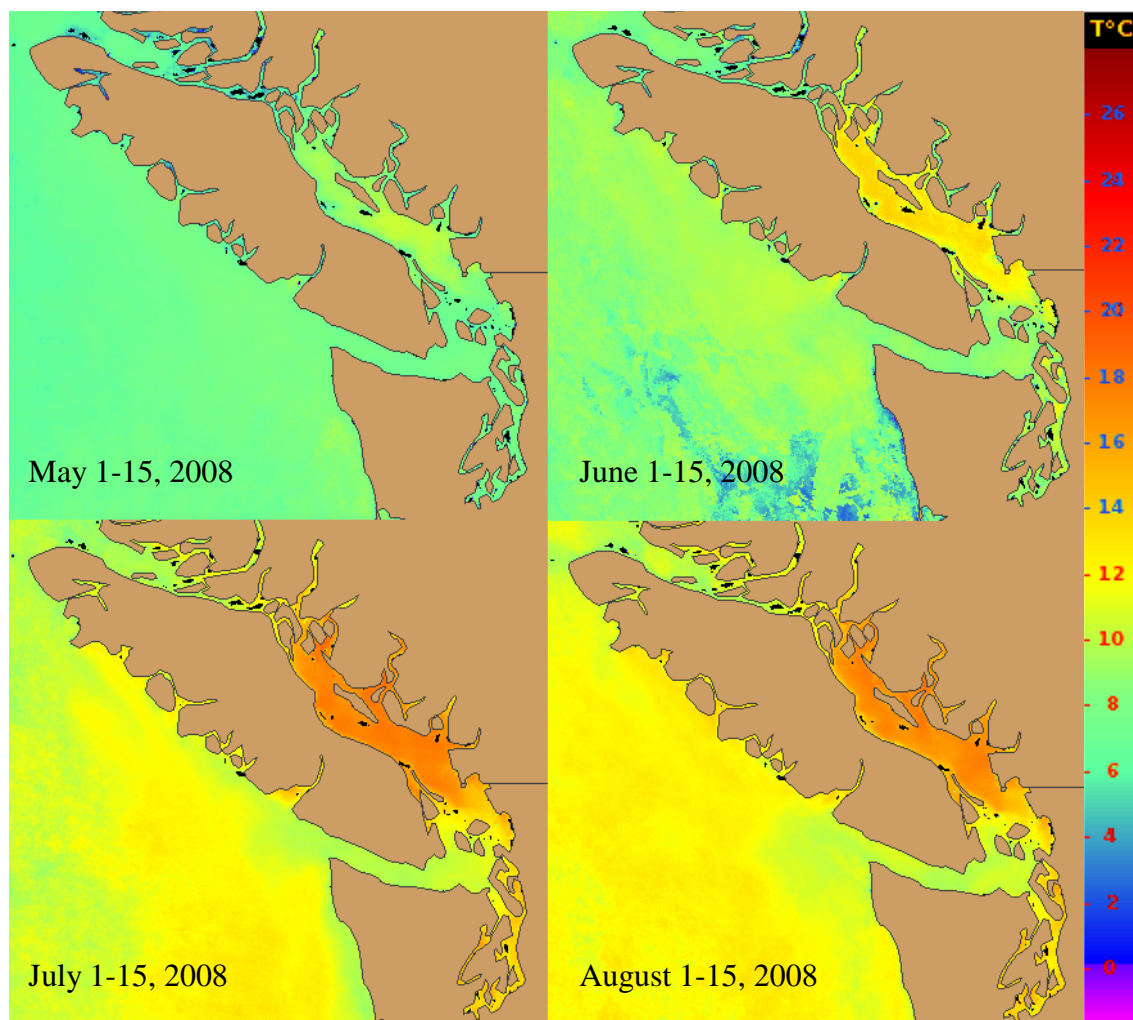
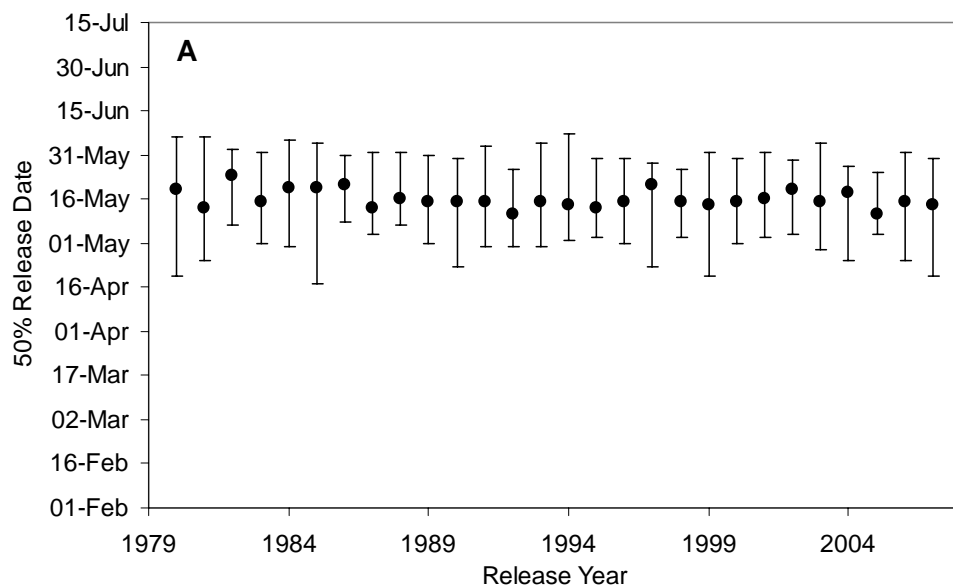


Figure 2. Satellite imagery of the Strait of Georgia and Puget Sound showing the higher sea surface temperature in the Strait of Georgia in May, June, July and August 2008. Each image is the combined average over the first 15 days of each month.



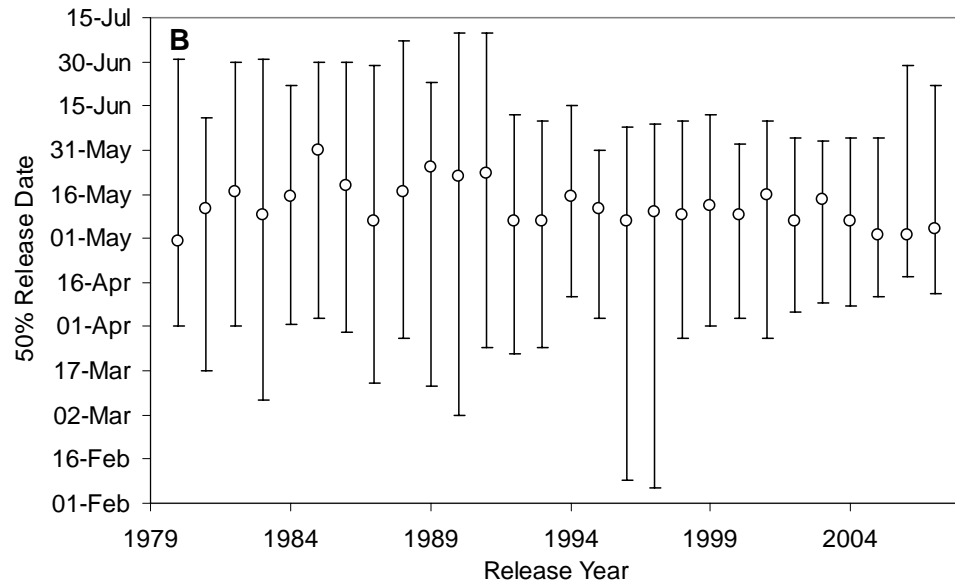
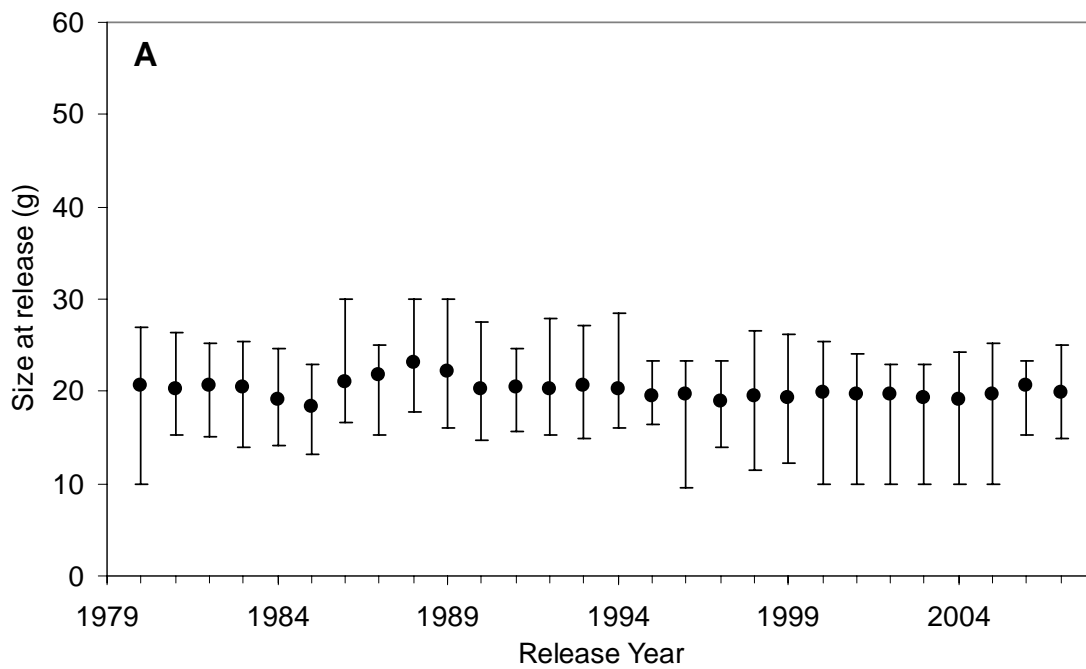


Figure 3. Time that 50% of juvenile coho salmon smolts are released from hatcheries around the Strait of Georgia (A) and Puget Sound (B). Error bars indicate the 5th and 95th percentiles.



