Pacific Large Aquatic Basin Climate Change Impacts, Vulnerabilities and Opportunities Assessment – Marine Species and Aquaculture

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PACIFIC LARGE AQUATIC BASIN CLIMATE CHANGE IMPACTS, VULNERABILITIES AND OPPORTUNITIES ASSESSMENT – MARINE SPECIES AND AQUACULTURE

by

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ABSTRACT

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To complement risk assessment activities completed for Fisheries and Oceans Canada's Aquatic Climate Change and Adaptation Services Program in 2013, this report assembles an inventory of climate change impacts, vulnerabilities and opportunities for key biota in Pacific Large Aquatic Basin (LAB), focused on lower trophic production, commercially important marine and aquaculture species, and marine mammals. A literature survey of 12 species/species groups was used to compile the responses to changes in relevant climate-related physical ocean parameters in Pacific LAB. Parameters of interest included ocean surface temperature, dissolved oxygen, acidification, upwelling/winds, currents, stratification, salinity, freshwater discharge, and sea level rise. Consideration was paid to conceptually linking the spatial distribution of resources across Pacific LAB with projected oceanographic changes in three sub-basins: West Coast Vancouver Island, Strait of Georgia, and North Coast. The report demonstrates many of the most lucrative commercial fishery species harvested in all sub-basins are believed to be vulnerable to various changes in ocean climatology, but many gaps in knowledge exist, particularly on the effects of climate forcing on recruitment. As a reflection of the scientific literature, many more impacts and vulnerabilities than opportunities were identified for any species. The main conclusions suggest 1) alteration in stratification, current patterns and strength and related primary productivity could affect where early life stages of invertebrates and groundfish concentrate in abundance and their subsequent ability to move or settle nearshore; 2) observations of species responses recorded during 'extreme' ocean conditions that are analogous to projected ocean climate futures suggest highly migratory southern pelagic species will expand their range and possibly increase in numbers should trophic processes support greater abundance; 3) direct impacts of increased ocean pH on young fish and all stages of calcifying organisms are not known but could pose significant risk to related fisheries in Pacific LAB and potential indirect impacts on species lower in the food chain are alarming; 4) marine mammals, lower trophic species and macroinvertebrates appear to be vulnerable groups in general, though differences among species emerge given differences in vulnerability of various life history stages, current distribution, and trophic dependencies; and 5) though aquaculture species are vulnerable to some climate-related parameters, the industry may be adaptable should regulators be sufficiently prepared. All regions of Pacific LAB should expect to see changes in the abundance and/or distribution of key fishery resources in the future including the possibility of a reduced ability to predict resource abundance. The report suggests that there are significant gaps in knowledge not least of which is the lack of understanding of the combined effects (possibly synergistic) of multiple climate stressors. Pacific LAB can prepare for an altered ocean climatology that is different to past variability resulting in the responses by marine species and assemblages and possible change in productivity and/or ecosystem function of marine sub-basins.

RESUME

Hunter, K.L., and Wade, J. (Eds). 2015. Pacific Large Aquatic Basin climate change impacts, vulnerabilities and opportunities assessment – marine species and aquaculture. Can. Manuscr. Rep. Fish. Aquat. Sci. 3049: viii +242 p.

Dans le but de compléter les activités d'évaluation des risques réalisées pour le Programme des services d'adaptation aux changements climatiques en milieu aquatique de Pêches et Océans Canada en 2013, ce rapport dresse un inventaire des impacts, des vulnérabilités et des opportunités liés au changement climatique pour les principaux biotes dans le Grand bassin aquatique du Pacifique (GBAP), axé sur la production des niveaux trophiques inférieurs, les espèces marines et aquacoles importantes sur le plan commercial, et les mammifères marins. Une étude documentaire portant sur 12 espèces/groupes d'espèces a été utilisée pour compiler les réponses relatives aux changements de paramètres physiques des océans pertinents liés au changement climatique dans le GBAP. Les paramètres d'intérêt comptaient la température de la surface de l'océan, l'oxygène dissous, l'acidification, la remontée des eaux/les vents, les courants, la stratification, la salinité, le débit d'eau douce et la hausse du niveau de la mer. Une attention particulière a été portée sur l'établissement d'un lien conceptuel entre la répartition spatiale des ressources dans le GBAP et les changements océanographiques prévus dans trois sous-bassins : la côte ouest de l’île de Vancouver, le détroit de Georgie et la côte Nord. Le rapport démontre que plusieurs espèces commerciales les plus lucratives pêchées dans l'ensemble des sous-bassins sont considérées comme vulnérables aux divers changements de la climatologie océanique. Il existe toutefois plusieurs lacunes dans les connaissances, particulièrement en ce qui concerne les effets du forçage climatique sur le recrutement. Comme il est décrit dans la littérature scientifique, beaucoup plus d'impacts et de vulnérabilités que d'opportunités ont été déterminés pour une espèce quelconque. Voici les conclusions principales : 1) la variation de la stratification, des régimes et de la force des courants, et de la productivité primaire connexe pourrait influer sur les lieux de concentration en abondance d'invertébrés et de poissons de fond aux premiers stades biologiques, ainsi que sur leur capacité subséquente de se déplacer ou de s'établir près de la rive; 2) les observations de réponses d'espèces lors de conditions océaniques « extrêmes » correspondant aux prévisions de climats océaniques futurs suggèrent que les espèces de grands migrateurs pélagiques du sud étendront leur aire de répartition et connaîtront des croissances de population si les processus trophiques soutiennent une plus grande abondance; 3) les impacts directs de l'augmentation du pH de l'océan sur les jeunes poissons et sur l'ensemble des stades d'organismes calcifiants ne sont pas connus, mais pourraient poser un risque considérable aux pêches connexes dans le GBAP; les impacts indirects potentiels sur les espèces plus basses dans la chaîne alimentaire sont inquiétants; 4) en règle générale, les mammifères marins, les espèces des niveaux trophiques inférieurs et les macroinvertébrés semblent constituer des groupes vulnérables, bien que l'on constate des différences entre les espèces en fonction des différences relatives à la vulnérabilité des divers stades du cycle biologique, à la répartition actuelle et aux dépendances trophiques; 5) bien que les espèces aquacoles soient vulnérables à certains paramètres climatiques, l'industrie pourrait s'adapter si les organismes de réglementation sont suffisamment préparés. L'ensemble des régions du GBAP Pacifique doit s'attendre à des changements de l'abondance et de la répartition des principales ressources halieutiques à l'avenir, y compris la possibilité d'une capacité réduite de prévoir

l'abondance des ressources. Le rapport suggère qu'il y a d'importantes lacunes dans les connaissances, dont notamment un manque de compréhension des effets combinés (peut-être synergique) de plusieurs agents de stress climatiques. Le GBAP peut se préparer à une climatologie océanique modifiée, différente des variations passées, laquelle engendrera des réponses d'espèces marines et de communautés d'espèces, ainsi que des changements potentiels dans la productivité et la fonction des écosystèmes des sous-bassins marins.

1.0 INTRODUCTION

In 2011, Fisheries and Oceans Canada (DFO) initiated the Aquatic Climate Change and Adaptation Services Program (ACCASP) to improve understanding of climate change and prepare for climate-related impacts on the Department's business. Climate change is a complex issue that has the potential to affect DFO's ability to meet its diverse mandate. It is difficult to predict how, where and when the impacts will occur and at what magnitude, or where key vulnerabilities or opportunities may lie. Program efforts have been directed toward the development of region-specific trends and projections of major climate drivers, as well as an inventory of notable impacts, vulnerabilities and opportunities relating to climate change. Four Large Aquatic Basins (LABs) (Atlantic, Arctic, Freshwater and Pacific) are completing similar activities for the Department.

The 'unequivocal' changes in climate linked to human influences on the planet occurring at the global level (IPCC 2014) are affecting the Pacific coast of Canada (Mote and Salathe 2010; Christian and Foreman 2013; Foreman et al. 2014). Though Pacific LAB is subject to general effects of large scale change and variation in climate, specific sub-regional impacts of climate drivers, anthropogenic stressors, and their cumulative effects across sub-basins will not be the same. An inventory of known climate drivers and the distribution of biological and infrastructure elements across sub-basins is needed to begin to assess climate change risks to DFO in Pacific LAB.

In this report, we summarize the state of knowledge of climate change impacts, vulnerabilities and opportunities for specific marine resources and aquaculture in Pacific Large Aquatic Basin (henceforth Pacific LAB). The assessment of vulnerabilities, impacts and opportunities was made based on multiple sources of biological information and relied on the physical oceanography projections made by Pacific LAB's Trends and Projections team (Christian and Foreman 2013).

1.1 Organization of the report

We used a screening level approach to inventory the potential impacts, vulnerabilities and opportunities (IVO) of projected climate change on selected commercially valuable finfish and invertebrate species supporting capture and culture fisheries in Pacific LAB. This report focuses on climate change impacts, vulnerabilities and opportunities associated with lower trophic levels, Pacific LAB's 8 most lucrative non-salmon capture fishery species (Pacific Halibut, Pacific Hake, Sablefish, Dungeness Crab, Spot Prawn, Geoduck, Pacific Herring, and North Pacific Albacore Tuna), 2 most lucrative culture fishery species (Atlantic Salmon and Pacific Oyster), and other important ecosystem components including lower trophic levels, Pacific Sardine, and marine mammals.

Inventorying IVO was completed by creating species profiles (Sections 3.0 and 4.0). Profiles document species information on life history, distribution and environmental preferences, ecosystem interactions and abundance/recruitment. Fisheries information was included to document recent fishery trends, and current management and stock assessment processes that either do or do not incorporate climate change considerations in their practices. Climate change sensitivity related to abundance, distribution and phenology is discussed for each species or species group.

Oceanographic trends and projections were provided for climate-related ocean and freshwater parameters across Pacific LAB sub-basins where data is available (Christian and Foreman 2013). IVO was developed by cross-referencing literature-based climate sensitivities with ‘local’ projections of physical ocean parameters. The result is a set of literature-supported information suggesting climate linkages, possible mechanisms, and gaps in knowledge for marine species of major commercial and/or ecological importance in the region. Given the breadth of this exercise, the editors acknowledge that the process of developing a comprehensive inventory at this spatial scale will be iterative. In most cases climate projections are not available at an appropriate biological scale. We also acknowledge that significant conceptual gaps exist which makes available oceanographic information unusable in some instances. Therefore we present information on IVO from a DFO perspective accompanied by gaps in knowledge that might be pursued as part of ongoing investigations in ACCASP and other relevant DFO Programs. Readers are directed to Christian and Foreman (2013) for the detailed physical and oceanographic assessment.

Impacts of environmental changes on organisms directly dependent on freshwater habitats, such as Pacific salmon, will be the focus of a separate report. In addition to the impacts of physical parameters on marine biota, climate change will present considerable challenges to aspects of DFO’s mandate not addressed here including Species at Risk and their recovery and invasive species. Additionally, infrastructure planning and costs for Small Craft Harbours and Pacific salmon enhancement facilities are particularly concerning in areas that experience high river discharge and/or drought but the scope of this report does not include those issues (see AMEC 2011; DFO 2013a).

2.0 PACIFIC LARGE AQUATIC BASIN

Geographic components of the Pacific LAB that fall under the responsibility of the Department are the marine and coastal waters along the west coast of Canada, as well as rivers, lakes and streams bearing anadromous fishes. There are four spatial sub-divisions of marine systems in Pacific LAB for the purposes of ACCASP: Strait of Georgia, west coast of Vancouver Island (WVCI), North Coast and Gulf of Alaska (Fig. 2.1). The Strait of Georgia subdomain includes all Canadian waters of the Salish Sea (which includes the Strait of Juan de Fuca and Puget Sound as well as the Strait of Georgia proper). WCVI includes costal and continental shelf waters to 300m depth contour in the Canadian domain off the west coast of Vancouver Island. The North Coast region roughly overlaps the Pacific North Coast Integrated Management Area (PNCIMA). The Gulf of Alaska includes all oceanic waters beyond the continental shelf (as defined e.g. by the 300 m depth contour). While there may be biophysical justifications for further subdividing these basins, they are aggregated here for primarily practical rather than conceptual reasons (e.g. lack of data). The authors are aware of existing bioregions developed within Fisheries and Oceans Canada (DFO 2009a); however for the purposes of ACCASP, a slightly altered scale was used.

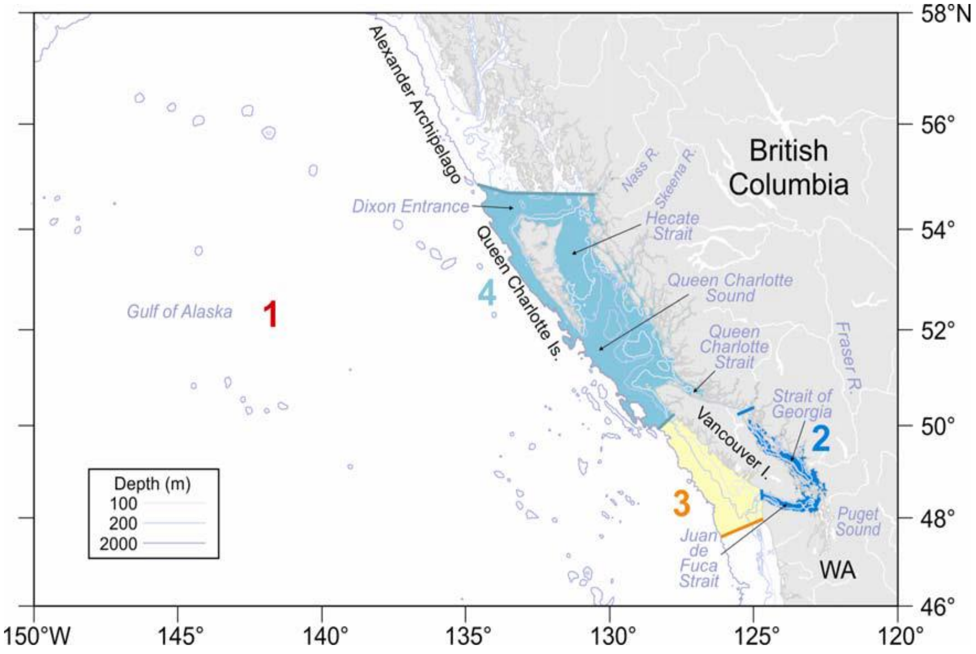


Figure 2.1. Pacific LAB, as defined by the Aquatic Climate Change Adaptation Services Program, is divided into four sub basins: Gulf of Alaska (1), Strait of Georgia (2), West Coast Vancouver Island (3) and North Coast (4).

Information and knowledge gaps relating to climate change and variation varies greatly by sub-basin. The Gulf of Alaska sub-basin comprises a large open-ocean environment that plays an important role in North Pacific Ocean dynamics. Of the relatively little knowledge we have about the oceanography and marine ecosystems of this sub-basin, we understand that it is highly important for Pacific salmon marine rearing and survival. Because Gulf of Alaska remains extremely data poor, we do not address climate change IVO in this sub-basin.

The remainder of Pacific LAB is a very large area that comprises a distribution of highly diverse geomorphology, oceanography, hydrography, ecology and human stressors. The characters of both marine and freshwater environments differ considerably across the region. Significant differences in factors in the marine environment such as wave exposure, depth, subsurface relief, seabed substrate and current regimes lead to different ocean climatology, habitat distribution and species assemblages. Freshwater systems that support anadromous fishes are located throughout the region, and in many cases, extend well into terrestrial zones. In freshwater environments, hydrographs can be dominated by snowpack or rainfall and this character varies with geography along the coast.

Strait of Georgia, WCVI, and North Coast are affected by a relatively well understood, highly variable marine transition zone and are influenced mainly by major coastal currents (southward Alaska Current, northward California Current; Fig. 2.2). Large portions of the ice-free coastline feature narrow continental shelf areas, steep bathymetry, mountainous landscapes, deep fjords and elongated inlets (Thomson 1981). The seasonal cycle of wind stress varies greatly along the coast. Prevailing winds are seasonal with southward winds driving patterns of coastal marine upwelling in summer) and northward winds drive down-welling in winter (Fig. 2.2). Seasonal cycles of heavy precipitation and peaks of snow and glacial melt influence hydrographs (Whitfield and Cannon 2000) and affect coastal circulation both by enhancing near-surface stratification and via currents induced directly by the large freshwater flux. The marine component of Pacific LAB is unique because of extremely low oxygen concentrations and low $CaCO_3$ saturation states found at very shallow depths of the oceanic thermocline.

Figure 2.2. Prevailing ocean currents and four major oceanic domains as defined by Ware and McFarlane (1989).

The transition zone position of the Pacific LAB (Fig. 2.3) results in physical and chemical changes to the marine environment at annual to decadal time scales. Alternation of El Niño-Southern Oscillation (ENSO) events, North Pacific Gyre Oscillation forcing (Di Lorenzo et al. 2008), as well as warm and cold-phases of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997) influence large climate variation in the transition zone (Fig. 2.3; Chavez et al. 2011; Appendix 10.1).