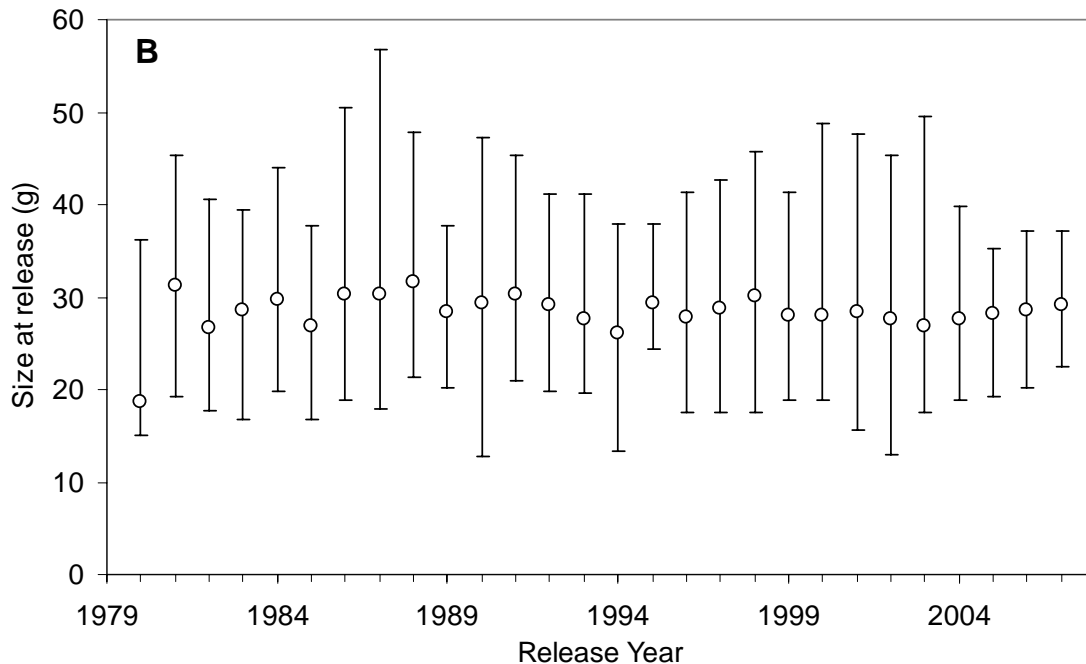


Figure 4. Size (g) of coho salmon smolts when they are released from hatcheries around the Strait of Georgia (A) and Puget Sound (B). Error bars indicate the 5th and 95th percentiles.

A24: CONTROL STUDY FOR ACOUSTIC TAGS SURGICALLY IMPLANTED IN JUVENILE CHINOOK SALMON IN THE MARINE ENVIRONMENT

C.M. Neville and R. Beamish

The ERI partially funded a study (4K) to examine the mortality associated with implanting acoustic tags in juvenile Chinook salmon in the marine environment. Tagged Chinook salmon were maintained in net pens in 2010 to determine tag loss and tagging mortality for juvenile chinook salmon. The studies were a replicate of a study that was conducted in Cowichan Bay in 2008. In 2010, three sites were used; Campbell River (Hidden Harbour net pens), Nanaimo (PBS net pens) and Cowichan Bay. In each study there were 4 groups of fish. Group A consisted of 30 fish were tagged with dummy acoustic tags that matched the size and weight of the VEMCO V7-2L tags used in our telemetry studies. Group B consisted of 30 fish and were treated identical to group A except that they were sutured up without placing a tag in their abdomonel cavity. Group C was a group of 30 fish that were the first control group. They were treated with anaesthetic and had their adipose fin removed but had no surgical procedure. Group D was the second control of 30 fish. They were tranfered directly to study tank without any anaesthetic treatment and were not measured prior to study. In all studies, fish were held post surgery in the net pens for two weeks. The 2008 study in Cowichan Bay was similar except there was no group that underwent surgery without having a dummy tag implanted into their abdominal cavity.

There was no mortality or tag loss of the 30 fish at the Campbell River site in 2010. At the Nanaimo location in 2010, one fish lost its tag through the incision location and none died. The Cowichan net pen study in 2010 was lost due to a large tear in the net pen during a major wind storm in the estuary.

This work provided some baseline information on the effect of acoustic tags on the survival of juvenile chinook salmon. The information was used in a paper presented to the NPAFC in 2010 (Neville et al. 2010). A primary paper referencing information from this study is currently in preparation.

Literature cited

Neville, C.M., R.J. Beamish, and C.M. Chittenden. 2010. The use of acoustic tags to monitor the movement and survival of juvenile chinook salmon in the Strait of Georgia. NPAFC Doc. 1286. 19 pp

A25 DEVELOPMENT OF GENERALIZED INDICATORS FOR THE STRAIT OF GEORGIA MARINE ECOSYSTEM

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A core aspect of ecosystem-based management of marine systems is the development of indicators of the state or condition of the ecosystem. The desire to develop such indicators is rooted in the need to reduce the complexity of natural systems to an (ideally) small set of synthetic indices of ecosystem state, and to measure the progress of management towards the policy objectives for that ecosystem. In human health, an analogy might be body temperature and heart (pulse) rate which allows a rapid assessment of immediate condition but without any indication of cause. Different classes of ecosystem indicators have been recognised, including a distinction between 'contextual' and 'management' indicators. Contextual (also called 'descriptive') indicators provide information on the background conditions, which may include conditions over which humans have no control. Indicators of atmospheric and oceanographic climate such as temperature and salinity, plus synthetic indicators such as the Southern Oscillation and Pacific Decadal Oscillation indices, are examples of contextual indicators. Management (also called 'control' or 'performance') indicators summarise information on conditions over which humans have (some) direct control and, at least conceptually, should be able to measure the results of management actions. Other classes of indicators include 'total welfare' indicators, which provide some measure of overall sustainability of the system, including human social systems, leading to the broader concept of coupled social-ecological marine systems.

The objectives of this project are to:

- i) develop a Driver-Pressure-State-Impact-Response framework for the Strait of Georgia marine ecosystem;
- ii) use this framework in a structured approach to begin identifying a core set of indicators of ecosystem state and ecosystem responses to drivers and pressures in the Strait of Georgia; and
- iii) develop an approach to use these indicators to assess and integrate impacts and changes in the Strait, and to outline options for management responses.

A framework that has gained broad acceptance in other sciences, and which is beginning to be explored for marine systems, is the Driver-Pressure-State-Impact-Response (DPSIR) concept (e.g. Smeets and Weterings 1999; Rapport and Singh 2006). In this framework, 'Driving' forces, such as climate change or human population growth, exert 'Pressures' on the environment (e.g. fishing effort) which change the 'State' of the

environment with possible 'Impacts' to the functioning of the system. Societies may then provide a 'Response' to these changes by modifying the 'Pressures' or 'Drivers' (Degnbol and Jarre 2004). Each of the levels in this DPSIR framework use indicators to summarise their condition. Ultimately, there needs to be a close relationship between indicators and policy objectives. Degnbol and Jarre (2004) and Rice and Rochet (2005) provide criteria for desirable indicators. Although directed towards ecosystem-based fisheries management, their criteria are sufficiently general to apply to ecosystem-based marine management more broadly. General principles are that the indicator should be sensitive (to the process being indexed), observable, acceptable, and related to the management objectives. The best indicators would be those which are easily measured, cost effective, and easily understood. Table 1 provides a selection of potential indicators within a DPSIR framework for the Strait of Georgia marine ecosystem.

To develop ecosystem indicators, time series of potential indicator variables must be assembled. Once assembled, comparisons among these time series also provide an overview of the state of the marine ecosystem (or the coupled social-ecological system if socio-economic variables are included). Figure 1 provides such a comparison since 1970 for a selection of possible indicators for the Strait of Georgia. Four groups of indicators are apparent, based on their pattern of variability since 1970: (1) time series with high values since the early 1990's, e.g. crab landings, seals, killer whales, herring, pink and chum salmon abundances; (2) high values in the middle of the time series (from the early 1980's to early 1990's), e.g. seabird abundances, Black Creek and Quinsam Creek coho salmon marine survivals; (3) high values in the early part of the time series (1970 to early 1980's), e.g. most groundfish species; and (4) a group with no clear trend, consisting of atmospheric indices such as the Pacific Decadal Oscillation.

To identify variables with 'high leverage' which may serve as good indicators of system conditions, this project has been exploring the use of Bayesian Belief Networks (BBN's, e.g. see the report by Araujo et al., this volume). A BBN constructed for a sub-set of these indicators from Table 1 using the time series displayed in Figure 1, is presented in Figure 2. Construction of the relationships underlying this network, so that it can be used to predict the probabilities of having good, average, or poor states for each of these variables, is in progress. Such a network can also be used to identify which variables can serve as useful indicators for ecosystem conditions and for ecosystem objectives.

Conclusions

Has the Strait of Georgia changed?

The answer is "Yes", at least within the context of the length of time series being studied in this project, i.e. since 1970. Indices of a number of fish species have declined since the 1970's, in particular catches of groundfish species. A number of indices were high during the mid-1980's to early 1990's, but have been lower since then, for example many seabird species. But there are also a number of time series which have had their highest values since the mid-1990's, in particular herring, seals, killer whales, and some salmon species, although not all of these have remained high into the later 2000's. The Strait of Georgia marine ecosystem is therefore different in 2009 compared with 1970, but whether it is in worse condition depends on the point of view and the objectives. For example, fishing for halibut has clearly declined but the viewing of marine mammals has clearly increased.

Potential indicators of ecosystem state:

For indicators of the entire ecosystem, 'end-of-chain' nodes such as seals or transient killer whales can serve as appropriate indicators as they integrate the productivity

conditions that support them. However, their response times to perturbations of ecosystem conditions may be slow, because of their longer life spans. For indicators of conditions and specific pathways within the ecosystem, 'central' nodes with multiple connections, for example the timing of the spring chlorophyll bloom, chlorophyll bloom intensity, or herring spawning biomass, will be useful. Note that variables relating to chlorophyll in the Strait are identified as potentially important indicators, but at present are poorly monitored. Overall, Bayesian Network models show promise as tools to integrate ecosystem observations and to predict outcomes (with probabilities) that can be useful to resource managers, although there is a need to validate these models. Work on these issues is continuing within this project.

Acknowledgements

We thank those who have provided data for this project, in particular: Lizette Beauchemin, Brenda Waddell, Sandra Bassett, Jake Schweigert, Susan Allen, Jaclyn Cleary, Sue Grant, Brian Rusch, Gary Borstad, Leslie Brown, Yong Mei Liu, Jim Irvine, Rick Thomson.

References

Araujo, A, Holt, C., Curtis, J and Perry, I. (this volume) Bayesian Belief Networks as decision-support tools for ecosystem-based management. CSAS Research Document.

Degnol, P. and Jarre, A. 2004. Review of indicators in fisheries management – a development perspective. *Afri. J. Mar. Sci.* 26: 303-326.

Rapport, D.J. and Singh, A. 2006. An EcoHealth-based framework for State of the Environment reporting. *Ecol. Indicators* 6: 409-428.

Rice, J.C. and M-J. Rochet. 2005. A framework for selecting a suite of indicators for fisheries management. *ICES J. Mar. Sci.* 62:516-527.

Smeet, E. and Weterings, R. 1999. Environmental indicators: typology and overview. European Environment Agency, Technical Rept. 25. Copenhagen. 19 pp.

Drivers	Pressures	States:	Impacts:
Human pop'n	Upland agriculture	Contaminants /	Benthic invert
Seafood demand local	Shoreline habitat loss	water quality	landings –
Seafood demand	Marine shipping	Invasive spp.	commercial
export	Industrial activity	Aquaculture prod.	Benthic invert
Energy demand	Urban wastewater	Nutrient conc.	landings - rec
Tourism	Fishing effort – com.	Turbidity	Demersal fish l.
Atmos. Pressure	Fishing effort – rec.	Sedimentation	Pelagic fish l.
patterns	Aquaculture – area	Mixed layer depth	HABs
Greenhouse has conc.	Mech.disturbance	Water flushing	Toxins in
	Temperature	time	seafood
	Vertical mixing	Macrophytes	
	Winds	(Food webs)	
	Currents	Biodiversity /	
	Episodic inflows	trophic	
	Freshwater rivers	structure	
	Acidification		

Table 1. Sample of potential indicators of ecosystem Drivers, Pressures, States, and Impacts within a DPSIR framework for the Strait of Georgia, BC.

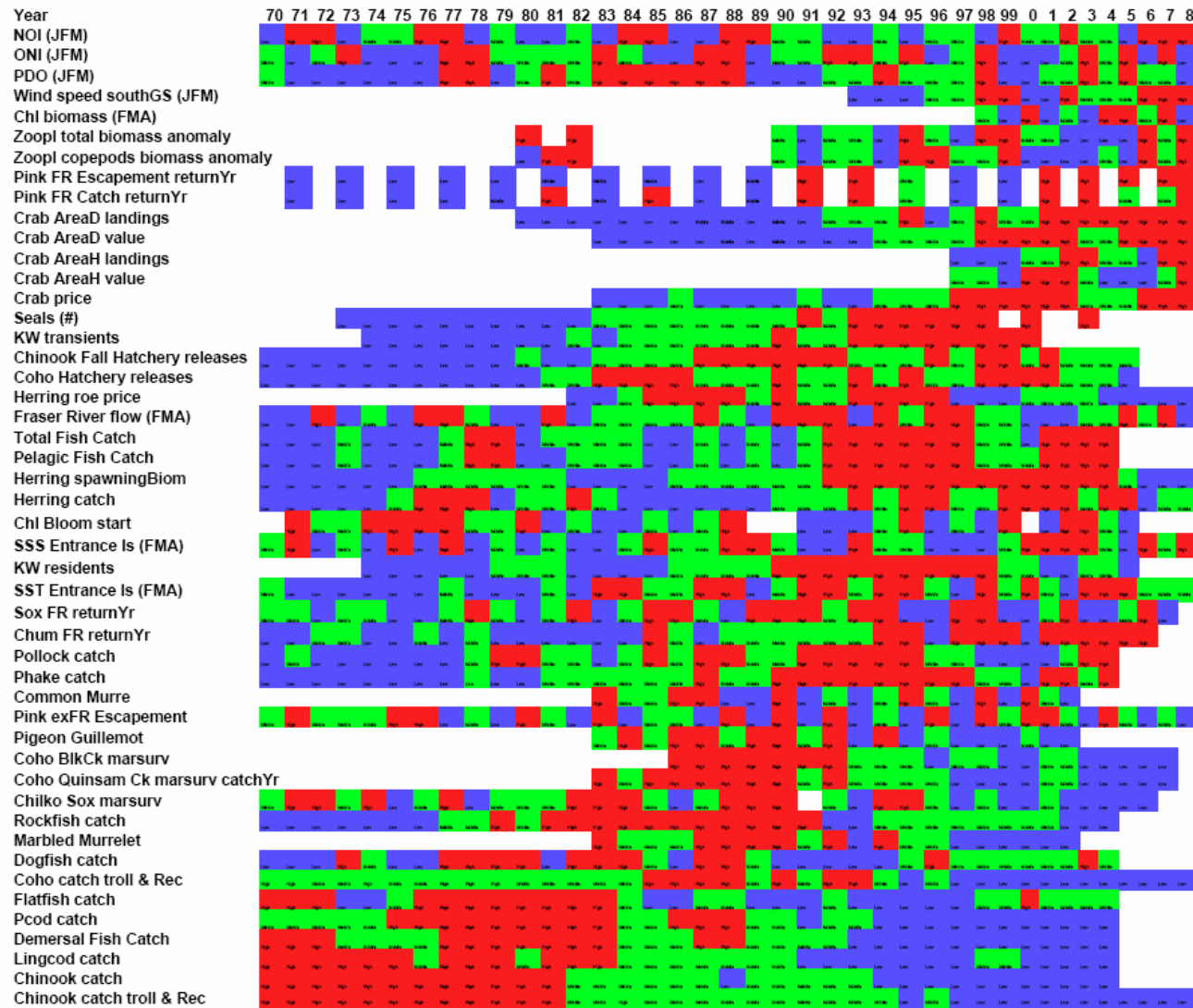


Figure 1. Time series of variables for the Strait of Georgia marine ecosystem. Data for each variable has been recalculated into thirds and are displayed in blue for years in the lower third of the values (i.e. the lower 33% of the values of the time series), green for years in the middle 33% of the time series, and red for years in the upper 33% of the time series). Variables have then been clustered based on the similarity of their time series variations.