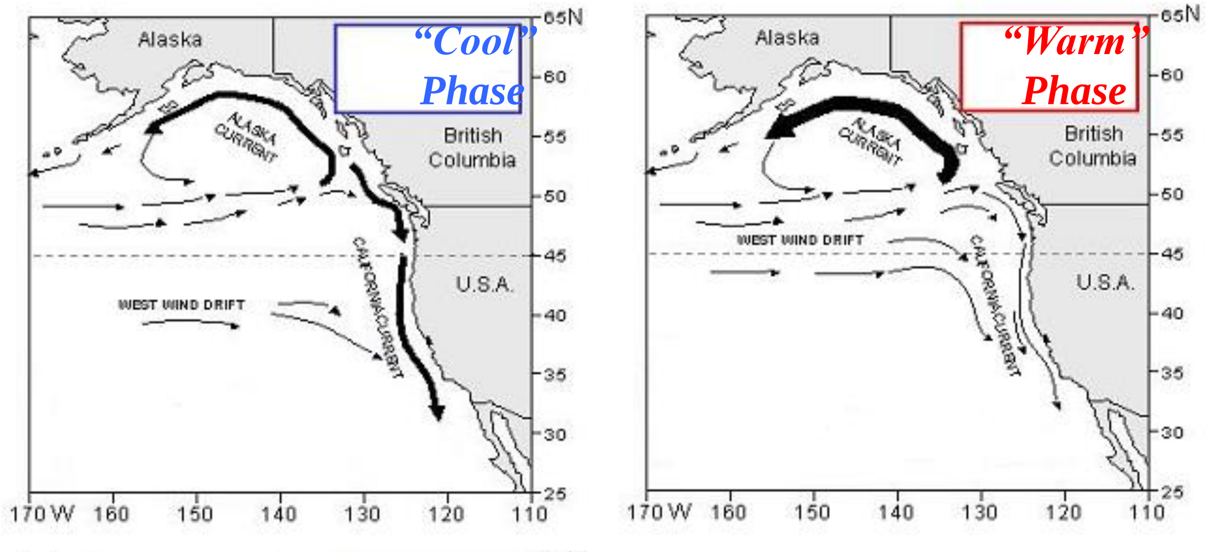


Figure 2.3. Schematic image of the cool v warm circulation patterns in the NE Pacific, verified in Keister et al. (2011) and Bi et al. (2011).

Primary productivity trends in the Strait of Georgia and WCVI indicates that cool conditions (i.e. PDO negative, NPGO positive) support higher quality lower trophic level communities, with a higher abundance of lipid-rich subarctic species (Bi et al. 2011; Keister et al. 2011). During warming conditions, community composition has been shown to change as warm water species intrude further north and persist in greater numbers (except perhaps in the Strait of Georgia region) and many locally dominant subarctic species do poorly (Section 3.0). There are also short term changes in distribution and abundance of some fish species in response to changes in oceanographic conditions which are thought to be cyclical, and possibly longer term impacts on recruitment patterns (Section 4.0). The cumulative effects of these warming or cooling conditions in conjunction with more long term changes in climate conditions are not known however.

2.1 Pacific LAB and climate change

The three types of climate forcing observed in the Pacific LAB are unidirectional (i.e. warming, sea level rise, ocean acidification), variable (annual and decadal climatology) and episodic (storms, high river discharge events). This report assesses the potential impacts and vulnerabilities of unidirectional drivers, in part because trend and projection analyses are not available for variable or episodic forcing.

Based on work completed in the eastern subarctic Pacific (Freeland et al. 1997; Christian and Foreman 2013), and at the global scale (IPCC 2014), it is now clear that the global oceans are absorbing most of the additional heat generated by carbon emissions, sea levels are rising at some locations, and changes in the hydrological cycle causing changes in salinity and pH, are evident. These changes will bear important consequences for aquatic systems and their human usage in Pacific LAB (Halpern et al. 2010; Hollowed et al. 2013), thus affecting DFO's associated mandate and business (DFO 2013a).

Regional ocean phenomena in Pacific LAB impose challenges in distinguishing between anthropogenic and natural variability in the relatively short available time series (Christian and Foreman 2013). Still, trends show a coherent picture of warmer, fresher, less oxygenated, and more acidic waters where monitored along Pacific LAB's outer coast (Christian and Foreman 2013). Clear signals in marine systems may show lags in response to climate change, relative to other areas. Climate forcing insights may prove particularly valuable if future changes are expressed through increased variance in ENSO or NPGO activity, as Di Lorenzo et al. (2010) have predicted.

Freshwater environments in Pacific LAB are experiencing the effects of climate change differently than coastal or marine zones. There are detectable effects of climate change on temperature, snow-pack and hydrology appearing in freshwater aquatic systems (Morrison et al. 2002; Tillman and Siemann 2011; Hinch and Martins 2011). Projections of air temperature for the terrestrial areas of Pacific LAB confer that continued temperature increases are expected, with the greatest increases occurring in the latter part of this century (e.g. Mote and Salathe 2010; PCIC 2013).

2.2 Ocean climate physical parameters

Sea surface temperature

Climate influences sea surface temperature through general warming of the overlying atmosphere, the amount of sunshine during a season or year, the degree of stratification in marine systems and the temperature of stream and river inflows. Line P is a transect of stations off the coast of Pacific LAB where large-scale oceanographic events and general ocean circulation are monitored and studied (Fig. 2.4a). Offshore upper-ocean (10-50 m) observations on Line P in the Northeast Pacific over the past 55 years and coastal temperature observations taken at British Columbia lighthouses over the past 75 years (Fig. 2.4b) show a long-term warming trend across Pacific LAB on the order of 0.1^{o}C per decade (Fig 2.5; Irvine and Crawford 2012). Less ocean temperature warming is observed with increasing water depth.

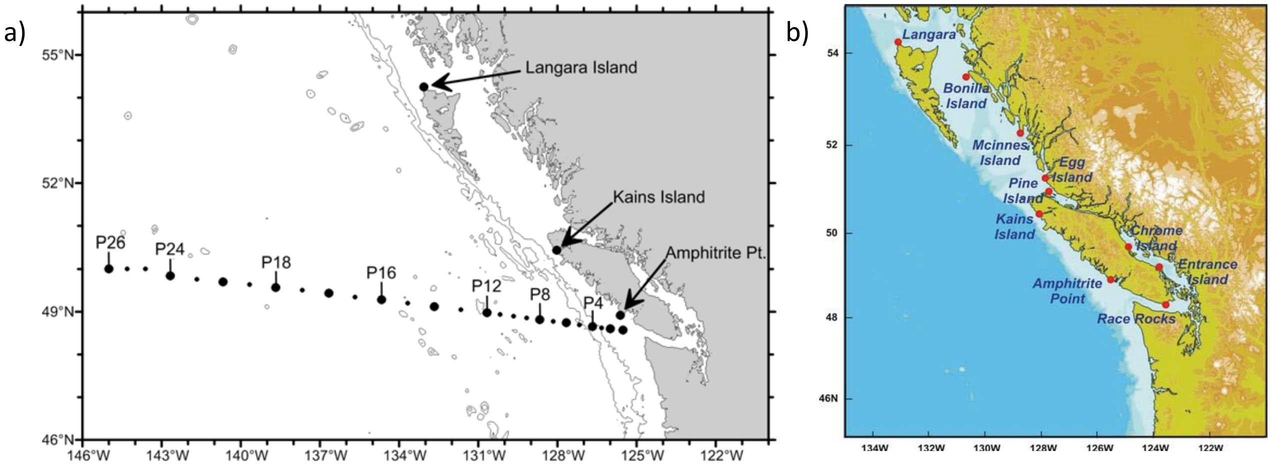


Figure 2.4. Location of a) Ocean Station Papa (Line P) and b) British Columbia lighthouse stations. Figures reprinted from Christian and Foreman (2013).

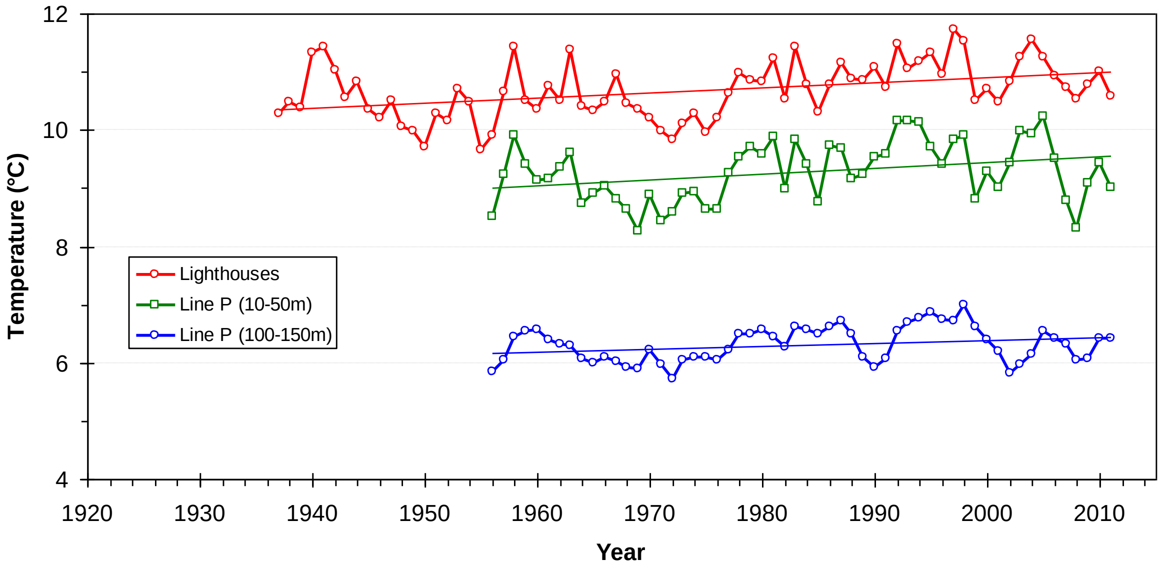


Figure 2.5. Annual-mean indices of ocean temperature in the Pacific Ocean off Pacific LAB, from DFO monitoring programs reported in Irvine and Crawford (2012), with linear trend lines superimposed. Reprinted from Foreman et al. in Christian and Foreman (2013). Refer to Christian and Foreman (2013) for more information on the sea surface temperature data record and monitoring procedures.

Ocean temperature is a factor determining the distribution of coastal marine organisms, although local extremes of other physical properties (salinity, oxygen, pH) and settlement of larvae at available habitat can affect population abundance on a local level. There is a projected 3^0C coast-wide increase for sea-surface temperature in Pacific LAB marine waters over the next 50 years (Christian and Foreman 2013). A change in temperature of this magnitude will impact marine food webs and is sufficient to have lasting impacts on marine organisms, including those profiled in this report. However, in Pacific LAB, increases in sea surface temperature have been tied historically to climate forcing (ENSO, PDO) which involve changes in physical ocean conditions in the transition zone due to transport of different water masses into the LAB from subtropical regions. Much of what we understand about the responses of organisms to temperature also involves additional parameters operating at the same time, including fishing activity and other stressors. What is not understood is how a significant increase in temperature will drive physical ocean interactions and whether the system will behave similarly as with 'climate forcing' or if an entirely new set of circumstances will emerge (Rykaczewsiki and Dunne 2010). Concern has been expressed that projected climate change will bring about impacts that go outside the realm of historical observation (DFO 2013a) where the value of past climate-ecosystem dynamics as analogs for future changes will be less certain (Chavez et al. 2011).

Upwelling

Another notable type of variability that affects living marine resources in Pacific LAB is related to coastal upwelling that supplies nutrients to the upper ocean (Bakun 1990; Checkley and Barth 2009). Seasonal changes in ocean currents that occur in conjunction with changes in significant wind patterns occur annually along the coast. Winds affecting WCVI and North Coast sub-basins are upwelling-favourable in summer and downwelling-favourable in winter. In the spring, coastal branch of the California Current moves back into the shelf regions, an event known as the 'spring transition' (Huyer et al. 1979). The timing of the transition can vary widely, an important feature, because changes to the strength and timing of upwelling winds can impact the matching (i.e. phenology) and actual cascade of trophic interactions that are strong determinants of regional productivity. These seasonally dominant winds are strong determinants of species interactions (predator-prey).

Although there is evidence that upwelling is starting 1 day later per year on average (Foreman et al. 2011), perhaps the most noteworthy point is that the start dates are extremely variable, spanning nearly 3 months – for example, upwelling was initiated in mid-March (in 2007) but in 2005 significant amounts of upwelling were not seen until mid-July. Increases in upwelling-favorable winds have slowed or reversed warming trends in some nearshore regions (García-Reyes and Largier 2010) and are expected to continue to have this effect (Foreman et al. 2011).

Coastal upwelling is also associated with hypoxia and ocean acidification. There is evidence that oxygen content of deep water which upwells into the California Current Ecosystem is decreasing in concentration and that upwelling waters are becoming more acidified, topics discussed next.

Ocean acidification

The increasing concentration of carbon dioxide in the atmosphere is resulting in widespread increases in the concentration of carbon dioxide and carbonic acid in the oceans (Takahashi et al. 2006), and hence to lower pH values across the world's oceans (30% change over the last century; Solomon et al. 2007; Doney et al. 2009). Though there is very little data available in Pacific LAB to support trend analysis in either open ocean and coastal waters at this time, existing open ocean observations support the global increasing trend in ocean acidification

(WMO 2014; Wong et al. 2014). Recent trends from other locations suggest a downward trend in surface pH of about 0.0017/yr., and in aragonite saturation of 0.007/yr (Christian and Foreman 2013). Deviations from the global mean are expected to be small at the ocean surface but could be significant in the thermocline (Christian and Foreman 2013). The ocean carbon system in Pacific LAB coastal areas is comparatively much more variable and too few data exist to establish a trend for ocean acidification. Little to nothing is known about terrestrial sources of ocean acidification (e.g. polluted run-off) that would impact coastal areas in Pacific LAB.

The California Current Ecosystem, including WCVI, is exposed to coastal upwelling that brings deeper cold waters that are naturally acidic to the surface ocean into continental shelf waters (Feely et al. 2008). Upwelled water is naturally rich in CO_2 but also carries an ever-growing load of human-generated aqueous $CO_{2.}$ Phytoplankton uptake and outgassing of CO_2 to the atmosphere over the continental shelf remove some of the excess dissolved inorganic carbon that would otherwise interact with CO_2 to produce excess hydrogen (acidifying) ions. Conversely, when the phytoplankton bloom sinks, oxidation of organic matter reduces the pH as well as oxygen concentration of bottom waters on the shelf (Ianson et al. 2009). Thus, in this region, coastal marine ecosystems are particularly vulnerable to ocean acidification impacts for two reasons: upwelling waters have low pH and oxidation of organic matter produce by the upwelling results in even lower pH and reduced saturation state (Ianson 2013). The barrier to upwelled water formed by the strong Vancouver Island Coastal Current may inhibit exposure of shallower depths to acidified waters (Thomson et al. 1989; Bianucci et al. 2011).

To buffer the change in ion concentration, carbonate ions stored in structures of marine animals (e.g. shells, skeletons, exoskeletons) as Ca_2CO_3 are dissolved to release carbonate ions into seawater. Therefore, impacts of increasing acidity linked to decreasing saturation states in Pacific LAB are expected to be greatest on calcifying organisms that provide some of the largest regional fisheries landings and values (Haigh et al. 2014; Ekstrom et al. 2015).

Globally, over the last century, the depth below which aragonitic shells dissolve – known as the aragonite saturation depth or horizon – has become shallower by typically, 30-50 m (reference!). In the North East Pacific Ocean, the saturation horizon is naturally shallow – as little as 100 m below the surface (reference!) and above 60m depth over 40% of the time during summer over the continental shelf (linked to intense blooms, Ianson 2013). Changes to saturation state of carbon compounds required by marine organisms to develop and grow may result in significant impacts on marine ecosystems and productivity (Berge et al. 2006; Doney et al. 2009; Gazeau et al. 2011; Bednaršek et al. 2014; Waldbusser and Salisbury 2014; Waldbusser et al. 2014).

Sea level change

Global sea level rise is a monotonic trend superimposed on background natural variability. It is caused by several major factors including climate-related changes in ocean volume as a result of increasing temperature which increases the volume of seawater (Bornhold and Thomson 2013). Global sea level is rising at 3.2 mm/year and about 70% of the coastlines worldwide are projected to experience sea level change within 20% of the global mean sea level change (IPCC 2014). Sea level rise will not be uniform and will be region-specific.

Changes in sea level rise vary significantly throughout Pacific LAB. This is because of the regional significance of the vertical components which are either tectonic movements or isostatic rebound post glaciation (Thomson et al. 2008). One or the other of these components plays a more significant role in sea level trend at a location (Thomson et al. 2008; Mazzotti et al. 2008). Sea level rise is mitigated somewhat on the BC coast by tectonic uplift of the land in some locations (Fig. 2.6; Mazzotti et al. 2008). Deviations of sea level rise from the global mean at most locations along the coast are likely to be small. Sea level has risen by 3.1 cm at Victoria and 2.0 cm at Vancouver over the past 50 years (Thomson et al. 2008). At Tofino, sea level has declined by 8.4 cm over the same period, while at Prince Rupert it has risen 10 cm in 77 years (Thomson et al. 2008). The Fraser delta is particularly vulnerable because of natural subsidence that is further influenced by urban development along the delta (Bornhold and Thomson 2013).