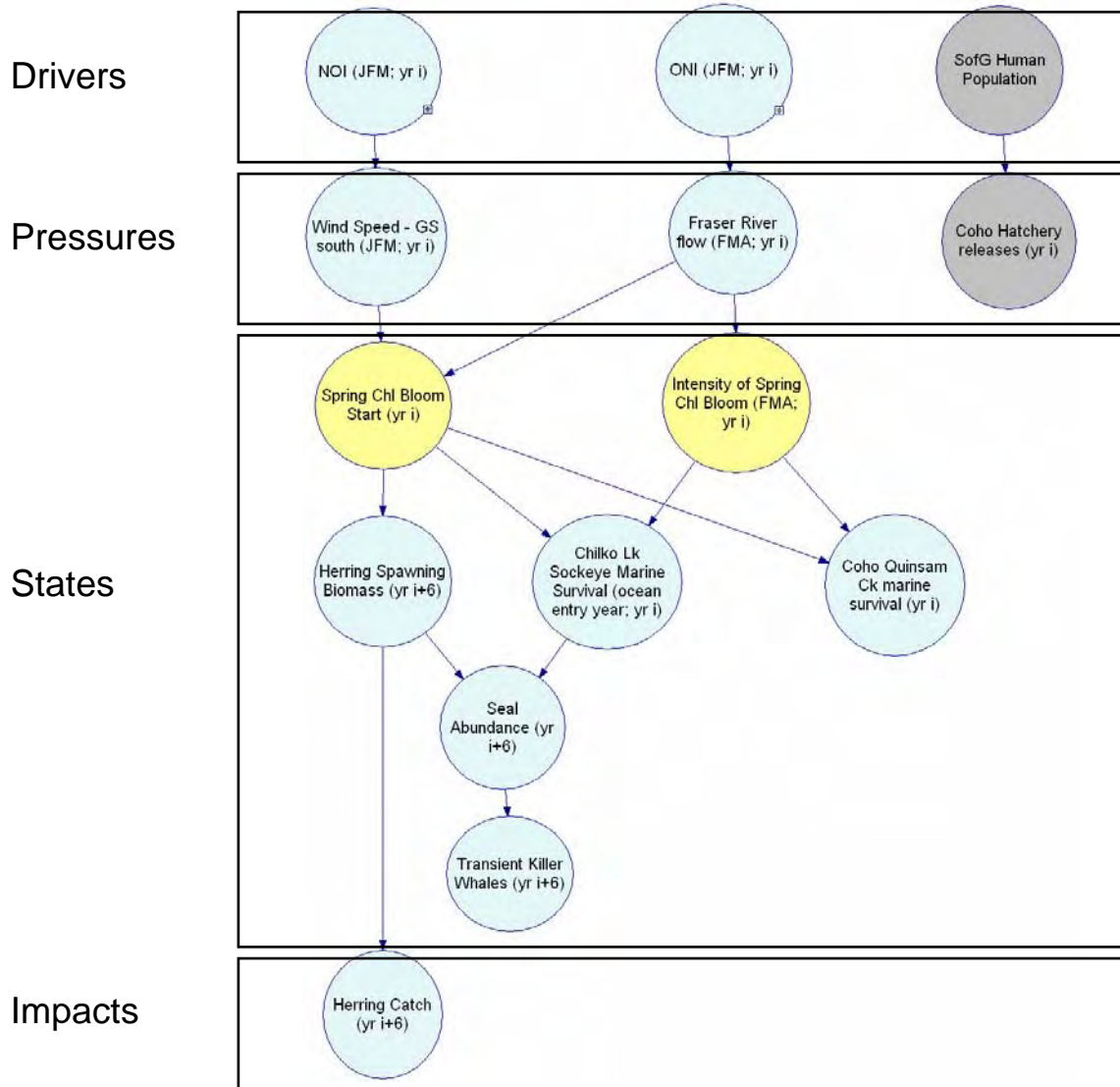


Figure 2. Example Bayesian Belief Network for the Strait of Georgia, presented following a Driver-Pressure-State-Impact-Response framework, for the ecosystem components connecting atmospheric indices to physical and biological variables to the production of herring, seals, transient killer whales and Chilko Lake sockeye marine survivals.

A26: DEVELOPMENT OF AN OCEAN CIRCULATION MODEL FOR THE STRAIT OF GEORGIA

Diane Masson

An application of the Regional Ocean Modeling System (ROMS) is being developed for the Strait of Georgia. This model is the ocean dynamics component of an end-to-end modeling system representing all ecosystem components from primary producers to top predators, linked through trophic interactions and affected by the physical environment. ROMS, is a free-surface, terrain-following, primitive equations ocean model widely used by the scientific community for a diverse range of applications. The physical model is

forced by freshwater inflow from major rivers, tidal forcing at open boundaries, as well as wind stress and heat flux at the ocean surface. The model is being developed to reproduce realistic circulation features and water properties (temperature and salinity) for the Straits of Georgia and Juan Fuca over a typical seasonal cycle as well as to capture year to year variability.

The model grid exists in both 1 km and 2 km horizontal resolution and has 31 sigma layers in the vertical and includes, in addition to the Strait of Georgia, Juan de Fuca Strait and Puget Sound. It is forced by the 8 leading tidal constituents at the open boundaries: K_1 , O_1 , P_1 , Q_1 , M_2 , S_2 , N_2 , and K_2 . Monthly discharge from a total of 18 coastal rivers is included, the Fraser River being the dominant freshwater source. Seasonal temperature and salinity observed vertical profiles are used at both the mouth of Juan de Fuca Strait and the northern end of the Strait of Georgia to prescribe properties of water flowing into the domain. Average monthly values of atmospheric parameters observed at Vancouver airport are used to compute the heat flux at the surface.

Because the model output will be used to force a lower trophic model, simulating a realistic near surface stratification is a primary concern. As such, one needs to force the model with a realistic wind stress. Initially, the wind stress was extracted from simulations by the atmospheric MM5 coastal model (UW) (Fig. 1a). It was however noted that this model does not capture well topographic effects near the coast (Tinis et al., 2006). In an attempt to improve atmospheric forcing, new wind stress field were prepared using hourly data for 30 local wind observation stations. The measured wind stress vectors were interpolated onto the model grid using a thin plate radial basis function. The resulting wind fields appear to better capture local orographic effects such as the steering of the winds along the axis of Juan de Fuca Strait as well as the summer land-sea breeze in the central Strait of Georgia (Fig 1b).

Using the improved hourly wind stress, a yearly simulation was successfully completed for 2007. Detailed analysis and validation of the model results are on going but some preliminary results are presented here. Fig. 2 gives both the measured (a) and modeled (b) vertical temperature distribution, through the year, at the Nanoose station located in the deep central basin of the Strait of Georgia. At the surface, the modeled temperature closely follows the observations, from a winter low of about 6 °C to a summer maximum of about 17 °C. At depth, the much smaller seasonal temperature variations are well captured by the model, with a winter maximum and a summer minimum, although the modeled temperature are generally too high by about 0.5 °C. At mid-depth, the model appears to also capture the seasonal signature of the sill depth intrusions, relatively cold in the spring and warm in the fall.

The Strait of Georgia is a complex dynamical oceanic system with significant variability on a wide range of time scales. The existing model of the Strait of Georgia appears to capture the main features of the seasonal variability in temperature and salinity. The model validation will now be extended by including an extensive comparison with various current datasets. Also, the various forcing will be prepared for a 10 year period (1998-2008) in order to examine the year to year variability. Ultimately, future climate projections of local atmospheric forcing will permit to address the problem of climate induced changes in the strait (e.g. warming trend as described in Masson and Cummins, 2007).

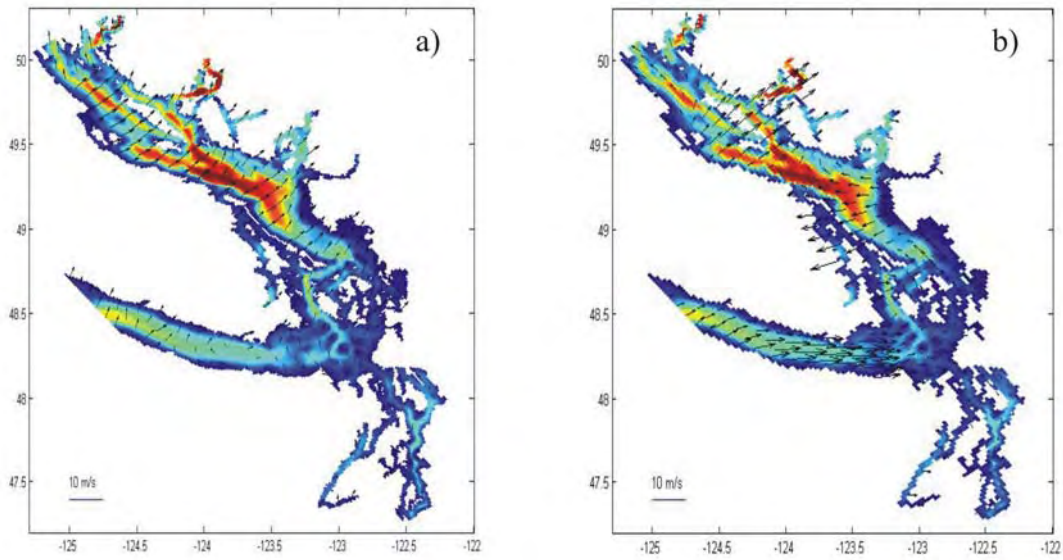


Figure 1 Mean hourly surface wind vectors on July 1, 2007 (23h00), from the MM5 atmospheric model (a) and from observations (b) (color contours are for ocean depths)

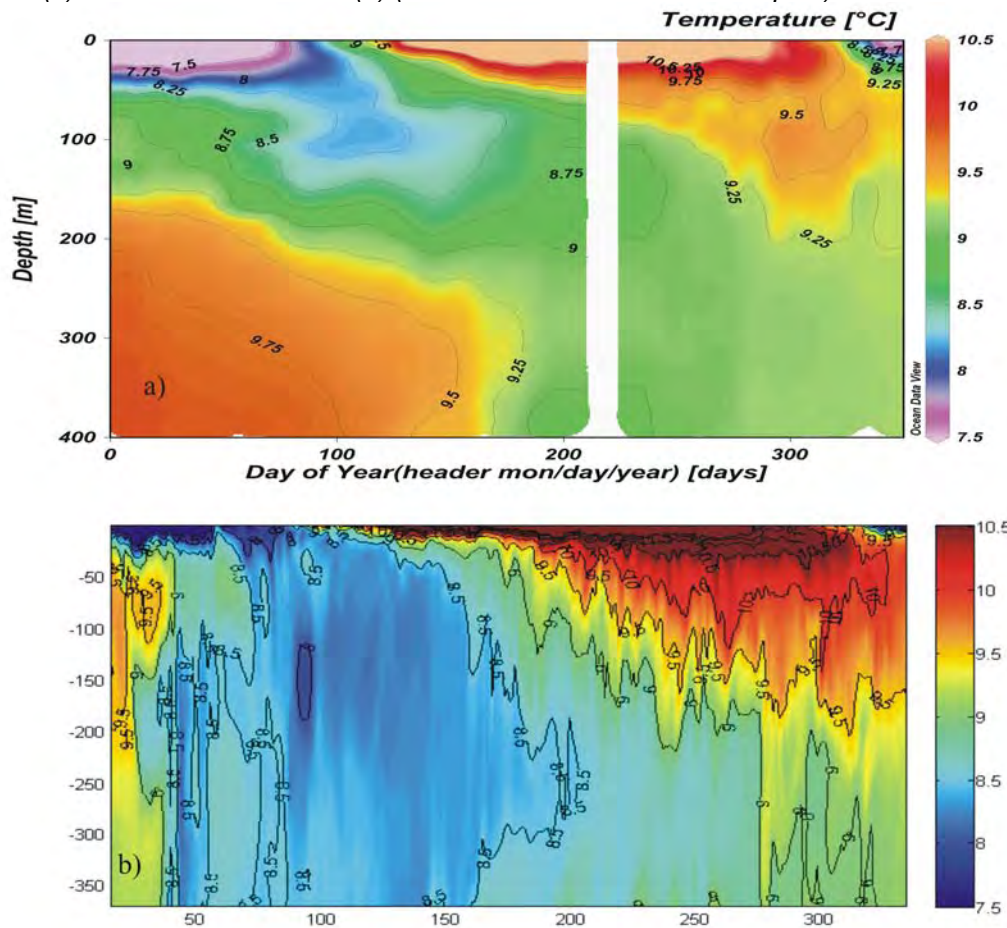


Fig. 2 Vertical distribution of temperature through the year measured (a) and modeled (b) at the Nanoose station (central Strait of Georgia) for 2007. Note the 2 different colour schemes.

References

Masson, D., and P.F. Cummins, 2007. Temperature trends and interannual variability in the Strait of Georgia, British Columbia. *Cont. Shelf Res.*, 27, 634-649.

Tinis, S.W., R.E. Thomson, C.F. Mass, and B.M. Hickey, 2006. Comparison of MM5 and buoy winds off the West Coast of North America. *ATMOSPHERE-OCEAN*, 44(1), 1-15.

A27: GROUND FISH IN THE STRAIT OF GEORGIA

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Historically, groundfish species supported an important fishery in the Strait of Georgia, currently, however, they are generally at low abundance levels such that most commercial (and some recreational) fisheries have been closed. Species caught have included various flatfish and rockfish species along with Pacific cod, hake, pollock, dogfish and lingcod. At present, groundfish stocks in the Strait of Georgia tend to be highly localized and relatively small (with two exceptions) compared to more productive areas like the Queen Charlotte Basin. Most species occur at depths of between 50 and 100 m. Knowledge on groundfish in the Strait of Georgia is largely derived from commercial catch data, with a few exceptions (such as occasional acoustic surveys for Pacific hake).

Three gear types have been used in commercial groundfish fisheries in the Strait of Georgia: bottom trawl, midwater trawl, and hook and line. Historically, the hook and line fishery was directed at inshore rockfish, lingcod, dogfish, Pacific cod and halibut, landing small quantities to local markets which persisted for more than 60 years. In recent years, the fishery has focused on small landings of flatfish and cottids to local live markets. Most of the trawl fishing took place in the mid-southern portion of the Strait. There is presently no commercial fishery for halibut in the Strait, likewise the Strait has been closed to commercial lingcod fishing since 1991, and the inshore rockfish fishery was drastically reduced in 2000. At present, the only significant commercial hook and line fishery is for spiny dogfish. Midwater trawls have been used to target Pacific hake and walleye pollock.

Trends in catch

Total landings of all groundfish species declined from around 2000 t in the early 1950s to around 500 t at present (Figure 1). Total landings for flatfish species declined from 205 t to 100 t over the same period, although they have been fairly stable since the late 1980s. Pacific cod landings declined from 1300 t in 1954 to zero by 1995. The largest fishery in terms of biomass removals has been mid-water trawl, which targets Pacific hake and walleye Pollock (Figure 2). It peaked at 20,000 t in 1995 and has fluctuated since then based on market conditions and the size of hake caught. Catch by this gear type is 90-100 % hake. The hook and line fishery for inshore rockfish persisted at a low level for many years. However, beginning in the early 1980s with the development of a live market in Vancouver, fishing pressure increased and, with unrestricted growth, landings peaked in the late 1980s at ~ 500 t. Catches were stabilized in 1992 when quota management for these species was established. However, by 2003 inshore rockfish were acknowledged as being trouble and quotas were drastically reduced so that the all-sector catch for Inshore Rockfish in the Strait of Georgia is now 26 t (Figure

3). Lingcod landings in the Strait of Georgia peaked in the early 1960s then declined until the late 1980's when it was closed entirely.

Catch per unit of effort (CPUE) in the bottom trawl fishery (25% qualified) has been used to examine trends in relative abundance for several commercial species over the period 1954-95. Since 1995, the fishery has been managed using trip limits or Individual Vessel Quotas, so that CPUE is not comparable with the previous time period. A decline is apparent for all species (Figure 4). It is greatest for Dover sole and Pacific cod and least apparent for Rock sole and English sole. The data presented in Figure 4 are preliminary, and CPUE has not been adjusted for changes in fishing power. Thus the rate of decline is probably greater than that shown here.

Trends in biomass

Biomass estimates in the Strait of Georgia are available for three species of groundfish: Pacific hake, dogfish and lingcod. The biomass of hake comes from hydroacoustic surveys, whereas those for dogfish and lingcod are determined by age-structured assessment models. It is believed that Pacific hake and dogfish make up most of the biomass of resident groundfish species in the Strait of Georgia (Pacific hake: 50,000 – 130,000 t; spiny dogfish 18,193 – 62,673 t). Historically, lingcod has also been an important component (estimated at 14,000 t in 1925, 4,000 t in 2001). The biomass of lingcod declined from 14000 t in the 1920s to under 2000 t by the early 1990's, at which time the commercial fishery was closed. The recreational fishery for lingcod was closed in 2002 but reopened in 2005 after the stock had shown some recovery; it has continued to recover since that time.

Future potential changes

Environmental forcing factors have been shown to be important for a number of species in areas outside of the Strait of Georgia, suggesting they may also be important for stocks within the Strait of Georgia. Most notable are the influences of temperature and transport at the early life history (egg and larval) stages. The overall range of groundfish species along the west coast of North America is considered to be a general indicator of how species will respond to environmental forcing. A number of species are near the limit of their geographic range and significant changes in the environment (e.g. global warming) may affect their abundance relative to species in the geographic centre of their range. In the absence of fishing, a temperature increase may favour Dover sole, English sole and Petrale sole while it could negatively impact Pacific cod and rock sole.

Conclusions

The groundfish community in the Strait of Georgia has undergone a dramatic change over the last four decades, with reduced abundances of Pacific cod, lingcod and inshore rockfish. Presently, Pacific hake and dogfish account for a large proportion of the groundfish biomass in the Strait. A number of species are likely to respond to change in ocean transport and temperature. At least five species (rock sole, Pacific cod, English sole, Pacific sanddab, Pacific hake) are near the limit of their geographic distribution and could be affected (positively or negatively, depending on the species) by global warming trends.

There are considerable needs for research of groundfish in the Strait of Georgia. A longline hook and line survey for rockfish has just been started. Remotely operated vehicle surveys are also being undertaken to assess recovery of rockfish populations. Mid-water acoustic surveys for hake need to be repeated. Additional bottom trawl

fishery-independent surveys are also needed, as is work examining trends in fisheries abundance and environmental forcing.