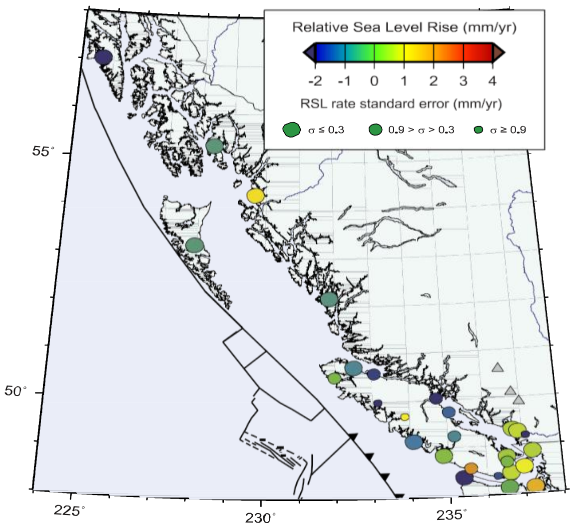


Figure 2.6. Annual rates of uplift (mm per year) of the land along the Pacific LAB coast (Mazzotti et al. 2008).

Mean sea level is correlated with climate models for the northern coast of Pacific LAB (Abeysirigunawardena 2010). More frequent or intense El Niño events or earthquakes may become more serious risks as mean sea level increases. In the Strait of Georgia specifically, salinity plays an important role in sea level rise demonstrating the strong influence of river discharge in this sub-basin (Bornhold and Thomson 2013).

<u>*Dissolved oxygen*</u>

Resulting from major ocean circulation patterns, the upper 100 m of the Pacific LAB contains old water that was last in contact with the atmosphere between 30 – 50 years ago. Due to gradual oxidation of organic matter with time, subsurface waters of the continental margin of the west coast of North America are chronically low in dissolved oxygen and pH but high in nutrients. Hypoxia can affect the behaviour and development of many organisms when oxygen declines below ~1.4 ml/l in seawater, about 20% saturation (Gray et al. 2002) although fish might feel the effects at somewhat higher concentrations. Low oxygen events can have short term and long term impacts on marine species. Benthic invertebrates have been shown to suffer mortality during low oxygen events (Grantham et al. 2004; Chan et al. 2008); fish kills are associated with hypoxia events as well (Palsson et al. 2008). Recently, regions of hypoxia in North East Pacific continental shelf waters have occurred most commonly, north of 44° N latitude. They were most severe over the widest areas of the US continental shelf, off Hecate Bank, Oregon (44-44.6 °N) and over the broad shelf regions off the coast of Washington State. It has been estimated that hypoxic waters off Washington and Oregon covered up to 62% (15,600 km^2) of the continental shelf during some years (2002, 2007, 2008), and < 10% in others (2003, 2010) (Peterson et al. 2013). These hypoxia events are only seen in the lower 20 m of the water column in mid- and outer-shelf waters in these areas, not nearshore, thus it is only organisms that occupy deeper waters of the continental shelf that might be affected by the occasional “low-oxygen events”.

Declines in oxygen concentration at mid-water depths along Line P (in Pacific LAB) have also been observed (Whitney et al. 2007). Further north, strong summer stratification of the water column in Queen Charlotte Strait (North Coast) often results in low oxygen concentrations of deep waters (Cummins et al. 2010). Upwelling favourable winds expose the continental shelf to low oxygenated waters across the North Coast. In areas of restricted circulation such as many of British Columbia's coastal inlets, deep waters can be hypoxic (Gross 1972).

Measurements of dissolved oxygen along Line P fluctuate, but there is no trend and no episodic hypoxia events have occurred according to expert knowledge (Crawford and Peña 2013a). However, a warmer surface ocean results in stronger stratification, making it more difficult to mix surface ocean water, thus over time, less mixing will result in less oxygen being provided to the interior of the ocean that eventually circulates to the Pacific LAB coast. Therefore, an increasing trend in hypoxia may arise in the future. The short time series on oxygen in Pacific LAB inhibits the formation of projections of future oxygen saturation in coastal sub-basins.

Other ocean properties

Stratification - Stratification is the natural separation of ocean waters of different densities and is important to the mixing, circulation and productivity of the oceans. Warm fresher (less dense) waters sit atop of colder saltier waters; waters are mixed through upwelling, downwelling and storm action as well as seasonal cooling of surface waters. Mixing is very important to marine biota as it bring nutrients to the surface and oxygen to deeper waters, thus providing a means of ventilating the ocean. Warming during spring stratifies waters in Pacific LAB trapping phytoplankton near the surface, resulting in a spring bloom in the nutrient rich water. Prolonged or strengthened stratification can have negative impacts. As the temperature of coastal waters increase, the thermocline becomes a more powerful boundary, making it more difficult for the nutrient rich waters to reach the surface (Palacios et al. 2004). Reductions in upwelling and mixing have resulted in local or widespread biomass loss and changes in species composition (Veit et al. 1996; McGowan et al. 2003; Sydeman et al. 2009). It is expected that future changes to ocean conditions will impact stratification, but it is difficult to make statements about future conditions given current data and model limitations.

Anthropogenic global surface ocean warming is indicating increased upper-ocean vertical stratification in water density. This is expected to be reinforced by freshening near-surface waters in most mid- to high latitude regions, but offset and dominated by increasing near-surface salinities over offshore subtropical waters (due to increased evaporation) (Dave 2012). Observed long-term trends important to Pacific LAB indicate a long-term increase in stratification with an associated reduction in vertical mixing. However, these changes are still dominated regionally by decadal-scale variability.

A long standing hypothesis for the California Current is that increased surface temperatures will result in increased water-column stratification which in turn will reduce mixing and result in a decreased supply of nutrients to the euphotic zone (McGowan et al. 2003; Roemmich and McGowan 1995; King et al. 2011) with deleterious consequences for fish. However a recent modeling study has suggested a different and more positive scenario: Rykaczewski and Dunne (2010) show that increases in nitrate supply and productivity occur in the California Current despite increases in stratification and limited changes in wind-driven upwelling. They attribute the increased nitrate supply to enrichment of deep source waters (North Pacific Central Water) entering the region that results from decreased ventilation of the North Pacific. Knowledge and data limitations inhibit the formation of projections for stratification in Pacific LAB.

Currents - Dominant circulation from winds and currents tend to delineate boundaries of the sub-basins. Complex circulation patterns along the Pacific LAB coast driven by winds have significant effects on the productivity of marine organisms (Ware and Thomson 2005), and likely on dispersal of early life history stages. Areas of high current increase circulation and are almost always well-mixed, and typically represent areas of high biological productivity. Significant fluctuations in climate-linked (and seasonally alternating) poleward (in winter) and equatorward (in summer) currents drive temporary shifts in abundance and distribution of plankton and other transient species along the Pacific LAB coast. Changes to current patterns that interact with dominant upwelling and downwelling winds may alter seasonal productivity associated with the spring transition. Projected changes to regional winds based on global ocean models show fractional increases in magnitude and directional changes (2030-49 and 2080-99) with stronger increases projected in summer (Merryfield et al. 2013). Projections generated by a regional ocean model (Masson and Fine 2012) suggests flows may increase in regions of the North Coast sub-basin, including possible larger Haida Eddies, but projections for other regions (WCVI shelf, California Under Current) are limited by the existing model domain resulting in considerable uncertainty (Foreman et al. 2013; Appendix 10.3).

Nutrients – The transport of nutrients onto the continental shelf relies heavily on seasonal strong on-shore winds that initiate upwelling of deep waters. Major ocean-atmosphere interactions, particularly the ENSO phenomenon, can suppress upwelling and cause variability in nutrient levels and affect productivity (Whitney and Welch 2002; Checkley and Barth 2009). Knowledge and data limitations inhibit the formation of projections of nutrient profiles in Pacific LAB.

Salinity - Ocean salinity is an important contributor to ocean circulation and vertical mixing and hence to marine ecosystems. Together with temperature and pressure (depth), salinity determines the density of seawater. Changes in salinity occur in response to precipitation, evaporation and freshwater run-off from the continent. These all vary with anthropogenic and natural climate change but also have strong regional variability, resulting in more spatial structure in salinity than in other variables such as temperature. Salinity in Pacific LAB over the past 60 - 80 years has been dominated by similar inter-annual to multi-decadal variability as temperature (Irvine and Crawford 2012). However, unlike temperature, sea surface salinity as measured at lighthouse stations across sub-basins show variable trends. North Coast stations show a freshening trend for the past 20 years, while the Strait of Georgia and WCVI stations show no consistent trend. All three stations do however show low frequency variations in sea surface salinity but not in association with El Niño or La Niña events (Cummins and Masson 2013). Measured changes in freshwater discharge will likely affect marine organisms and aquaculture operations in regions and seasons affected by interconnected changes in freshwater discharge, local ocean circulation and salinity. Knowledge and data limitations inhibit the formation of projections for salinity in Pacific LAB.

2.3 Cumulative effects

There are additional and likely large risks from climate change on aquatic biota when we consider the cumulative effects of interacting ocean parameters (Fig. 2.7). Effects will potentially be additive, multiplicative, antagonistic and/or synergistic with associated variability across space. It may be obvious that large scale drivers such ENSO and PDO have important individual and cumulative consequences to ecosystems at the local and regional level, yet if the climate becomes more unrecognizable, understanding biological responses will be increasingly difficult as responses can't usually be tracked on a short-term basis. These effects may also be highly localized in scope or widespread through a region or population. Though hotly debated by climate modellers, projected changes in dominant atmosphere-ocean interactions (e.g. ENSO; Power et al. 2013) can at best only forecast changes 20-30 years in the future. Short-term or near-term forecasts (1-3 years in advance) are not scientifically rigorous because of the inherent variability of the climate system.

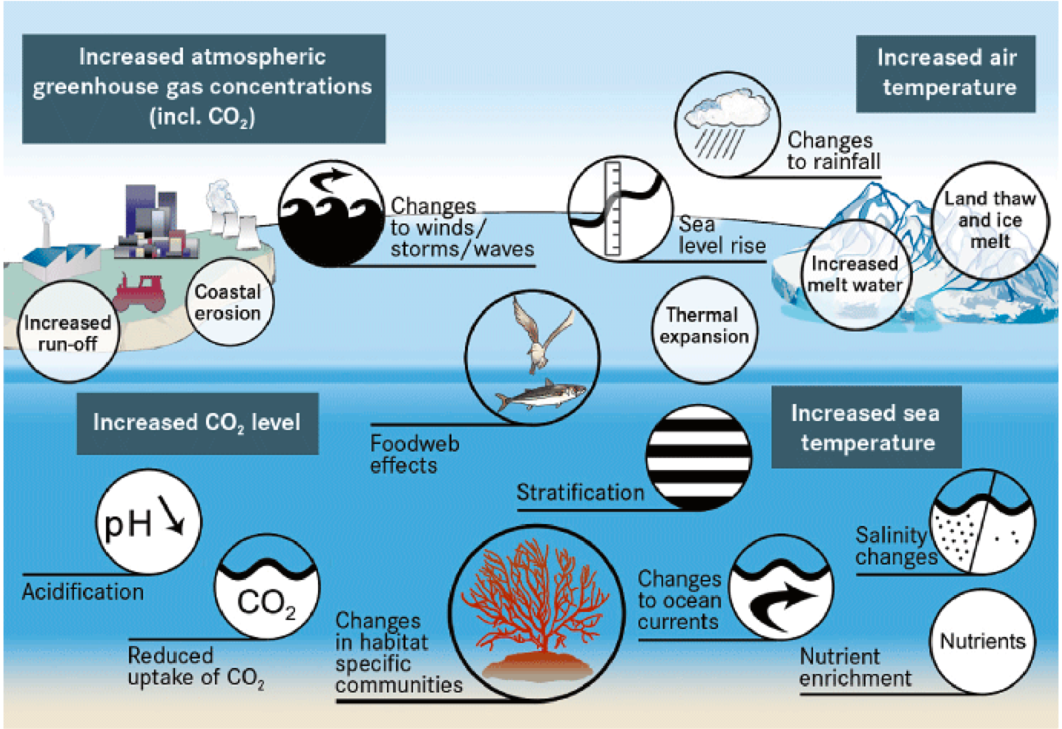
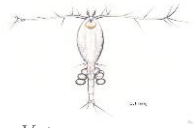


Figure 2.7. Summary of climate change and acidification interactions and impacts in the ocean. Figure reproduced from OSPAR (2010).

The effects of multiple factors on abundance and distribution of fish along the Pacific coast have been investigated. Predictions based on bio-climatic envelope models include coarse scale range and abundance shifts resulting in changes to species assemblages and overall increased landings for North East Pacific ocean fisheries (Cheung et al. 2009; 2010; Ainsworth et al. 2011). Other systematic predictions of biological futures have used conceptual modeling exercises to forecast climate-driven changes to fish populations in more local environments. For the California Current Ecosystem, the response of animals to shifts in productivity linked to changes in ocean stratification off WCVI was the strongest driver of future distributions (King et al. 2011). Other methods to evaluate cumulative impacts may involve frameworks that rank marine species climate change vulnerability (e.g. Hunter et al. 2014).

In summary, there are several key climate-related physical parameters operating in Pacific LAB that control and modify marine ecosystem responses over space and time. As these parameters shift in their characteristics, responses of the marine species and ecosystems for which DFO maintains the responsibility to manage will undergo change.

3.0 LOWER TROPHIC LEVELS



Sonia Batten and Bill Peterson

KEY POINTS

- Warmer sea surface conditions induce a shift to a greater abundance of southern zooplankton species along the North East Pacific Ocean. Continued warming may shift the dominant species from the lipid-rich northern assemblage to the lipid-poor southern species.
- Increased water column stratification may reduce nutrient content of upwelling water leading to reductions in primary and secondary productivity.
- Timing of reproduction by local species and timing of seasonal feeding migrations to the northern California Current may change in association with changes in the timing of the spring blooms and onset of upwelling.
- Ocean acidification is a high concern for lower trophic levels as many species are themselves calcifying organisms or rely directly on calcifying organisms for food.

3.1 FACTORS CONTROLLING ABUNDANCE AND DISTRIBUTION

Time series of annual and seasonal abundance and species composition of lower trophic levels are available for some areas in Pacific LAB and along the Oregon coast. The analyses presented in this section are based on these time series. Details of the sampling programs for lower trophic levels in and around Pacific LAB cited in this section of the report are found in Appendix 10.2.

3.1.1 Circulation patterns

Surface currents in winter are from the south (the Davidson Current) and transport “southern” species of plankton northward. These waters are relatively warm (10-12°C). In spring, once coastal upwelling is initiated, coastal currents reverse, and water flows from the north which transports “northern” species to the northern California Current and temperatures can cool to as low as 8°C nearshore if upwelling is very strong.

3.1.2 Seasonality

The latitude of the regions of interest dictates strong seasonality in day length, temperature, and winds which in turn generate strong seasonality in abundance of the lower trophic levels. Low light levels in winter prevent the phytoplankton from growing at a high rate and in consequence, winter zooplankton concentrations are also low with many of the larger zooplankton showing an ontogenetic migration to greater depths over winter where they remain dormant. A spring increase in phytoplankton is clearly evident in the shelf regions, driven by increasing light, increase stability of the water column, and the availability of nutrients brought to the surface by the strong winter mixing. An increase in zooplankton abundance also occurs in the spring driven by the phytoplankton increase.

Overlaying these typical annual cycles is the influence of larger scale hydroclimatic variability. Warm or cool conditions can persist for several years, as illustrated by the Pacific Decadal Oscillation index (Appendix 10.1). Wind patterns indexed by the North Pacific Gyre Oscillation (Appendix 10.1) can alter the circulation and thus the properties of the water that the plankton inhabits. The three Pacific LAB sub-basins will be influenced to a differing degree by both large scale and local processes. As a semi-enclosed sea, the Strait of Georgia plankton populations are affected by changes in the source water from offshore, regional climate and local inputs of freshwater which drives the estuarine circulation of the Strait. Plankton species composition in West Coast Vancouver Island and the North Coast sub-basins will be more influenced by coastal upwelling and large scale circulation.

3.1.3 Seasonal cycles of abundance

Mean seasonal cycles of phytoplankton indices from the Continuous Plankton Recorder (CPR) in the WCVI sub-basin are shown in Figure 3.1. Each index shows a different seasonal cycle; mean total number of diatoms are slightly higher in summer than in spring, while mean total number of dinoflagellates are highest in late summer and fall. Diatoms are normally ~ten times more abundant than dinoflagellates in CPR samples at this location. The Plankton Colour Index (PCI) has highest values in early spring, likely when small cells are common.

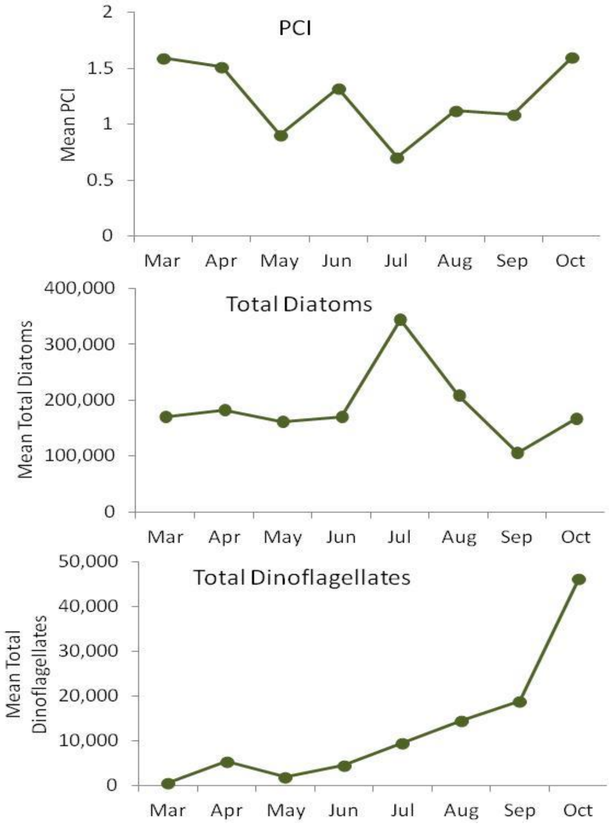


Figure 3.1. Seasonal cycles in the three phytoplankton indices derived from Continuous Plankton Recorder data. PCI = Phytoplankton Colour Index (see Appendix 10.2 for sampling details).