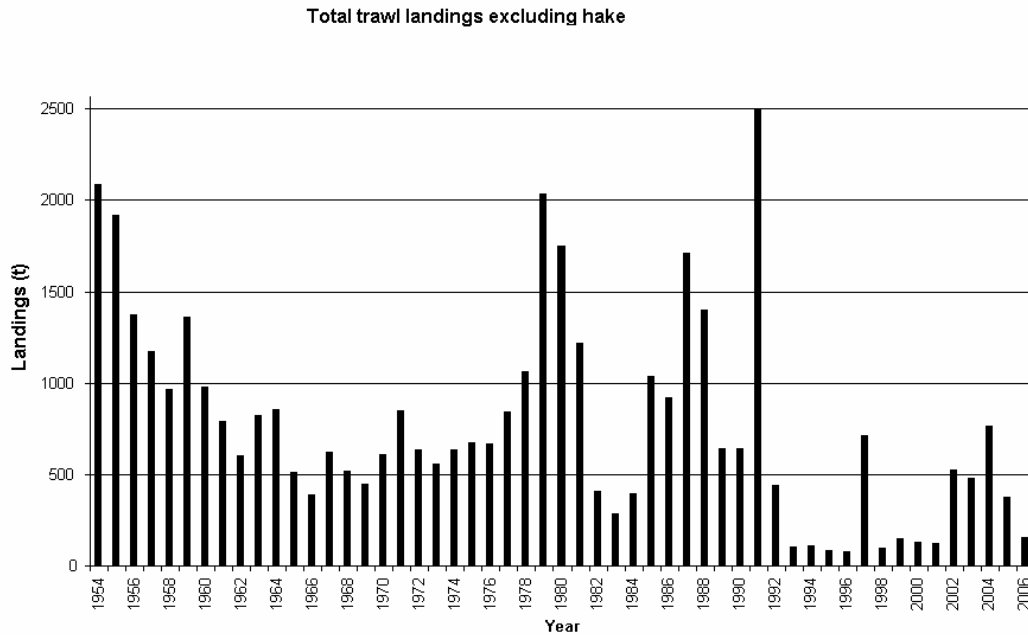


Figure 1. Total trawl landings (t) of groundfish in the Strait of Georgia, 1954 – 2006.

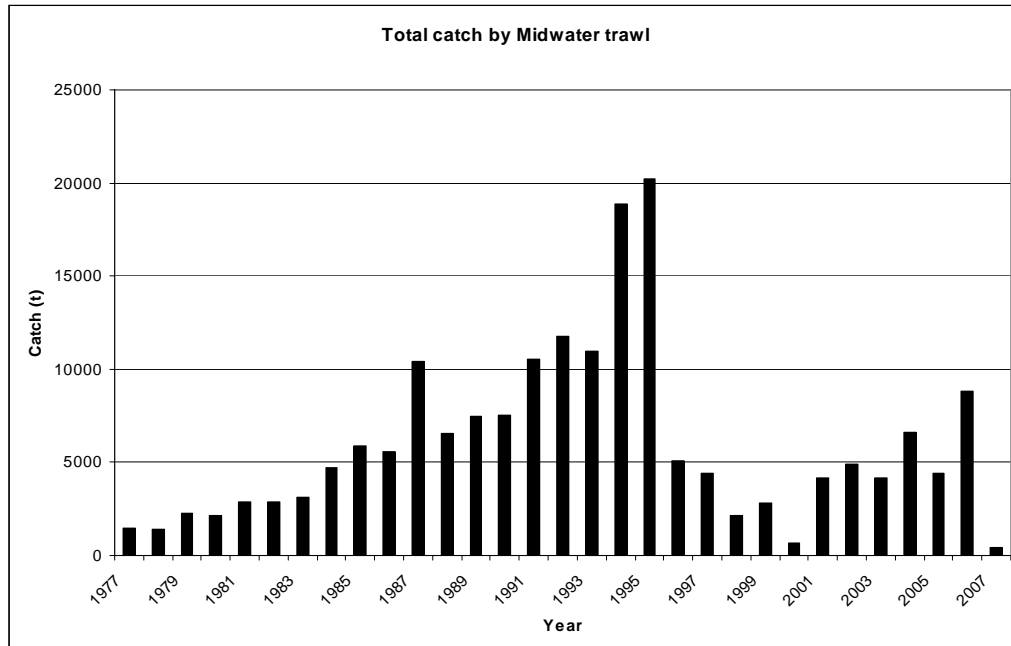


Figure 2. Total catches of commercial mid-water trawl gear in the Strait of Georgia. Pacific hake comprise approximately 90-100% of these catches.

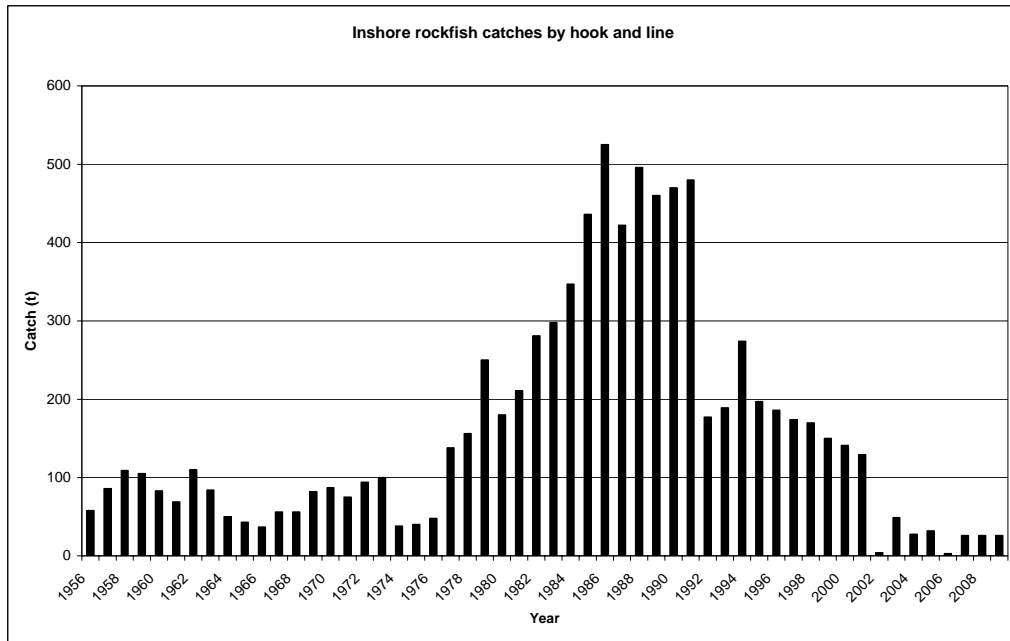


Figure 3. Catches of inshore rockfish species in the Strait of Georgia, from hook and line gear.

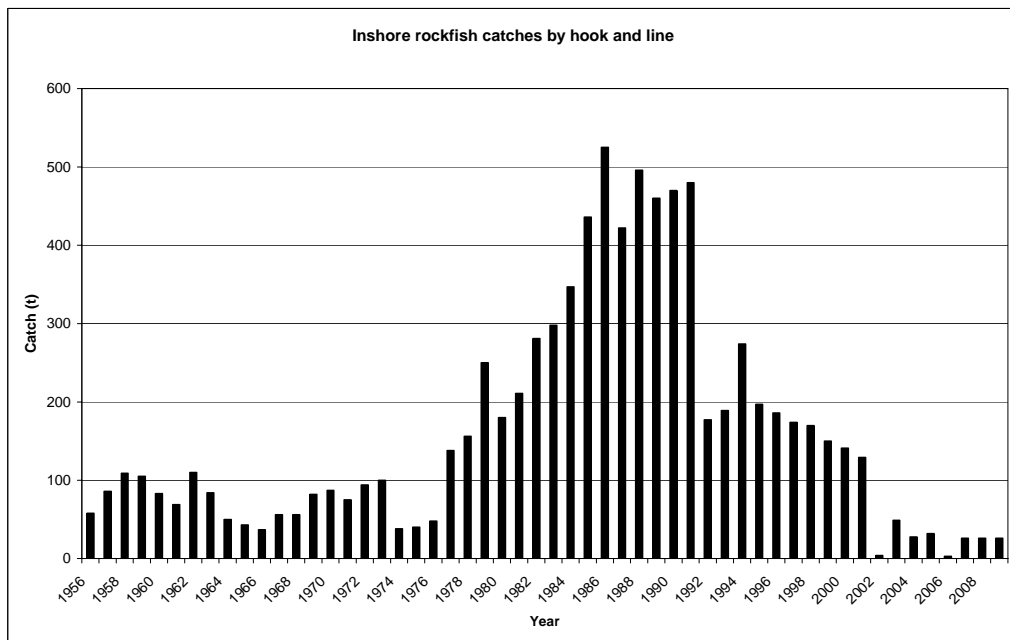


Figure 4. Catch per unit of effort (CPUE) in the bottom trawl fishery as a measure of changes in relative abundance for several commercial species over the period 1954-95.

A28: DIET OF HARBOUR PORPOISE AND DALL'S PORPOISE IN THE STRAIT OF GEORGIA AND STRAIT OF JUAN DE FUCA

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Introduction

Harbour porpoise and Dall's porpoise occur in the Strait of Georgia and Strait of Juan de Fuca. These species are generally known to feed on schooling fish and squid, however to better understand their role in the Strait of Georgia ecosystem specific information about their diet is warranted. In this study diet was investigated by identifying and enumerating prey fragments (bones, otoliths, beaks) in stomach contents from stranded and killer whale killed porpoise. Most samples analysed in this study are from strand events since 2000. Results are compared with those from the 1990's collected using the same methods and in the same study area (Walker *et al.* 1998) and since 2000 (Hall 2004).

Carcasses came from the central and southern Strait of Georgia, however, most came from the southern Gulf Islands and the area off Victoria and with a seasonal peak in spring and a smaller peak in August. This was true for both porpoise species and it was also true for the porpoise samples analysed in the 1990's by Walker *et al.* (1998). The spatial and temporal pattern is evident among all stranding incidents for these species in the study area (DFO Marine Mammal Incident Program unpubl. data). Given the seasonal pattern in the samples the diet information collected reflects spring and summer diet.

This progress report encompasses analyses commencing in 2007-08 and continuing through 2010-11. However samples processed in 2009-10 and 2010-11 have only recently been submitted to Pacific Identification Inc. Their results will be included when they become available (Table 1).

Diet Results to Date

Harbour Porpoise

Among 17 stomachs processed, three were empty. A total of 517 prey individuals were identified among the remaining 14 stomachs. Fish dominated the diet both numerically and by frequency of occurrence. Seven species of fish were identified as well as squid (cephalopod beaks have not been identified to species) and polychaete worms. Four of the fish species identified in this study were also identified among 10 fish species and three squid species in 26 harbour porpoise samples from the 1990's (Walker *et al.* 1998). These were Pacific herring, Pacific hake, walleye pollock and shiner perch. In total, 13 fish species were identified in the diet of harbour porpoise in the Strait of Juan de Fuca and Strait of Georgia (Table 2).

Dall's Porpoise

Among ten stomachs a total of 923 prey individuals (876 fish) were identified. Six fish species were identified as well as cephalopods and polychaete worms. Four of the fish species were also identified in the Walker *et al.* (1998) study. These were Pacific herring, Pacific hake, walleye pollock and California lanternfish (a Myctophid). Walker *et al.* (1998) identified a further 10 fish species in 22 Dall's porpoise as well as several species of squid. In total 16 fish species have been identified in the diet of Dall's porpoise in the study area (Table 3).

Dietary Comparison between Harbour and Dall's porpoise

Dietary overlap: Pianka's index was used to calculate the degree of dietary overlap (Vieira and Port 2007). The results indicated a high degree of dietary overlap (niche overlap: 0.97, $P < 0.006$). While a high degree of dietary overlap was evident there may also be some niche separation evident in terms of size of fish selected. Fish length and weight were estimated from otolith measurements (Harvey *et al.* 2000). Analysis was limited to fish species for which published regressions exist. The size of herring consumed by harbour porpoise ranged from 93 to 201 mm ($n = 71$) whereas those from the Dall's porpoise were 139mm to 202mm ($n = 30$). The walleye pollock samples from harbour porpoise ranged from 83 to 120mm ($n = 5$) whereas those from the Dall's porpoise ranged from 120 to 374mm ($n = 7$). Walker *et al.* (1998) also noted that Dall's porpoise seem to consume larger gadids than did harbour porpoise and observed similar patterns in prey size consumed.

Dietary Differences: There were also dietary differences between the two species. The presence of Myctophids (lanternfish) in the Dall's porpoise samples and their absence from harbour porpoise samples suggests Dall's porpoise are feeding at least part of the time in deeper waters (Walker *et al.* 1998). Although the cephalopod beaks have not yet been identified to species in this study or used to estimate size of prey, there were almost three times as many beaks found in the Dall's porpoise samples as in the harbour porpoise samples. Walker *et al.* (1998), however, found very large numbers of *Loligo opalescens* in their harbour porpoise samples and relatively few in Dall's porpoise, whereas they found more Gonatidae squid in the Dall's than in the harbour porpoise samples suggesting deeper water foraging by Dall's porpoise.

Conclusion

Analysis of stomach contents provides important information about the diet of these two porpoise in the Strait of Georgia, however, the data are still relatively limited by a small sample size and it is likely that interpretation of results will change some what as more samples are added. The diet of these porpoise species includes a wide range of prey taxa with evidence of dietary overlap between the species. Frequency of occurrence, relative abundance and percent occurrence by mass provide various indications of the relative importance of different prey. There are, however, biases with these data to consider. It is likely that different prey species pass through the digestive tract at different rates and are eroded at different rates so that some species may be over represented while others are under represented. The contents of a stomach may not represent the most recent meal, particularly where the animal was ill before dying. It will be important to continue to increase the sample size by continued collection and processing of samples and potentially through collaboration with others with data from this study area to increase sample size (e.g. Walker *et al.* 1998).

References

- Hall, A.M., 2004. Seasonal abundance, distribution and prey species of harbour porpoise (*Phocoena phocoena*) in southern Vancouver Island waters. M.Sc. thesis, University of British Columbia, 100 pp.
- Harvey, J.T., T.R. Loughlin, M.A. Perez, and D.S. Oxman. 2000. Relationship between fish size and otolith length for 63 species of fishes from the eastern North Pacific Ocean. U.S. Department of Commerce, NOAA Technical Report NMFS 150. 36pp

Vieira, E. M. and D. Port. 2007. Niche overlap and resource partitioning between two sympatric fox species in southern Brazil. *Journal of Zoology*. 272: 57–63.

Walker, W.A., Hanson, M.B., Baird, R.W., and Guenther, T.J. 1998. Food habits of the harbour porpoise, *Phocoena phocoena*, and the Dall's porpoise, *Phocoenoides dalli*, in the inland waters of British Columbia and Washington. AFSC Processed Report 98-10, National Marine Fisheries Service. Pp 63-75.

Fiscal Year	Processed		Prey Identification		Otoliths measured	
	Harbour	Dall's	Harbour	Dall's	Harbour	Dall's
2007/08	7 (1)	6 (1)	7 (1)	6 (1)	yes	yes
2008/09	10 (5)	4	10 (5)	4	yes	yes
2009/10	4	0	in progress ¹	0	to follow ²	n/a
2010/11	11	0	in progress ¹	0	to follow ²	n/a

¹ samples have only now been sent for identification

² once samples are returned from Pacific Identification Inc., otoliths will be measured

Table 1. Summary of the number of porpoise stomachs processed and analysed to date. Additional samples from animals outside the study area are in ().

Prey Item		This study, n = 17	Walker <i>et al.</i> 1998, n = 26	Hall 2004, n = 4
Family*	Species			
Clupeidae		X	X	
	Pacific herring (<i>Clupea pallasii</i>)	X	X	
	Pacific sardine (<i>Sardinops sagax</i>)	X		
Gadidae		X	X	
	walleye pollock (<i>Theragra chalcogramma</i>)	X	X	
	Pacific hake (<i>Merluccius productus</i>)	X	X	X
Pyschrolutidae		X		
	Blackfin sculpin (<i>Malacocottus kincaidi</i>)	X		
Engraulidae		X		
	Northern Anchovy (<i>Engraulis mordax</i>)	X		
Embiotocidae		X		
	Shiner perch (<i>Cymatogaster gracilis</i>)	X	X	
Osmeridae			X	
	Eulachon (<i>Thaleichthys pacificus</i>)		X	
Batrachoididae			X	
	Plainfin midshipman (<i>Porichthys notatus</i>)		X	
Zoarcidae			X	
	Blackbelly eelpout (<i>Lycodopsis pacifica</i>)		X	
Ammodytidae			X	X
	Pacific sandlance (<i>Ammodytes hexapterus</i>)		X	X
Scorpaenidae			X	
	<i>Sebastes</i> sp (juv)		X	
Cottidae			X	
	Northern sculpin (<i>Icelinus borealis</i>)		X	
Bothidae			X	
	Pacific sanddab (<i>Citharichthys sordidus</i>)		X	
POLYCHAETA		X	X	
	Mud worm (<i>Nereis vexillosa</i>)		X	

Table 2 continued.