Copepods monitored in WCVI dominate the mesozooplankton in any one month making up at least 60% of the abundance and more normally closer to 90%. The CPR does not sample the larger euphausiids and hyperiids well owing to the small aperture in the device through which the seawater passes, nevertheless euphausiids are found in 44% of samples, hyperiids in 20% and together they contribute about 1-10% of the zooplankton abundance recorded. Chaetognaths, appendicularia and pteropods are other commonly occurring groups that each make up 1 or 2% on average. Decapod larvae occur in over 45% of samples but typically in low numbers.

Copepods are divided into two groups, those larger than 2mm which typically have an annual life cycle and may spend a good portion of the year overwintering at depth, and smaller copepods less than 2mm long, which generally have several generations within a year. In shelf regions such as WCVI small copepods are more numerous than in offshore regions, and even though the smaller stages are likely under-sampled by the CPR they were still 20-50 times more abundant than the large copepods. However, the large copepods contribute much more to the overall biomass than do the small copepods, and they tend to be rich in lipids, making them a good food source for small fish and even seabirds. The two copepod groups differ in their seasonal cycles, shown in Figure 3.2, with small copepods most abundant later in the year while large copepods have a peak in spring.

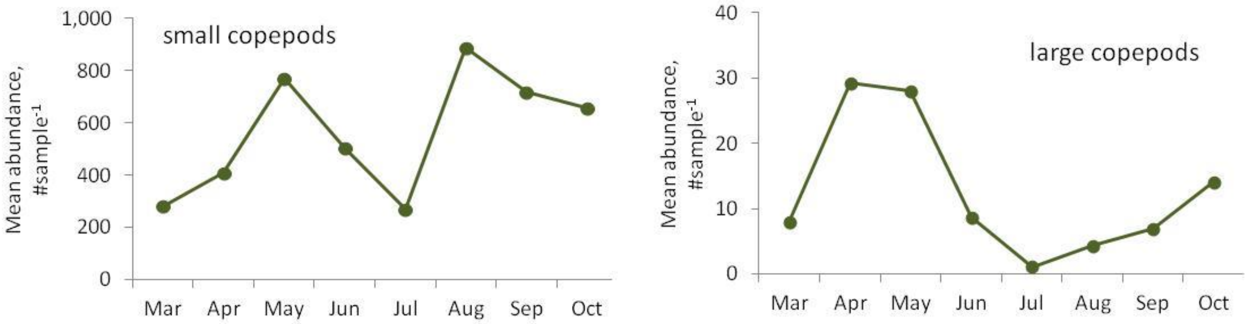


Figure 3.2. Seasonal cycles of small (<2mm) and large (>2mm) copepods derived from Continuous Plankton Recorder data from the WCVI region (see Appendix 10.2 for sampling details).

3.2 SUMMARY OF TRENDS BY PACIFIC LAB SUB-BASIN

3.2.1 Strait of Georgia

This section summarises Mackas et al. (2013), and references therein, which has brought together several zooplankton sampling programs from the deep water Strait of Georgia region from 1990 to 2010. Much of the Strait of Georgia is deeper than the adjoining WCVI sub-basin, although still shallower than the oceanic subarctic Pacific. Relatively large seasonal and interannual temperature fluctuations occur throughout the water column, with a lag of about 4-5 months between the surface and 200-400m (Masson and Cummins 2007). The primary productivity and phytoplankton biomass of the Strait of Georgia is large (Harrison et al. 1983; Masson and Peña 2009) and zooplankton biomass was also found to be high. Although a large number of species were found overall much of the biomass was accounted for by relatively few species. The Strait of Georgia, WCVI, and oceanic NE Pacific share the same zooplankton species by and large, but the dominant components of the Strait of Georgia zooplankton community were more similar to the oceanic subarctic Pacific Ocean than to the BC continental shelf populations.

There was a notable absence of southern-origin species in the time series, even though these species become abundant along the continental shelf in warm years. The strong estuarine circulation of the Strait of Georgia was thought to be responsible since most of the water carrying plankton enters below 50m depth owing to the shallow sill at the mouth of Juan de Fuca Strait, thus it carries in deep water plankton. Large crustaceans (copepods, euphausiids and amphipods) made up the majority of the Strait of Georgia zooplankton. These groups undergo strong diurnal or seasonal vertical migrations and their interannual variability was very large, between one and two orders of magnitude. Strait of Georgia zooplankton had, to a large degree, a pattern of interannual variability, encompassing at least two trophic levels and supporting the conclusion that bottom-up processes control zooplankton communities in the Strait of Georgia. Despite widespread overall indications that cool conditions were more favorable to the zooplankton, individual zooplankton often differed in the direction and degree of their responses to local and direct indicators (water column temperature anomalies within the Strait of Georgia vs. larger scale and indirect indicators (e.g. PDO, NPGO) of warm vs. cool climate). The environmental time series with strongest average correlation with the zooplankton anomalies were the NPGO and the start date of the Fraser River freshet. These two environmental time series were also strongly correlated with each other (r = 0.77). PDO was found to not be an important index in explaining Strait of Georgia zooplankton variability.

3.2.2 West Coast Vancouver Island

Phytoplankton

Figure 3.3 shows the interannual variability of each phytoplankton index within the time series. If 2008 is removed (spring sampling was missing entirely for this year) there is an increasing trend in diatoms and a decreasing trend in dinoflagellates through the albeit short time series. PCI increases slightly. Dinoflagellates are significantly more abundant in years that are warmer, with a positive PDO (with SST, $r^2=0.68$, $p<0.01$) while diatoms show a slight negative relationship with the PDO. The latter years of the time series have been cooler and a negative PDO has predominated since 2008 which explains the trend. The NPGO showed a slight negative relationship with the dinoflagellates, but not with the PCI or diatoms.

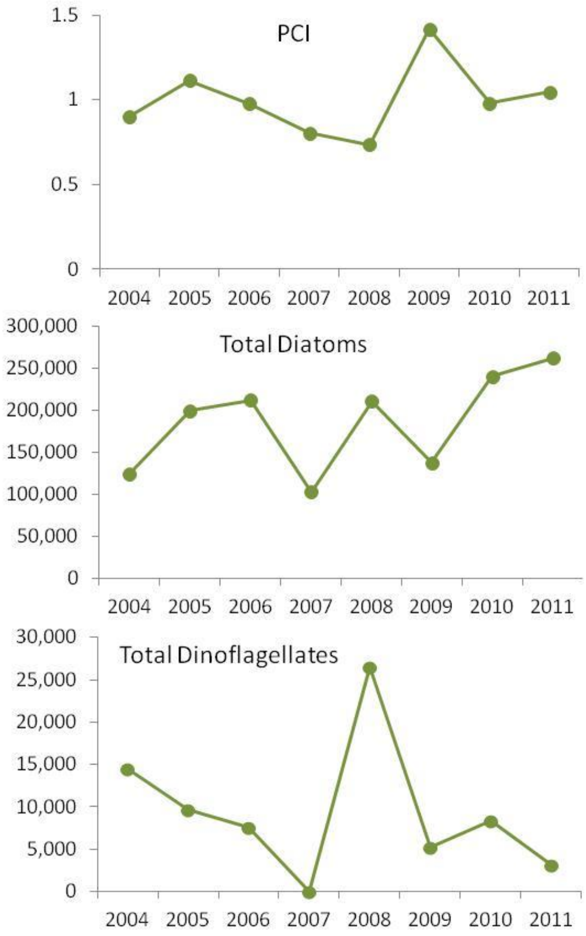


Figure 3.3. Interannual variability (mean of April to September) in the three phytoplankton indices derived from Continuous Plankton Recorder data. PCI = Phytoplankton Colour Index. Prior to calculating the annual mean, missing months were filled according to the formula: (monthly mean for that month*annual mean for that year)/overall monthly mean.

Zooplankton

There are no linear trends in these short zooplankton time series for the WCVI region (Fig. 3.4) but the variability can be related to ocean climate. Small copepods show a positive correlation with SST, with higher abundance observed in warm years (i.e. 2005, 2008). If 2008 is removed (when no sampling took place until summer) then the correlation is significant ($r^2=0.47$, $p<0.05$). Small copepod abundance also had a weak positive correlation with the PDO and a weak negative correlation with the NPGO. Large copepods have a weak negative correlation with the PDO. Pteropods have a strong, significant, negative correlation with temperature and the PDO ($r^2=0.70$, $p<0.01$ with the PDO, if 2008 is removed, r^2 drops to 0.60, $p<0.02$). Appendicularia have a negative correlation with the PDO, and a positive correlation with the NPGO. Both are significant ($p<0.05$) if 2008 is included but weaken if that year is excluded. Chaetognaths show a positive correlation with the PDO which is stronger than that with temperature, and a weak negative correlation with the NPGO.

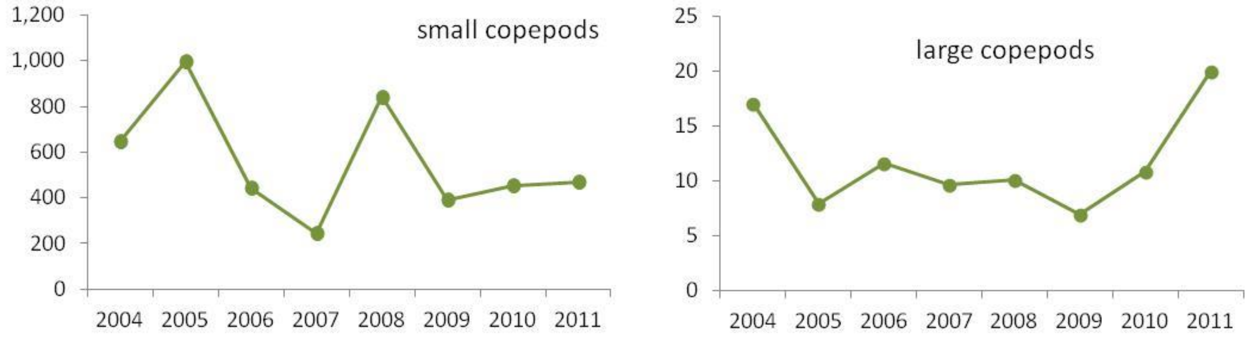


Figure 3.4. Interannual variability (mean of April to September) of small and large copepod abundances, from Continuous Plankton Recorder data. Prior to calculating the annual mean, missing months were filled according to the formula: (monthly mean for that month*annual mean for that year)/overall monthly mean.

The Mackas West Coast surveys (Appendix 10.2) revealed an increase in gelatinous plankton during the recent decade (not well sampled by the CPR), particularly salps and jellyfish. Additionally, this dataset also found that cool years showed positive anomalies in boreal shelf and subarctic copepods while warm years showed generally negative anomalies in these groups but positive anomalies in southern copepods and chaetognaths.

3.2.3 North Coast

Little difference was found between the trends in the plankton communities of WCVI and North Coast in the Mackas West Coast surveys. In fact there is a high degree of synchrony across the wider region, with data from the Newport Line (Appendix 10.2) showing similar patterns (Fig 3.5). A change in sign of the PDO (colored bars) is accompanied by a change in the biomass of "northern copepods" and "southern copepods". The northern copepod biomass is an average of the biomass of three lipid-rich species that are dominant in the coastal Gulf of Alaska and shelf waters of the Bering Sea: *Calanus marshallae*, *Pseudocalanus mimus* and *Acartia longiremis*. Positive anomalies of these species indicate transport of cold waters from the north (from southern British Columbia) into the California Current, as shown by Keister et al. (2011) and Bi et al (2011). On the other hand, "southern copepods" have high biomass anomalies only when the PDO is in positive phase. These species (listed in Hooff and Peterson 2006) are common in warm waters offshore of southern British Columbia, Washington and Oregon as well as in coastal waters of the southern California Current. They are also present in coastal waters of the northern California Current in winter indicating onshore movement of offshore waters and/or stronger northward transport of coastal waters in winter.

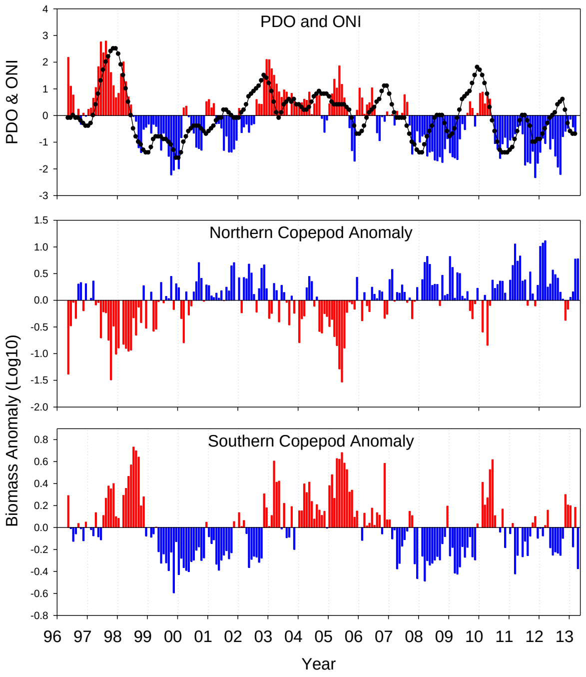


Figure 3.5. Time series of monthly values of the Pacific Decadal Oscillation, northern copepod biomass anomalies and southern copepod biomass anomalies sampled along the Newport Line, off the Oregon coast.

3.3 LOWER TROPHIC LEVELS AND CLIMATE CHANGE

A challenge facing any attempt at projections of the impacts of climate change on marine biota is detecting trends in data with inherently high interannual variability in both physical forcing and biological responses. This is particularly true in recent years during which high variability in dominant climate modes of the North Pacific and in climate-related physical parameters have been observed. In this report, indices of climate variability (Appendix 10.1) have been used to explain the variability in the plankton data and assess likely impacts of climate change.

Another notable type of variability affecting lower trophic levels is related to coastal upwelling. Although there is evidence from Newport, Oregon that upwelling is starting 1 day later per year on average (Foreman et al. 2011), the most noteworthy point is that the start dates are extremely variable, spanning nearly 3 months. Responses of lower trophic levels to this variability have important ecosystem consequences in Pacific LAB (Mackas et al. 2007; 2012).

3.3.1 Abundance and distribution

Zooplankton in the North Coast, WCVI regions and off Oregon show distribution and abundance patterns that correlate well with PDO and ENSO. Cool water species are generally more abundant in PDO negative years and warm water species are more prevalent in warm, PDO positive and/or El Niño years. Strait of Georgia zooplankton populations, while also generally showing a ‘cool is better’ response, track the NPGO more significantly than the PDO. Too few studies have looked at the effects of the NPGO on biota to allow insights into how changes in NPGO activity might affect biota.

Though projections for oceanic oscillations that contribute to climate forcing are not available (but see Power et al. 2013), conceptual consideration of increased variation in climate forcing is of significant importance to biotic responses to climate-related impacts. Should there be increased variability in the frequency or magnitude in ocean climate modes, it may interfere with cool-phase and warm-phase ecosystem dynamics. The relationship between zooplankton and the PDO has implications for the bioenergetics content of the food chain – warmer conditions induce a shift to lipid-poor southern-species along the North East Pacific Ocean (Hooff and Peterson 2006; Li et al. 2006). With continued warming, this could be detrimental to both resident and migratory biota because the food chain would be anchored by small, lipid-poor copepods. The result could be poor recruitment of fishes, poor egg laying success by nesting seabirds, and poor feeding conditions for all higher trophic level taxa. The Strait of Georgia is also affected by large scale climate forcing of the North East Pacific Ocean, but is only weakly exposed to the climate-linked fluctuations that are evident along the outer coast. Overall, increased variability in climate forcing could make it even more difficult to detect trends between physical forcing and biological responses at the lowest trophic levels.

Increases in water column stratification are expected due to global ocean warming and is thought to lead to decreased nutrient content of upwelling water. Indeed, a long standing hypothesis related to global warming is that increased surface temperatures will result in increased water-column stratification which in turn will reduce mixing thus decreasing nutrient supply to the euphotic zone in the California Current (McGowan et al. 2003; Roemmich and McGowan 1995; King et al. 2011) with deleterious consequences for fisheries**.** However a recent study has suggested a different and more positive scenario: Rykaczewski and Dunne (2010) showed that increases in nitrate supply and productivity occur in the California Current despite increases in stratification and limited changes in wind-driven upwelling. They attribute the increased nitrate supply to enrichment of deep source waters (North Pacific Central Water) entering the California

Current that results from decreased ventilation of the North Pacific. It is noteworthy that decreases in dissolved-oxygen concentration and increasing acidification accompany projected increases in nitrate.