Prey Item Family*	Species	This study, n = 17	Walker <i>et al.</i> 1998, n = 26	Hall 2004, n = 4
CEPHALOPODA		X	X	
Loliginidae			X	
	California market squid (<i>Loligo opalescens</i>)		X	
Onychoteuthidae			X	
	Boreal Clubhook Squid (<i>Onychoteuthis borealijaponica</i>)		X	
Gonatidae			X	
	Berry armhook squid (<i>Gonatus berryi</i>)		X	
CRUSTACEA			X	
Penaeidae			X	
	shrimp (<i>Sergestes</i> sp.)		X	

Table 2. Prey species identified in harbour porpoise stomach samples in the study area

Prey Item Family*	Species	this study, n = 10	Walker <i>et al.</i> 1998, n = 22
Clupeidae		X	X
	Pacific herring (<i>Clupea pallasii</i>)	X	X
Osmeridae			X
	Eulachon (<i>Thaleichthys pacificus</i>)		X
Gadidae		X	X
	walleye pollock (<i>Theragra chalcogramma</i>)	X	X
	Pacific hake (<i>Merluccius productus</i>)	X	X
Pyschrolutidae		X	
	Blackfin sculpin (<i>Malacocottus kincaidi</i>)	X	
Myctophidae		X	X
	California headlight fish (<i>Diaphus theta</i>)	X	X
	Northern lampfish (<i>Stenobrachius leucopsaurus</i>)		X
	Broadfin lampfish (<i>Lampanyctus ritteri</i>)		X
	<i>Protomyctophum</i> sp.		X
Bathylagidae		X	
	Northern smoothtongue (<i>Leuroglossus schmidti</i>)	X	

Table 3 continued			
Family*	Species	this study, n = 10	Walker <i>et al.</i> 1998, n = 22
Zoarcidae			X
	Blackbelly eelpout (<i>Lycodopsis pacifica</i>)		X
Ammodytidae			X
	Pacific sandlance (<i>Ammodytes hexapterus</i>)		X
Cottidae			X
	Northern sculpin (<i>Icelinus borealis</i>)		X
	<i>unident cottid</i>		X
Bothidae			X
	Pacific sanddab (<i>Citharichthys sordidus</i>)		X
Pleuronectidae			X
	Rex sole (<i>Glyptocephalus zachirus</i>)		X
	Butter sole (<i>Isopsetta isolepis</i>)		X
	English sole (<i>Parophrys vetulus</i>)		X
POLYCAETA		X	X
Nereidae			X
	Mud worm (<i>Nereis vexillosa</i>)		X
CEPHALOPOD			
A		X	X
Loliginidae			X
	California market squid (<i>Loligo opalescens</i>)		X
Gonatidae			X
	Berry armhook squid (<i>Gonatus berryi</i>)		X
	Fiery Armhook Squid (<i>Gonatus pyros</i>)		X
CRUSTACEA			X
Crangonidae			X
	Shrimp (<i>Crango sp.</i>)		X

* Entries in capital letters are to class or subphylum

Table 3. Prey identified in Dall's porpoise stomach samples in the study area.

A29: IMPACTS OF UNEXPLORED MAJOR STRESSORS, EEDCS AND PPCPS ON THE STRAIT OF GEORGIA ECOSYSTEM. INFLUENCE OF CONTINUOUSLY INCREASING HUMAN POPULATION.

Dr. Michael G. Ikonomou, Fisheries and Oceans Canada, IOS, Sidney, BC. Prof. F. Gobas, School of Resource & Environmental Management, SFU, Burnaby, BC

Context and Approach:

Major current sources of coastal and freshwater pollution in BC are effluents from sewage treatment plants, effluents from pulp mills and agricultural runoff all of which are major sources of estrogenic endocrine disrupting chemicals (eEDCs). The continuously increasing urbanization of coastal areas of BC and an aging pollution are expected to cause increases in the emissions of eEDCs, pharmaceuticals and personal care products (PPCPs) from sewage treatment plant effluents into the Strait of Georgia. Legacy contaminants (dioxins, PCBs, PBDEs and some metals) have been or are about to be regulated and their emissions into the SoG can be expected to decrease over time. However, at present there are no regulations associated with the handling of eEDCs and PPCPs or the discharge of these substances into freshwater and marine environments. There is a plethora of data relating to legacy contaminant levels in the SoG ecosystem from which bioaccumulation and fate models have been developed. On the contrary, the fate and environmental impacts of eEDCs and PPCPs are largely unknown and a literature study we carried out recently showed that there are virtually no data relating to the presence eEDCs and PPCPs in the SoG marine environment. Food-web, fate and bioaccumulation models developed for the legacy organohalogen contaminants may not readily apply to eEDCs and/or PPCPs because these substances have very different physicochemical properties, bioaccumulation characteristics and environmental behavior. "Traditional" toxicological methods fall short in their ability to address the broad scope of deleterious effects of eEDCs and PPCPs. For example, substances that are deemed "not acutely toxic" in standard assays may indeed have sublethal adverse effects that occur at doses far below those considered safe. This coupled with the annual introduction of a multitude of new chemicals in the context of a changing environment presents a phenomenal challenge for predicting and assessing the impacts of eEDCs and PPCPs on fish in impacted ecosystems lies ahead. There is substantial evidence in Canada and elsewhere showing that chemicals and combinations of chemicals can feminize male fish, contribute to amphibian declines, and alter how hormones function. Lack of exposure data, exposure models and poor characterization of toxicological effects limit the ability to respond to this environmental threat by developing water quality guidelines, discharges limits (e.g. for sewage treatment plants) and other methods. It is possible that fish populations, including local species and migrating salmon populations, are currently affected by eEDCs and PPCPs and stand to benefit from better control of these substances. However, to develop a sound scientific rationale for better control of eEDCs and PPCPs, it is important to gather better information (i) on the extent of discharge of eEDCs and PPCPs into aquatic environments; (ii) the presence and the environmental fate of these substances in the Strait of Georgia and (iii) the ecological effects of these substance on fish populations. In this proposal we lay out such a research strategy for the Strait of Georgia, as this is the most important receiving aquatic system for eEDCs and PPCPs because of its level of urbanization and receiving environment of discharges from the larger Georgia Basin watershed.

This fiscal year we aim to launch a small scale pilot study which will form the basis and rationale for a possible larger scale project to be pursued in the future. Our aim is to obtain an understanding of the impacts of eEDCs and PPCPs on the SoG marine ecosystem to (i) assess the current state of the of the SoG ecosystem in terms of environmental loadings, (ii) develop

bio-indicators for continual assessment of the impacted areas and (iii) develop models that will explore the fate of these emerging contaminants in the SoG.

Our plan is to conduct a research study containing 2 components: a) make measurements of selected EDCs and PPCPs in abiotic media (sediments) and some biota samples (invertebrates and representative ground fish) that will be collected near potentially impacted areas, such as the Iona GVRD municipal outfall, Ladysmith harbor, and at references sites in the SoG; and b) assess and apply computer simulation models to investigate the fate and environmental behaviour of these emerging contaminants in the SoG ecosystem. An assessment on the current conditions in terms of environmental levels and linkage to what these mean in terms of biological impacts will be performed.

The same sediment and biota samples that have been or to be collected as part of other collaborative studies conducted in these areas will be analyzed for target eEDCs and PPCPs. M.G. Ikonomou has developed novel analytical methods for the determination of eEDCs and PPCPs compounds in environmental samples. Analyses for these chemicals will be conducted in collaboration with the IOS LEACA COE. Dr. Su, a visiting fellow in my group, will be conducting a major part of the analytical work and that is going to reduce the project cost substantially.

Objectives:

- a. To make measurements of the spatial and temporal changes in concentrations of a comprehensive set of eEDCs and PPCPS in the SoG marine environment. This data set will be used to calculate budgets of these substances in SofG, to substantiate the role of the sources of these emerging contaminants and to provide a data set that can be used for evaluating performance of the model that will be developed as part of this study. The data to be obtained will be compared to concentrations of legacy contaminants such as PCBs, PBDEs and trace metals as sediment and biota data for these are available in the areas to be examined.
- b. Assess and apply computer simulation models to investigate the fate and environmental behaviour of these emerging contaminants in the SoG ecosystem. We will also aim to develop and test a model of the amplification of these contaminants in SoG aquatic food-webs due to their continuous input into this system.
- c. To examine underlying biological and chemical factors governing the fate of these emerging contaminants in water systems where municipal waste water is discharged. This effort is very important and will make a contribution to finding a solution to an emerging issue facing SoG and Canada at large. The proposed study, together with longer-term monitoring results, will assist in guiding development of appropriate technologies, sewage treatment plant upgrade strategies, and disposal procedures for eEDCs and PPCPs to minimize environmental contamination. Our results will also be equally useful to other jurisdictions in Canada, and elsewhere, to set policies and develop waste management strategies that support sustainable environmental quality and regional development.

At present Environment Canada is conducting a study assessing the levels of EDCs, PPCPs and other contaminants in the effluents of GVRD outfalls. We will have access to the data to be generated and our aim is to use that data and make linkages to our findings in terms of sources, pathways, fate and budgets of these contaminants in the impacted areas.

[illegible]

Table 2. Plankton samples by year and month collected but not analyzed from the Strait of Georgia.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
1991							1	1	1	2	10	
1992			28	30	24	12	9	10		18		18
1993			17		12	18	18	18		18	18	6
1994				18		18	4	12				3
1995				9			5		8			
1996			6	5		18		9	3			
1997	9	8	13	11	5	14	1	9		12	5	3
1998	6	2	10	12		10	9			8		9
1999		14	2	8		5	2	4	1	6	1	5
2000		6	9	3				4		8		
2001				2				2		2		
2002												
2003												
2004								2				
2005												
2006												
2007												
2008		36			12	12						
2009					40	30	24	24				
2010						12	30	27		12		