Other ocean properties that may affect lower trophic levels include acidification and low dissolved oxygen. The exposure of plankton *spp*. to increased pH could lead to disruptions in the food web. Little is known about impacts of a change in pH on key taxa that support other species in Pacific LAB. A 'poster child' for ocean acidification research are the tiny pelagic snails (pteropods) because their extraordinarily thin and delicate shells are susceptible to shell thinning and shell dissolution due to decreasing levels of $p\text{CO}_2$ and aragonite saturation. *Limacina helicina*, a vital link in the food chain, is common in both oceanic regions of the sub-arctic Pacific (McGowan 1971) and the boreal sub-arctic coastal waters of the northern California Current (Mackas and Galbraith 2012; Peterson and Miller 1977). Based on work in the Antarctic by Bednaršek et al. (2012), we know that shell damage can occur at values of Ω_{arag} around 1. Feeley et al. (2008) and Juranek et al. (2009) have both shown that deep waters on the continental shelf off Oregon have aragonite saturation values that are less than 1, which in theory (and principle) should lead to dissolution of *Limacina* shells. Mackas and Galbraith (2012) showed significant declines in *Limacina* biomass are seen only in their continental shelf samples off Vancouver Island, in the naturally acidic waters that are influenced by the coastal upwelling process. Furthermore, Bednaršek et al. (2014) recently showed that pteropods collected from the Oregon upwelling zone had shells that were heavily pitted, presumably because the waters in which they were living had aragonite saturation values < 1, whereas individuals collected in offshore waters where aragonite saturation was > 1 showed little or no damage.

Hypoxia or low dissolved oxygen is unlikely to affect surface ocean dwelling plankton species. However, the eggs of zooplankton have a density greater than sea water thus sink and could fall into the low oxygen water before hatching. Although the exact values of oxygen that can cause mortality are not known for many zooplankton species, for *Calanus marashallae*, a large copepod common off the BC, WA and OR coasts, eggs suffer mortality if oxygen is < 0.2 ml L^{-1} and begin to show decreases in survivorship when oxygen is < 0.9 ml L^{-1} (Peterson, unpublished data).

3.3.2 Phenology

One of the most important physical factors controlling ocean production in the California Current ecosystem (CCE) is coastal upwelling, especially the timing of the onset of upwelling, the length of the upwelling season, and the cumulative effect on primary and secondary production. This is particularly relevant off northern and central California, where upwelling is strongest. Interest in, and awareness of, variability in the seasonal timing of upwelling in the CCE is very high among fisheries oceanographers because of events observed during the summer of 2005. During that summer, the onset of upwelling was delayed by up to two months (Schwing et al. 2006; Kosro et al. 2006), leading to a delay in plankton production (Mackas et al. 2006). Changes in the timing of initiation of seasonal upwelling and length and strength of the upwelling season can therefore lead to changes in the timing and magnitude of abundance of key prey items available to other species.

The bulk of annual production in Pacific LAB occurs during the spring and summer when upwelling favorable winds dominate throughout the system and both nutrients and light are in good supply. Indeed, the conventional view has long held that production in the California Current system depends almost entirely upon local coastal upwelling processes during the so-called "upwelling season", a perspective reflected in the design of several interdisciplinary studies of ecosystem processes and productivity (e.g. GLOBEC: Batchelder et al. 2002; WEST: Largier et al. 2006; and COAST: Barth and Wheeler 2005). Thus, while the upwelling season is without question important, production events that can occur outside of the conventional upwelling season may have disproportionate influence on ecosystem dynamics. One such period occurs during early winter (January), when *Neocalanus* spp. and *Calanus marshallae* awaken from diapause (Liu and Peterson 2010) resulting in a rapid 2-5 fold increase in biomass of copepods in surface waters. At this time both *C. marshallae* and *Calanus pacificus* produce eggs using their stored lipids and by feeding on ciliate prey. The next window for production arrives shortly thereafter, in late winter (anytime between late-January and early March), during which an extended period of calm winds and clear skies allows phytoplankton to bloom in response to increased stratification, light and sufficiently high nutrient concentrations (ca.10 µM nitrate). Such blooms (first noted by Parsons et al. 1966), support a diatom-based food chain, elevated egg production by *C. marshallae* and *C. pacificus* and an early burst of egg production by the coastal euphausiid, *Thysanessa spinifera* (Feinberg et al. 2010). Indeed, this krill species produces a cohort at this time which matures in July thus becoming an important food source for juvenile salmon and other planktivores at that time. If there is no winter bloom, there is no cohort of *T. spinifera,* and a reduced biomass of this species in summer. Many higher trophic levels time their migrations to take advantage of increased food supply in the northern California Current System e.g. grey and humpback whales that give birth off Baja California and Peru, respectively, take up spring and summer residence in the NCC. The success of these feeding migrations likely depends both on the late-winter production events (which only occur in approx. half of the years studied) as well as an early start to the upwelling season. Years in which upwelling is late (e.g. 2005) or during which significant El Niño events occur (1997-98, 2003-2006 and 2009-2010) can have consequences for local spawners and long-distance migrators.

4.0 COMMERCIALLY AND CULTURALLY IMPORTANT MARINE SPECIES PROFILES

4.1 MARINE FISH AND MAMMALS

Pacific LAB supports a productive set of capture fisheries for finfish and invertebrates that is supported by productive lower trophic assemblages. There is a large diversity of marine mammals including at least 27 species experiencing a variety of direct and indirect climate impacts across Pacific LAB (see section 4J). In recent decades, capture fisheries have undergone a transition from a focus on Pacific salmon and Pacific Herring to involving harvests of a broader range of species (percent volume of landings 2006-2010: groundfish: 42 %; pelagics = 25 %; shellfish = 33 %; DFO 2014) and have a total annual value of about $300 million (DFO 2014). The North Coast sub-basin contains diverse groundfish habitat supporting a large production for fisheries as well as important Pacific Herring spawning locations. The most lucrative migratory pelagic fish stocks support valuable harvests mainly off WCVI. High-valued invertebrate species support fisheries mainly in inshore populations, with North Coast providing the greatest landings for the species evaluated here.

Climate change projected for marine areas of Pacific LAB (50 year horizon, Christian and Foreman 2013), suggest changes to the abiotic environment that are likely to induce responses at all levels of biological organization (DFO 2013a). Changes in ecosystem states and fish yields associated with natural variations in ocean climate in Pacific LAB have thus far been large enough that climate change is not yet independent from the internal variability in marine environments (Christian and Foreman 2013). Still, biological responses to variation influenced by climate modes prescribe much of our current understanding of the expected impacts from future climate change on biota in Pacific LAB. We now understand that modulations in ocean climate affect variability in the timing and duration of peak zooplankton biomass (Brodeur and Ware 1992; Tanasichuk 200*2;* Mackas et al. 2007), re-distribution of species during "warm ocean" years (Ware and McFarlane 1986; McFarlane and Beamish 1986; Fargo and McKinnell 1989), abundance (Jamieson et al. 1989; Ware and McFarlane 1995), growth and survival (Nielsen et al. 2008; Peterman and Dorner 2012), invasive or transient species interactions (Field et al. 2007; Brodeur et al. 2008), and alterations in growth and recruitment of associated with variation in food-webs (Ware and Thomson 2005; Mackas et al. 2007; Perry and Schweigert 2008). Such responses have to date remained well within the range of historic variation (DFO 2006-2008, 2009b, 2010, 2011; Irvine and Crawford 2012) and studies continue to demonstrate the complexity of these systems.

Despite Pacific LAB based patterns, the unique environments and climatologies of Pacific LAB sub-basins expose living marine resources to sub-basin specific climate stressors. Knowledge of the interactions of species with various climate parameters (trends and projected states) is incomplete, yet conceptual models emerge from climate-related studies as to the potential responses of biota to major climate drivers. A literature review on the biological characteristics, fishery management and climate change impacts, vulnerabilities and opportunities for select species is provided in sections 4A-J.

4.2 CULTURED SPECIES

Sheltered, ice-free and nutrient rich marine waters provide for suitable sites for finfish and aquaculture leases throughout the region. As a result, Pacific LAB supports a highly productive and highly valuable finfish and shellfish aquaculture industry. Since the 1990's, aquaculture production in the region has grown from contributing less than 5% of the total fisheries volume or value, to contributing more than 25% of the volume and 60% of landed value of all fisheries products (DFO 2014). Salmon culture, of which the majority is Atlantic Salmon, accounts for on average 89 % (79,000 tonnes) of the volume and 94% ($434 million) of total landed value of all Pacific LAB cultured fish (DFO 2014).

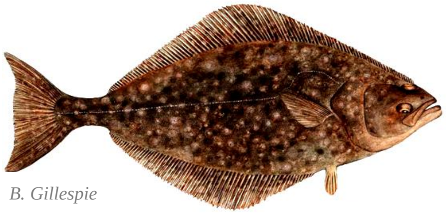
The majority of aquaculture production in the Pacific LAB is centred in two sub-basins: WCVI and, most importantly, Strait of Georgia. The majority of shellfish operations occur in the Strait of Georgia. In 2012, shellfish production in that sub-basin was 5204 tonnes or 79% of total production for Pacific LAB. North Coast sub-basin supports very few aquaculture operations to date. Current data on finfish production inhibits reporting by sub-basin but the majority of sites are located in southern areas of the North Coast (section 4K).

Exotic species form the basis of the Pacific LAB aquaculture industry. Following global trends, Pacific LAB's industry is growing and there is increasing interest in adding additional species (exotic and indigenous) to the activities (Gillespie et al. 2012). The most significant species being cultured within Pacific LAB, either by volume or value are: Atlantic Salmon (*Salmo salar*), Pacific Oyster (*Crassostrea gigas*), Manila Clam (*Venerupis phillippinarum*) and blue mussels (*Mytilus spp*.), (Table 4.1). The remainder of this section details climate change impacts, vulnerabilities and opportunities are presented here only for the most lucrative cultured species: Atlantic Salmon and Pacific Oyster.

Table 4.1. Major marine aquaculture species and value produced in Pacific LAB in 2010.

Species	Value ($Cdn)
Atlantic Salmon	$470,253,000
Chinook and Coho Salmon	$29,341,000
Sablefish	$3,393,000
Pacific Oyster	$8,872,000
Manila Clam	$6,890,000
Pacific and Giant Rock Scallop	$2,898,000
Mussels	$1,809,000
Geoduck Clam	$1,125,000
Varnish Clam	$260,000
California Sea Cucumber	$190,000
Littleneck Clam	$44,000
Total	$524,973,000

4.3 MARINE AND AQUACULTURE SPECIES PROFILES


B. Gillespie

A. Pacific Halibut
(*Hippoglossus stenolepis*)

Karen Hunter, Tim Loher and Robyn Forrest

KEY POINTS

- Studies on the potential impacts of climate drivers on population dynamics have not identified mechanistic links between halibut abundance and environmental correlates nor have they examined the Pacific Halibut response to future climate change.
- Long-term recruitment trends across the species range may be impacted by climate forcing should pronounced effects on oceanographic currents impact shoreward transport of halibut larvae to suitable nursery grounds.

A.1 BIOLOGICAL CHARACTERISTICS

A.1.1 Life cycle, age and growth

Pacific Halibut are the largest flatfish in the world, reaching a length of 2.7 metres and a weight of 300 kilograms. Maturity varies with sex, age, and size of the fish. Females grow faster but mature slower than males. Most males are mature by the time they are 8 years old, whereas the average age of maturity for females is about 12 years. The oldest recorded age of Pacific Halibut, derived from otolith-based aging techniques (Forsberg 2001), is 55 years, for both males and females (J.E. Forsberg, IPHC, Seattle, pers. comm.).

Pacific Halibut egg production varies with female size. A 23 kg female will produce about 500,000 eggs, whereas a female over 113 kg may produce 4 million eggs. Each winter, fish aggregate on spawning grounds along the edge of the continental shelf at depths of 183-457 m (IPHC 1998), and initiate spawning at depths ranging from at least 126-594 m and averaging approximately 400 m (Loher and Seitz 2006; Loher 2011). Females of the genus *Hippoglossus* are "batch spawners" (Finn et al. 2002) that in the wild appear to move markedly off-bottom (i.e. by 150 m, on average; Seitz et al. 2005; Loher 2011) to release eggs into the water column to be fertilized by males. Pacific Halibut eggs are planktonic and have been found at depths of 100 to 200 m near the outer edge of spawning grounds in January and February (Thompson and Van Cleve 1936), and a combination of historical winter survey data and electronic archival tagging suggest that the egg-release period in the eastern Gulf of Alaska and British Columbia extends from at least mid-December through mid-March (Loher 2011).

Movement of eggs produced from spawning in Canadian waters is driven by ocean current patterns. Transboundary movement of eggs may result, but is more likely to occur at the larval stage (Skud 1977). Eggs float in offshore slower moving deep currents of heavier water, but not in areas of shallower water with low salinity (Thompson and Van Cleve 1936). It has been reported that eggs hatch after 15 to 20 days at 5-6^{o}C and 12 to 14 days at 7-8^{o}C (IPHC 1998).

Larvae undergo metamorphosis turning from a "round fish" to a "flatfish" early in the life cycle. Larvae develop and rise toward the surface at 5-6 months of age and begin drifting into shallow shore waters (Thompson and Van Cleve 1936). Larvae develop and grow while drifting upward in the water column and being pulled in a counter-clockwise direction around the Northeast Pacific Ocean (IPHC 1998).

There is little information on growth rates of wild Pacific Halibut. Size-at-age has fluctuated over the data record (1923-2012) (Clark and Hare 2002a), with changes in northern areas of the distribution showing much larger variation than southern areas (Clark et al. 1999; Stewart et al. 2013a). The importance of ecologically and anthropogenically-derived mechanisms controlling these interpretations are not understood, though multiple hypotheses are documented (Loher 2013).

A.1.2 Distribution, habitat and environmental preferences

Pacific Halibut are found along the continental shelf in the eastern North Pacific Ocean, the Bering Sea and Gulf of Alaska (GOA) (Fig. A1), as well as in the western Bering Sea, Sea of Okhotsk, and into the northern Sea of Japan (Mecklenberg et al. 2002). The central Gulf of Alaska is the centre of abundance of Pacific Halibut on the west coast of North America. Pacific

Halibut live on the ocean bottom at depths of up to 1000 metres. Younger fish use shallower habitats closer to shore, but are generally not found in near shore environments. Based on results from tagging studies, it is also known that adult Pacific Halibut (>100 cm) in the Gulf of Alaska spend the majority of their time at temperatures ranging from 5-11^{o}C (Loher and Seitz 2006).

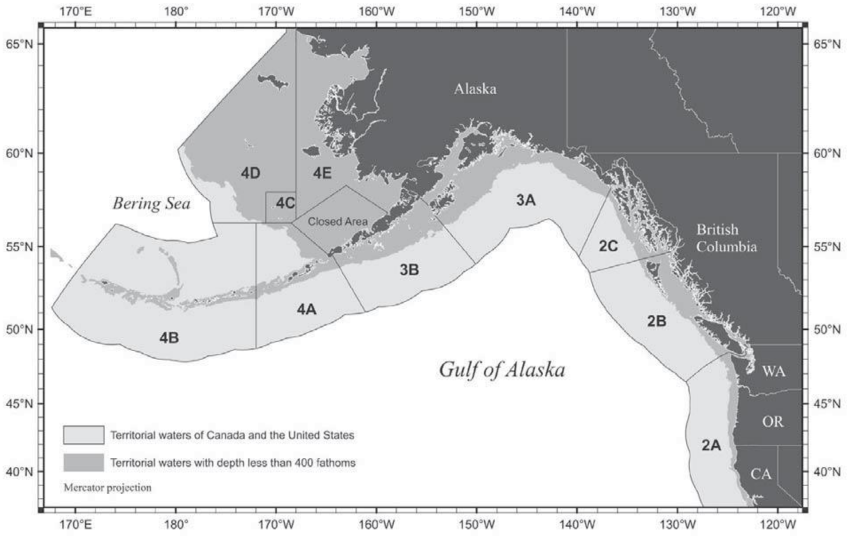


Figure A1. IPHC regulatory areas for the 2012 Pacific Halibut fishery. Regulatory areas are a proxy for the distribution of the species in the Northeast Pacific Ocean.

In Canadian waters, important spawning grounds have been identified as Cape St. James, Langara Island and Frederick Island (IPHC 1998). Other reported spawning locations include Goose Islands, Hecate Strait and Rose Spit. There is reason to believe that spawning occurs in less concentrated aggregations in many other areas within their range because mature females can be found in areas outside these spawning grounds (IPHC 1998).

Settlement of Pacific Halibut larvae is concentrated at depths <40m and is generally restricted to sediments composed of a combination of sand and mud (Norcross et al. 1997). Laboratory experiments have demonstrated broader habitat use and a preference for increasing grain size as individuals grow is likely correlated to individual burial capability (Stoner and Ottmar 2003). While the region west of Kodiak Island and into the Bering Sea is often cited as comprising the primary nursery range for the eastern Pacific Halibut stock (e.g. Clark and Hare 1998), nursery habitat (defined as successful settlement and rearing of age-0+ individuals) is known to occur throughout the eastern Gulf of Alaska (Best 1974; Loher and Wischniowski 2006) and as far south as Dogfish Bank, in BC waters (Loher and Wischniowski 2008). The relative contribution of any of these areas to fishery recruitment is unknown. Nursery areas are important to young halibut for two to three years before they begin a migration counter current to their egg and larval phases, generally moving into southerly and easterly waters (Skud 1977).

Adult fish may move long distances on a seasonal basis (Loher and Seitz 2006). Adults also undergo short seasonal depth migrations from shallower feeding grounds in the summer to deeper waters in the winter linked to spawning (Loher and Seitz 2006). Spawning migrations of adult Pacific Halibut that summer in Canadian waters may have a northward component that can influence the distribution of fishable biomass across transboundary regulatory areas (Leaman et al. 2002), but the magnitude of these biomass shifts remains in question; analysis of different data sources has yielded order-of-magnitude differences in the amount of expected transboundary seasonal migration (Leaman et al. 2002; Loher and Blood 2009).

Early tagging studies suggested that stocks were relatively independent throughout ontogeny (Thomson and Herrington 1930), which was consistent with the rationale behind the closed-area stock assessments that the International Pacific Halibut Commission (IPHC) conducted from at least 1997 (Sullivan et al. 1997) through 2005 (Clark and Hare 2006). However, recent tagging studies (Webster et al. 2013) have confirmed the results of numerous historical tagging studies and analyses (Dunlop et al. 1964; Bell 1967; Bell and Best 1968; Skud 1975; 1977; Quinn et al. 1990) demonstrating that the notion of negligible adult migration between regulatory areas, upon which the closed-area assessments were based, was false. This led to a coast-wide assessment of the species beginning in 2006 (Clark and Hare 2006; 2007).

A.1.3 Predators and prey

Larval Pacific Halibut feed on plankton (Stickney and Liu 1999). Young halibut, between 1-3 years old (<30 cm), feed on small crustaceans and small fish (Novikov 1964). Larger halibut feed on a wider array of fishes and invertebrates (Best and St.-Pierre 1986). Adult food items are believed to be more limited than juveniles because as halibut increase in size, fish becomes a more important part of their diet (Best and Hardman 1982; Best and St.-Pierre 1986; Moukhametov et al. 2008).

The size, active nature, and bottom dwelling habits make adult halibut less vulnerable to predation than other species, although they can be prey for marine mammals (i.e. Stellar sea lions, seals, orca) and other fish (i.e. sand sole, Pacific cod). Pacific Halibut are known to feed on pelagic fishes despite their affinity for benthic habitat. Halibut at all life stages are cannibalistic (Best and St.-Pierre 1986).

A.1.4 Recruitment

Pacific Halibut enter or ‘recruit’ to the commercial fishery at 6-8 years old. The average age of Pacific Halibut in the commercial fishery is currently about 12 years old (Forsberg 2013). Age distributions in the commercial fishery have been relatively stable with most of the commercial catch age 8-15 years old (Forsberg 2013).

Strong year-class events (i.e. high survival of young fish) that appear cyclic in nature occur in Pacific Halibut (Deriso et al. 1985). However, the mechanisms that control this cycling cannot be assessed from available information (Parma and Deriso 1990). Two alternate hypotheses can be used to explain this cyclic recruitment. First, opposite trends in spawning biomass and juvenile production estimates suggest that recruitment is driven by density-dependent regulation (Deriso et al. 1985). Alternately, cycles of recruitment may also be influenced by environmental forcing through changes to currents that affect transport of eggs and larvae to nursery grounds and/or variation in ocean climate that influences primary production (Clark and Hare 2002a). Clark and Hare (2002a) suggested that climate forcing was the main driver of recruitment events, whereas density-dependent interactions as a result of changes in stock size have led to dramatic changes in growth patterns. Debate about the cause of cyclic patterns in halibut abundance dates back to the famous "Thompson-Burkenroad debate" of the 1950s (Skud 1975). Parma and Deriso (1990) concluded that historical data are consistent with both the density-dependence and climatic forcing hypotheses and discussed alternative adaptive policy options given this ongoing uncertainty.

There have been significant fluctuations in average size at age and recruitment patterns in the fishery over time as monitored by the IPHC (Clark et al. 1999; Stewart et al. 2013a). These trends are important features that continue to impact the effectiveness of management of Pacific Halibut fisheries and can have a strong influence on harvest policy considerations such as optimal size limits (Valero and Hare 2012) and regionally-explicit target harvest rates (Martell et al. 2013).

A.2 THE FISHERY

Pacific Halibut is harvested in substantial quantities along the coast of British Columbia by three fishery types: commercial fisheries (trawl and longline), First Nations fisheries (commercial communal and Food, Social and Ceremonial fisheries), and recreational fisheries. The commercial fishery has occurred since 1923 and is the largest of the three types. Some data on recreational and First Nations led fisheries distribution and catch weights exist for the BC coast (e.g. DFO 2012a). However, data are generally not collected using systematic monitoring and reporting systems despite efforts to improve accountability (DFO 2012b). We mainly discuss the commercial fishery here.

A.2.1 Management

This commercial fishery is jointly managed between Canada and the US under a bilateral convention (est. 1923) and based on recommendations by the IPHC. Regulations vary among fishery sectors, regulatory areas, and management bodies. Every year, IPHC sets the Total Constant Exploitation Yield (TCEY; see Stewart et al. 2013a for details) and Fishery Constant Exploitation Yield (FCEY) for each regulatory area (Fig. A.1). The FCEY is calculated by subtracting from the TCEY the removals associated with directed fishery wastage (sublegal fish discarded that are then assumed to die due to hooking mortality as well as mortality of all sizes from lost fishing gear), bycatch, sport and personal use fisheries (with the exceptions of Area 2A, where personal use and sport removals are included in the FCEY, and Area 2B where sport removals are included in the FCEY) (Stewart et al. 2013a). The primary source of personal use harvest in Pacific LAB is the First Nations Food Social Ceremonial fishery. IPHC relies on DFO for an estimate of FSC catch; since 2007, this harvest estimate has been fixed at 405,000 pounds. Fishery Constant Exploitation Yield (FCEY) is divided in Area 2B as 15% for recreational and 85% for commercial (DFO 2012b). Since 2004, reductions in the TCEY have translated into reductions in the total removals from all sources, as well as the FCEY.

All groundfish stocks in Canada’s Pacific fishery are managed by a single integrated fisheries management plan (e.g. DFO 2012b). This plan includes: 100% at-sea monitoring and 100% dockside monitoring for all groundfish fisheries; individual vessel accountability for all catch (both retained and released); individual vessel quotas (IVQs); and reallocation of IVQs between vessels and fisheries to cover catch of non-directed species. This is a multi-species management approach: vessels owners are accountable for all of their catch, regardless of whether it is retained, used at sea, or released at sea. Under the IVQ system, each commercial halibut “L” licence is granted a pre-determined share of the total allowable catch before the season begins. Combined with the IVQ system, a staggered fishing season, resulting from license holders being able to choose when they fish, allows fresh halibut to be moved into markets throughout the open season (i.e. for approximately nine months each year).

Other management actions include but are not limited to: size limits (minimum 81.3 cm); gear restrictions (hook and line); area restrictions; seasonal restrictions; trip limits for non-directed species (e.g. Sablefish, skate) (DFO 2012b). To reduce the amount of illegal halibut entering the market, each fish is tagged upon landing in order to trace back to point of landing if required (DFO 2012b).

A.2.2 Stock assessment

Pacific Halibut in the eastern Northeast Pacific Ocean (from the Bering Sea to the Oregon-California coast) is considered by the IPHC to be one population. Abundance and potential yield is estimated each year by the IPHC based on a scientific survey and stock assessment procedures. The stock assessment has been conducted on a coast-wide scale since 2006 (Clark and Hare 2006; 2007; Stewart et al. 2013a). Without dismissing the inherent uncertainty associated with fish recruitment, current harvest objectives are set to achieve a high level of yield while attempting to preserve female spawning stock biomass above the historically-observed minimum level in order to ensure long-term sustainability (Hare and Clark 2007). Average estimated age-6 recruitment is calculated from the stock assessment (Clark and Hare 2006), and then multiplied by the historical spawning-biomass-per-recruit to produce and estimate of the average spawning biomass in the absence of fishery removals.

In the past 10 years, the assessment has estimated the commercially harvestable biomass to have declined by around 50%; the size-at-age is also decreasing (Stewart et al. 2013a). A complete review of the data, models, and approach was conducted by the IPHC in 2012 (Stewart et al. 2013b). This review found that the model had not previously accounted for variation in the availability of different sizes of fish in different areas, through its use of a fixed, length-based selectivity function. This had resulted in a persistent, positive retrospective bias in the stock assessment in recent years (i.e. each new year of data resulted in successively smaller estimates of recent biomass and recruits). The 2013 stock assessment model was modified to allow the availability of different-sized fish to vary from year to year, resulting in correction to the previous retrospective bias problem (Stewart et al. 2013a). Current understanding is that recruitment and biomass were consistently overestimated in assessments between 2006 and 2011. Under the most recent assessment, estimated spawning biomass is around 5% above the threshold level at which a harvest reduction would be required (Stewart et al. 2013a). Under the current management strategy, inter-annual and decadal-scale environmental variability are acknowledged as a source of recruitment variability and are dealt with implicitly in the optimal harvest rate model (Clark and Hare 2002b; Stewart et al. 2013a).

A.2.3 Catch

The halibut fishery is one of the longest and best studied fisheries in the world, with over 100 years of information-gathering on the history of fishery removals, population trends, and life-history characteristics (Stewart et al. 2013a). Total annual halibut catch from all sources, including bycatch estimates and research removals, have ranged from 51 to 100 million lbs (23-45 million mt) over the last 17 years (Table A1). The average coast-wide catch over this time period is 86 million lbs (39 million mt).

Table A1. Removals of Pacific Halibut (1996-2012) combined for all regulatory areas (by source; million lb, net wt.); from Stewart et al. (2013a).

Year	Commercial fishery	Commercial wastage	Bycatch	Sport	Personal use	Total
1996	47.69	0.73	14.46	8.08	0.54	71.51
1997	65.49	1.05	13.51	9.03	0.54	89.61
1998	70.12	1.2	13.43	8.59	0.74	94.07
1999	74.7	1.34	13.84	7.38	0.75	98
2000	68.55	1.29	13.29	9.01	0.76	92.89
2001	70.97	1.44	13.16	8.1	0.77	94.45
2002	74.95	1.66	12.61	8.01	0.76	97.99
2003	73.36	1.77	12.58	9.35	1.38	98.44
2004	73.31	1.93	12.58	10.7	1.53	100.05
2005	72.11	2.03	13.26	10.86	1.54	99.8
2006	68.12	2.05	13.08	10.19	1.48	94.92
2007	63.03	2.29	12.27	11.46	1.49	90.53
2008	58.7	2.34	11.89	10.67	1.34	84.93
2009	52.18	2.62	11.38	8.75	1.31	76.24
2010	49.83	3.04	10.63	7.8	1.24	72.54
2011	39.61	2.21	9.9	7.08	1.24	60.04
2012	31.87	1.54	9.87	6.85	1.24	51.36

4.2.4 Canadian removals

The 2012 assessment conducted by the IPHC indicated that the Pacific Halibut stock has been declining over much of the last decade in most management areas. The assessment concluded that declines in harvest are the result of decreasing size-at-age, as well as poor recruitment strengths, and realized coastwide harvest rates that have been in excess of stated target levels since approximately 2001 (Stewart et al. 2013a). However, changes in realized harvest decisions also greatly impact the trends in fishery catch data and may account for declines in harvest over the same time period. The recent coast-wide declines seen in the IPHC scientific survey have not been documented in British Columbia (IPHC Regulatory Area 2B) over the past five years. In contrast, Area 2B has had a stable index of abundance in the scientific survey and a steadily increasing catch-per-unit-effort index in the commercial fishery (Stewart et al. 2013a). According to the British Columbia Seafood Industry, the landed value of Pacific Halibut of $45.6 million was the highest landed value of all seafood harvested in BC in 2011.

Total catch showed a decline in North Coast and WCVI from 2007 onwards that coincides with a reduction in quota since the introduction of the coast-wide stock assessment model (Fig. A2). BC's quotas are now tied to the coast-wide index of abundance which reflects the declining abundance in AK. Commercial catch per unit effort for fisheries in Area 2B has been very high and increasing over the same period (Fig.A2; Stewart et al. 2013). Commercial catch of Pacific Halibut in BC occurs mainly in the North Coast sub-basin, with a smaller harvest off West Coast Vancouver Island (WCVI) (Fig. A3). The Strait of Georgia sub-basin does not contribute to the Pacific Halibut harvest.

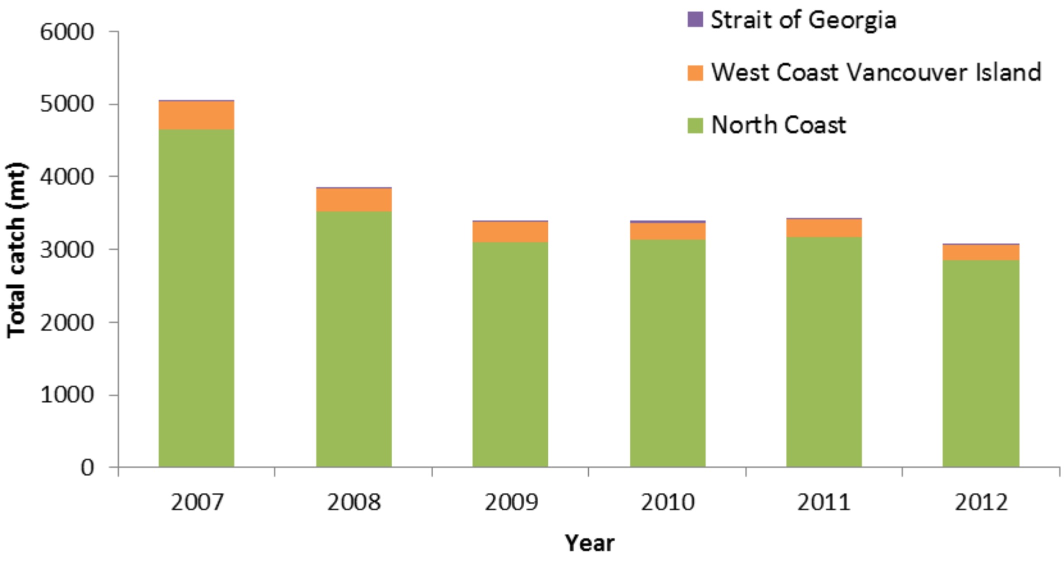


Figure A2. Total catch (mt) of Pacific Halibut (2006-2012) in Strait of Georgia, WCVI and North Coast sub-basins.

For the recreational fishery, creel survey data from 2012 (DFO 2013b) demonstrates that North Coast (281 mt) and West Coast Vancouver Island (207 mt) sub-basins retain the largest recreational catch. Recreational fishing for halibut occurs in the Strait of Georgia, but the catch is substantially lower (37 mt).

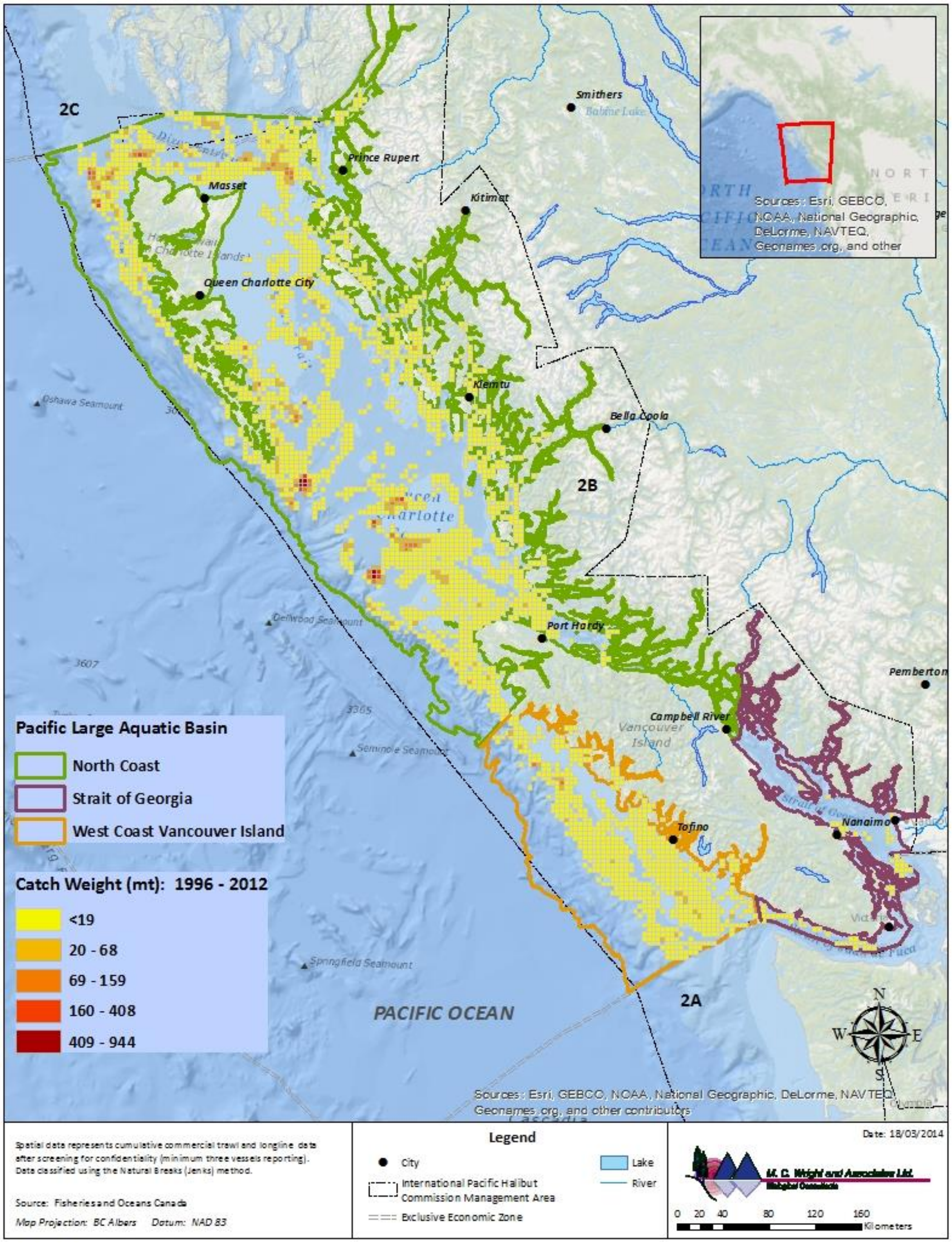


Figure A3. Distribution and cumulative catch of Pacific Halibut in groundfish trawl fisheries, in Pacific LAB, 1996-2012. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

A.3 CLIMATE CHANGE AND PACIFIC HALIBUT

Much of the investigations related to climate change and Pacific Halibut have studied relationships between biological trends and climate variation, as documented by ‘regime shifts’, and/or anomalies of the Pacific Decadal Oscillation (Clark et al. 1999; Clark and Hare 2002a). Although they have provided some insight on the potential impacts of climate drivers on population dynamics, these studies have not identified mechanistic links between Pacific Halibut abundance and environmental correlates nor have they examined the Pacific Halibut response to future climate change.

Generally, Pacific Halibut may be able to cope or adapt to projected thermal changes (e.g. 1.5-2°C coast-wide increase by 2060s, Christian and Foreman 2013) at adult stages because the species is not defined by a narrow habitat or temperature range. Size-at-age and recruitment of Pacific Halibut to the fishery has been related to interannual and interdecadal variation in ocean climate (Clark and Hare 2002a), with northern and southern stocks displaying variable and asynchronous trends over time. Causal explanations for changes in size-at-age and recruitment are not definitive (Skud 1975; Deriso and Parma 1988; Parma and Deriso 1990; Loher 2013). However, the cyclic and geographically asymmetric population parameters in Pacific Halibut across its range indicate a need to better understand the role of climate on this important fishery.

This species spends its life in deep waters of continental shelf and is unlikely to be directly impacted by climate-induced changes that occur at the surface. The potential effect of cumulative indirect changes should not be disregarded because of our current inability to quantify or understand their additive, multiplicative or cancelling effects.

Longevity evolved as a strategy to survive variable environmental conditions that affect reproductive success (Winemiller and Rose 1992). Longevity in Pacific Halibut indicates that over evolutionary time, the species has experienced periods of poor recruitment (King and McFarlane 2003; Beamish et al. 2008). While climate effects may have consequences on the distribution and/or abundance of Pacific Halibut in Canadian waters, the species is unlikely to experience considerable harm across the range of available ocean climate projections. The IPHC harvest policy has implicitly included consideration of climate change impacts through its recommended optimal harvest rate, which was calculated under the assumption of a low recruitment productivity regime (Clark and Hare 2002b).

A.3.1 Abundance

As with many marine fishes inhabiting Canadian Pacific waters, the greatest sensitivity to perturbations and change in climate may be the larval stage, with consequences for survival of young fish. Given that spawning and early rearing of larvae occurs in the winter months on the continental slope, consistent seasonal water temperature at depth in northern slope areas of BC and Alaska (DFO 2013b) may result in little to no change in survival of very young Pacific Halibut even if circumstances arise where surface waters experience greater changes in winter. Alternatively, climate forcing and interannual variability may have pronounced effects on the oceanographic currents upon which halibut larvae rely to ensure shoreward transport to suitable nursery grounds (Bailey and Picquelle 2002; *sensu* Sohn et al. 2010), thereby driving long-term recruitment trends.

Changes in plankton productivity may translate into changes in growth or survivorship during the larval phase, suggesting that management might do well to ensure protection of broad spawning periods (Loher 2011) that have likely evolved as "bet hedging" to safeguard against environmentally-mediated recruitment failure (*sensu* Cushing 1990). Despite not focusing on Pacific Halibut, a recent study showed otolith growth-increment chronologies for three Bering Sea flatfish species were synchronous with trends in ocean temperature (Matta et al. 2010). These findings suggest temperature may be mediating growth of flatfishes following settlement, in important northern rearing grounds.

A.3.2 Distribution

Trends in ocean climate may impact migration and distribution of Pacific Halibut. Dissolved oxygen and temperature at depth are thought to be particularly important for determining halibut movement and distribution. Analyses of ocean climate variables collected during Pacific Halibut surveys (2009-2011) do not show any certain impacts. However, distribution at the southern and northern ends of the species range may be affected should dissolved oxygen and temperature conditions, respectively, at depth in these areas become more stressful for Pacific Halibut (Sadorus 2012; Sadorus et al. 2014). Recruitment of halibut to the Canadian portion of the fishery is currently believed to be generated, for the most part, from juveniles emigrating from Alaskan rearing areas to the North Coast. Warming from south to north may cause a reduction in juveniles migrating into the Canadian zone (Beamish et al. 2008).

Projections of increased coastal wind strength in the summer, in addition to resulting impacts of increased sea surface temperature on stratification (Christian and Foreman 2013), may affect coastal currents and upwelling strength or timing. Changes to current strength along the continental slope, and/or in the Gulf of Alaska and Bering Sea, may have effects on westward and northward drift of eggs and larvae after spawning and subsequent recruitment (Beamish et al. 2008). In southern areas of the BC continental shelf, stronger coastal winds and weaker upwelling could impact productivity in the WCVI sub-basin especially (Ware and Thomson 2005), with impacts on recruitment and size-at-age of fishes, including Pacific Halibut.

Responses of groundfish occurring on the continental shelf to increases in level and distribution of hypoxic areas will likely result in declines in abundance and condition of fish areas. Fish may move inshore seeking the combination of higher oxygen concentrations and other key habitat features (e.g. sandy bottom).

A.3.3 Phenology

Similar to other groundfish species, a shift in timing of prey availability shift at key life stages would likely have negative consequences for halibut. There are no known studies that demonstrate this impact on halibut.

Table A2. Summary of conceptual impacts, vulnerabilities and opportunities linked to climate-related parameters for Pacific Halibut.

Physical parameter	Recruitment and abundance	Distribution and migration	Timing of life events
Sea surface Temperature	May be affected if conditions at depth become more stressful; Increased temperatures may lead to increased predation on larval and juvenile stages as predator population ranges change. Adults are likely immune. Improved abundance of prey resources may benefit the species.	Range of tolerable conditions at southern and northern ends of the species range may be affected; Behaviour at southern and northern ends of the species range may be affected; Juvenile migration from the north may be affected.	Relatively constant conditions at depth result in weak correlation between spawning and settlement timing and environmental variability.
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	Effects on westward and northward drift of eggs and larvae; Changes to currents may change shoreward transport of larvae to nursery grounds affecting survival and growth; Changes in currents that assist northward migration of prey and/or predator populations may affect larval and juvenile stages. Improved abundance of prey resources may benefit the species.	Movement behaviour may be affected; Juvenile migration from the north may be affected.	Changes to currents may change shoreward transport of larvae to nursery grounds affecting time of arrival
Stratification	No information	No information	No information
Upwelling winds	No information	No information	No information
Dissolved oxygen	May be affected if conditions at depth become more stressful, i.e. below ~1.4 ml l^{-1}	Juvenile migration from the north may be affected; Range of tolerable conditions at southern and northern ends of the species range may be affected.	No information

A.4 ECOSYSTEM LEVEL INTERACTIONS

Resource competition, particularly with Arrowtooth Flounder may be an important ecosystem interaction.

A.5 ADDITIONAL STRESSORS

The IPHC has identified yield and spawning biomass losses caused by bycatch as an area of continued concern (e.g. Stewart et al. 2013a). A reduction in bycatch rates in non-target fisheries could lead to increased optimal exploitation rates for the directed fishery. However, unreported bycatch can result in optimal exploitation rates that are set too high. Canada has implemented a Pacific Halibut bycatch quota of 1 million lb for trawl fisheries in order to address halibut mortality in its waters. All halibut caught with trawl gear must be released according to careful release guidelines. Release-mortality rates are estimated depending on condition of the individual fish when released. The average trawl bycatch in Area 2B over the years 2002-2011 has been stable at 0.25 million lb. All other sectors must obtain quota for any halibut they catch, subject to regulatory limits at the sectoral and individual licensee level.

Another concern for the management and resulting harvest of Pacific Halibut relates to the unexplained downward trend in size-at-age of fish, particularly in Alaskan portions of the population (Clark et al. 1999). Loher (2013) proposed research avenues to investigate a number of confounded mechanisms relating to the cause of this population trend.

A.6 GAPS AND UNCERTAINTY

Recent trends of below average recruitment and decreasing size-at-age have been important contributing factors in the coast-wide stock decline. Unfortunately, although the stock assessment can track these trends quite precisely, it does not provide information on the mechanisms causing these trends. The effects of recent estimated poor recruitment are likely to influence spawning biomass trends in the near-term, as these weak cohorts mature. Lag effects, occurring because young fish are not observed in the survey or fishery until they are 6-8 years old, can lead to further uncertainty. Regardless of harvest levels, potential increases in stock biomass will also be very sensitive to future trends in size-at-age and recruitment that may be influenced by ocean climate. Processes driven by environmental forcing represent a substantial and potentially inherent, source of uncertainty. A harvest policy that is robust to this specific uncertainty would be prudent (Parma and Deriso 1990; Walters and Parma 1996; Parma 2002).

Last, there are unknown effects relating to potential decreases in dissolved oxygen at depth and increased ocean acidity within the species range.

B. Pacific Hake
(Merluccius productus)

Joy Wade and Karen Hunter

KEY POINTS

- Based on observations during conditions of unusually high water temperatures and reduced or delayed upwelling, highly migratory southern species including Pacific Hake will likely become more abundant in Canadian waters.
- Although the pathways of effects of climate variation and change have been explored for this species, there remains a gap in understanding of the mechanisms that contribute to large recruitment variation in Pacific Hake.

B.1 BIOLOGICAL CHARACTERISTICS

B.1.1 Life cycle, age and growth

There are both coastal and inshore populations of Pacific Hake, distinguished by their range as well as biological characteristics. Fish from the coastal stocks have a larger body size than inshore stock fish and exhibit seasonal migratory behaviour, unlike inshore populations. The coastal migratory stocks and inshore stocks are completely separate as evident through parasite, otolith and genetic studies (Iwamoto et al. 2004).

Based on information on egg and larval distribution as well as observation of spawning aggregations, coastal stocks of Pacific Hake are believed to spawn off California between January and March (Stewart et al. 2011; Beamish et al. 2008). Strait of Georgia stocks spawn later and longer, between February and April (King and McFarlane 2006). In coastal stocks, Pacific Hake females mature and spawn at 3 to 4 years of age with lengths ranging from 34 to 40 cm (Best 1963; MacGregor 1966; 1971; Ermakov 1974). Dorn and Saunders (1977) reported age at maturity (100%) for coastal Pacific Hake is 4 years of age as compared to 5 years of age for Strait of Georgia stock. Coastal spawning aggregations are difficult to locate (Saunders and McFarlane, 1997) and as a result little is known of spawning behaviour. It is thought that hake release eggs in deeper water (130 - 500 m), after which they rise and concentrate in shallower water (40 - 60 m), dependent on strength of the pycnocline (Bailey et al. 1982). Coastal Pacific Hake larvae are abundant in the water column from December to May off California and Baja California; peaks however are concentrated in January and February (Bailey et al. 1982). Distribution of eggs and larvae may be impacted by the strength of the California Undercurrent.

The growth rate of Pacific Hake in the Strait of Georgia is slower and average size is smaller than that of the migratory stocks (Beamish and McFarlane 1985; McFarlane and Beamish 1985). There has been a precipitous decline in size of Strait of Georgia stocks (Beamish et al. 2008), adult size changed between the late 1970s to the 1990s from 44cm to 36 cm. Density-dependent factors including strong year classes in the 1990s combined with increased abundance in the Strait of Georgia are believed to cause this decrease in size (Beamish et al. 2008).

B.1.2 Distribution, habitat and environmental preferences

Pacific Hake is a semi-pelagic schooling species distributed along the west coast of North America generally ranging from 25^0N to 55^0N latitude (Fig. B1; Stewart et al. 2011). The coastal stock ranges from offshore California to Queen Charlotte Sound (Stewart et al. 2011). They are a schooling fish found near the bottom or at midwater depths (200-1000 m) over the continental shelf, primarily off of WCVI in Pacific LAB waters. Inshore stocks are non-migratory and have are known to inhabit large inlets in the Strait of Georgia, Puget Sound and Gulf of California. Typically, coastal stocks migrate in the spring from offshore areas to onshore and northern areas along the continental shelf and slope from northern California to Vancouver Island. During the summer they form mid-water aggregations along the Continental Shelf break.

In general, older Pacific Hake migrate the farthest north (Stewart et al. 2011). Other influencing factors on the variation in northern migratory distance may include the extension of Pacific Hake prey distributions in response to shifts in plankton availability under warm water conditions in southern areas (Horne and Smith 1997). Ermakov (1974) hypothesized that the timing of the spawning migration (south) was linked to the appearance of the Davidson Current off the coasts of Oregon and Washington.

Coastal stock juveniles, 0-1 year old, occur inshore of the 200-fathom isobaths off central and southern California, with older fish further offshore (Bailey et al. 1982). The inshore Pacific Hake stock spends its entire lifecycle within the Strait of Georgia and Puget Sound (McFarlane and Beamish 1985; Kabata and Whitaker 1981; King et al. 2012).

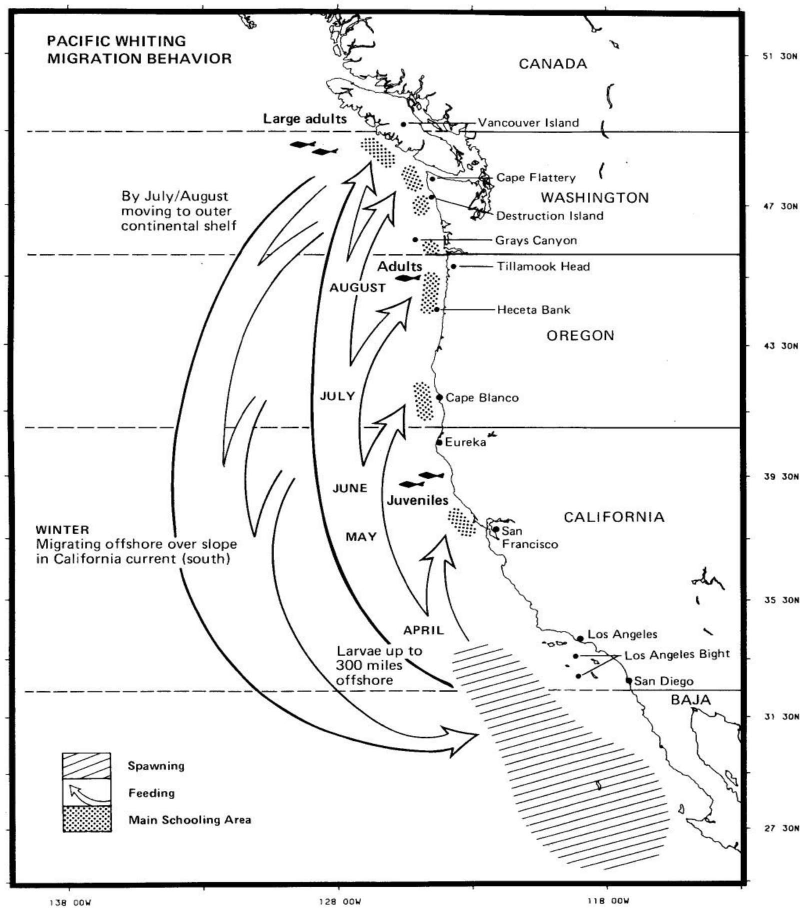


Figure B1. Migratory patterns of Pacific Hake. From Bailey et al. (1982).

B.1.3 Predators and prey

Pacific Hake are a highly predatory species, feeding on euphausiids, pandalid shrimp and pelagic schooling fish (Livingston and Bailey 1985). Strait of Georgia Pacific Hake feed mainly on euphausiids with some small pelagics, bathylagids and eulachon (*Thaleichthys pacificus)* (King et al. 2012). Pacific Herring (*Clupea pallasii*) are a large component of the diet of Pacific Hake off Vancouver Island. Buckley and Livingston (1997) have indicated that the separation of juveniles and adults reduces the population level effects of cannibalism in Pacific Hake. Larval Strait of Georgia Pacific Hake are reliant on inflowing nutrient rich deep water from offshore for their survival. In years when freshwater discharge from the Fraser River is low and winds are high, there is more entrainment of these nutrient rich waters with the surface waters, thereby increasing primary productivity (King et al. 2011). The diet of larval coastal Pacific Hake is composed mostly of mixed copepod life stages (Sumida and Moser 1980).

Pacific Hake make up an important part of the diet of many other piscivorous species, notably, Lingcod (*Ophiodon elongatus*) and Humbolt Squid (*Dosidicus gigas*) (Stewart et al. 2011).

B.1.4 Recruitment

Pacific Hake recruitment is highly variable. In the past ten years, recruitment has been estimated at some of the highest and lowest values in the time series (see Hicks et al. 2013). Though mechanisms associated with recruitment variation remain undocumented, hydrographic conditions and year class success may be linked through conditions that transport larvae and/or the concentration of prey at favourable inshore nursery areas (King et al. 2011). Years with warmer sea surface temperatures are usually accompanied by reduced upwelling and reduced offshore advection. This reduced advection may assist transport of early life stages to warmer inshore areas. The early life history of hake is thought to benefit from retention at inshore habitats where there may be increased prey availability and relative safety from cannibalism as the adults migrate further north during the same conditions (Buckley and Livingston 1997).

B.2 THE FISHERY

Pacific Hake is fished both offshore (coastal stock) and to a lesser extent, inshore. The offshore stock is a large, transboundary stock ranging from southern California to northern British Columbia, while the smaller, inshore stock is fished in major inlets in the Strait of Georgia, Puget Sound and Gulf of California (Gulf fishery). The coastal stock spawns in offshore waters during the winter and migrates to coastal areas between northern California and British Columbia in the spring, summer and fall (Stewart et al. 2011). The fishery takes place during this migration time. Because of their range, the quota for Pacific Hake is now set annually and harvested by both Canada and the US, this was not always the case.

The coastal Pacific Hake fishery takes place between April and December. Fish are caught primarily with large, mid-water trawls over bottom depths of 100-500 m. Presently in Canada, there are three fisheries for Pacific Hake; the domestic shore-side, Gulf fishery and the Joint Venture. In the domestic shore-side fishery, fish are caught outside the Strait of Georgia, stored in brine or frozen and are landed in BC. The Gulf fishery happens the same way, but fishing activities are restricted to the Strait of Georgia. Once shore-side capacity is filled, a portion of the catch may be allocated to Joint Venture (JV) operations but this has not consistently occurred. The Joint Venture fishery consists of a group of primarily foreign factory ships that accept hake directly from the fishermen at sea. Canadian fishing boats catch Pacific Hake and transfer their cod end to the factory ships; they do not handle the fish on board their own vessels. An estimate is made by observers on board the factory ships as to the volume of fish in the cod end which is then converted into tonnage. JV vessels produce surimi and fish meal for cakes almost exclusively. The majority of Pacific Hake landed in Canadian ports are processed in Ucluelet, Port Alberni and Delta into frozen fillets, surimi or mince. The US has not had a Joint Venture fishery since 1991. See Hicks et al. (2013) for a more detailed historical account of the Canadian and US Pacific Hake fishery.

B.2.1 Management

The Coastal Pacific Hake stock is currently managed under The Agreement between the Government of the United States and the Government of Canada on Pacific Hake/Whiting (The Agreement). Until 1997, Canada and the US prepared their own stock assessments and determined separate yields for a trans-boundary stock. Since 1997, the Pacific Fisheries Management Council (PFMC), a US organization, has utilized the Stock Assessment Review (STAR) process to evaluate assessment models for many species including Pacific Hake. Both Canada and the US utilized these results in decision making (Stewart et al. 2011). In 2006, The Agreement was formally ratified and has been considered in force since 2008. The Agreement designates four bilateral groups: the Joint Technical Committee, the Scientific Review Group, the Joint Management Committee and industry Advisory Panel. These groups are responsible for preparing the science advice, reviewing the science advice and setting the Total Allowable Catch. Under The Agreement, 26.12% and 73.88% of the coast-wide TAC is partitioned to Canada and the United States, respectively. Each country may carry over up to 15% of uncaught quota. Under The Agreement, coast-wide TACs are set using a target harvest rate with a 40/10 adjustment spawning stock biomass depletion (see Stewart et al. 2011).

B.2.2 Stock assessment

The spawning stock depletion used to apply the harvest control rule is estimated from an annual stock assessment. Over the last ten years different statistical catch-at-age stock assessment models have been applied, including competing Canadian and US models. However, in the last two years, the Joint Technical Committee has put forward a single base case model (Stewart et al. 2012; Hicks et al. 2013). The annual stock assessment model is fitted to acoustic survey data as well as commercial and survey age-composition data.

One challenge to Pacific Hake stock assessments is that they have been very volatile. One reason for this volatility is that the recruitment in the stock is highly variable.

B.2.3 Catch

The major fishery for this species occurs in US waters where landings are often greater than 70% of the total coast-wide landings (Table B1). From 2000-2002, there was a decline in coastal Pacific Hake landings attributed to a reduced quota reflecting a gradual decline in biomass (Beamish et al. 2008). Pacific Hake catches increased fairly rapidly following the 1977 regime shift and have for the most part, remained above the 1970-2004 average since the mid-1980s (Beamish et al. 2008). The modern fishery is much larger than earlier decades in the fishery's history (Hicks et al. 2013). This may also be partly due to the change in fishery type from small shore based operations to factory trawlers.

Recently, coast-wide landings have been above the long term average of 243,000 mt (2008 onwards; Hicks et al. 2013). A very large year class produced in 1999 was the predominant contributor to large catches between 2001 and 2008 (Stewart et al. 2011; Hicks et al. 2013). The cumulative removal from that cohort exceeded 1.2 million mt (Stewart et al. 2011). The 2010 and 2011 fisheries were comprised mainly of animals of the 2008 year class (Hicks et al. 2013).

Table B1. Recent commercial landings (1000s mt) of Pacific Hake. (Reproduced from Hicks et al. 2013)

Year	US at sea	US shore-based	US total	Canadian joint-venture	Canadian domestic	Canadian total	Total
2003	87	55	142	0	63	63	205
2004	117	97	214	59	66	125	339
2005	151	109	260	16	87	103	363
2006	140	127	267	14	80	95	362
2007	126	91	218	7	67	73	291
2008	181	68	248	4	70	74	322
2009	72	49	122	0	56	56	177
2010	106	64	170	8	48	56	217
2011	128	102	230	10	46	56	286
2012	94	63	157	0	47	47	204

B.2.4 Canadian removals

From 1966 to 2012, Canadian landings of Pacific Hake averaged at 56,000 mt with the majority of the catch harvested off WCVI (Fig. B2); total coastwide landings including the US harvest during this same time averaged 222,000 mt (Hicks et al. 2013). The landed value of Pacific Hake in Canada in 2011 was $16.5 million, exceeding that of Chinook, Coho, Pink, Chum or Sockeye Salmon (BC 2012). The same year, it had the fourth highest landed value of all groundfish, exceeded by Pacific Halibut ($45.6 million), Sablefish ($27.2 million) and rockfishes ($26 million). However, approximately three times the volume of Pacific Hake is needed to match the value of other groundfish species (BC 2012).

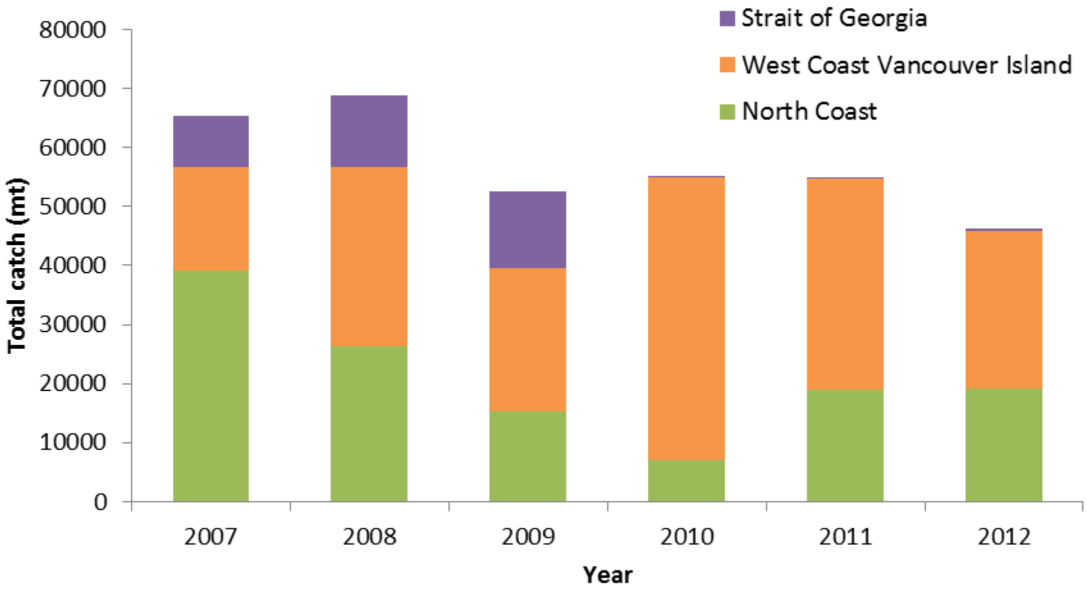
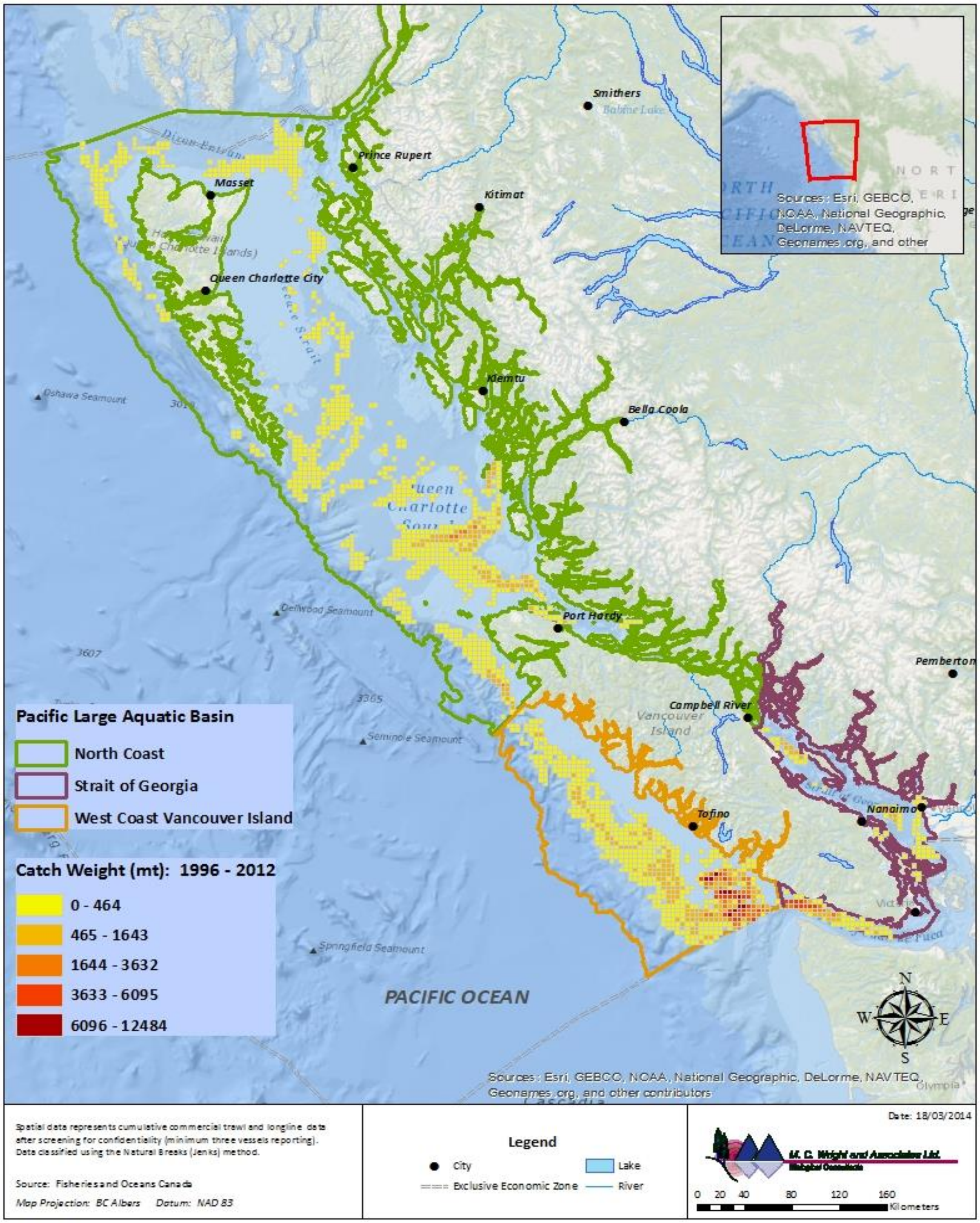


Figure B2. Total catch (mt) of Pacific Hake (2006-2012) in Strait of Georgia, WCVI and North Coast sub-basins. Strait of Georgia landings are generated by a separate inshore stock and are presented for comparison only.

Distribution of the offshore stocks follow the thermal extent of sea surface temperature resulting in the centre of abundance within Canadian waters to shift between West Coast Vancouver Island and North Coast over time (shown as contiguous distribution in Fig. B3).



Spatial data represents cumulative commercial trawl and longline data after screening for confidentiality (minimum three vessels reporting). Data classified using the Natural Breaks (Jenks) method.

Source: Fisheries and Oceans Canada

Map Projection: BC Albers Datum: NAD 83

Figure B3. Distribution and cumulative catch of Pacific Hake in groundfish trawl fisheries, in Pacific LAB, 1996-2012. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

B.3 CLIMATE CHANGE AND PACIFIC HAKE

B.3.1 Abundance

Pacific Hake abundance has been reported to change in correlation with changes in water temperature, mainly observed during warm periods associated with El Niño. As a result of physical processes during warm ocean years, abundances of offshore fish may increase as a result of increased larval survival (Hollowed and Bailey 1989). Increased recruitment may influence larger summer feeding migrations to move into Canadian waters and farther north (Bailey et al. 1982). Migratory stocks will experience cumulative impacts as the physical processes that support year-class recruitment undergo shifts. Pacific Hake are sensitive to experiencing recruitment failures and rapid population declines.

Increased abundance in the migratory population may in part be attributed to a higher biomass associated with lower fishing mortality and an increase in mean age in the population. Changes in distribution would therefore be dependent on the management of the stock. Benson et al. (2002) also associated climate predictions with stock distribution recognizing that fishing mortality had changed the subsequent stock structure. It is important not to overlook the effects of changing population structure and management practices when attributing distributional changes to climate variation.

Strait of Georgia stocks have been increasing in recent years. This has been attributed at least in part to an earlier abundance of plankton corresponding to the timing of spawning activities. It is not believed that reduced Fraser River flows are the leading factor to the improved larval survival but changes to inflowing bottom water and earlier spring flows (Beamish et al. 2008).

B.3.2 Distribution

Pacific Hake are sensitive to temperature changes in term of effects on migration, spawning and juvenile distribution (Benson et al. 2002; Phillips et al. 2007; Stewart et al. 2011). Pacific Hake have also been reported to migrate farther north during the summer in relatively “warm” water years and have been recorded as north as southeast Alaska during these warm years (Stewart et al. 2011). During El Niño events, a larger proportion of the coastal stock migrates into Canadian waters assisted by the intensified northern transport occurring during the time of migration (Dorn 1995; Agostini et al. 2006). Changes in distribution have also been observed during “colder” ocean conditions. In 2001 in particular, a southward shift in stock distribution was observed with a smaller proportion of the stock observed in Canadian waters (Stewart et al. 2011).

Spawners are also sensitive to changes in temperature. For example, during the “warm” period of the 1990s, spawning activity was recorded north of California (Stewart et al. 2011). In addition, juvenile settlement patterns shifted northward as evidenced by unusual numbers of juveniles off Oregon to British Columbia (Benson et al. 2002; Phillips et al. 2007). The potential effects of cannibalism due to the overlap in distribution of adults and juveniles are unknown. Using conceptual pathways of effects, King et al. (2011) concluded that Pacific Hake will respond to climate change by expanding its range northward.

B.3.3 Phenology

Changes in the timing of upwelling or increased stratification along the coast that inhibits the normal seasonal occurrence of specific copepod assemblages in the pelagic environment may affect survival of larval hake if food is not abundant at early life stages.

B.4 ECOSYSTEM LEVEL INTERACTIONS

In order to determine ecosystem level interactions for an individual species, the ecosystem itself must first be described. For the majority of species, there is only a rudimentary understanding of the ecosystem roles and interactions. There are snap-shots of information which can be pieced together to help create this description. For example, changes in physical oceanography such as surface and subsurface currents during spawning and early larval development may have impacts on year class survival and stock recruitment. Developing eggs and larvae of coastal stocks may be pushed away from highly nutritive areas by changes in current pattern. These effects may also be seen in years of poor mixing and subsequent low primary productivity for Strait of Georgia stock.

Warmer surface waters off the west coast of Vancouver Island may result in increased abundance of Pacific Hake in the summer. Changes in Pacific Hake abundance are one factor affecting the variation in Pacific Herring recruitment (Ware 1991). Pacific Herring survival was reported higher in the 1990s due to reduced predation by Pacific Hake (McFarlane et al. 2000).

Pacific Hake are a significant food source for other piscivorous species including lingcod and Humboldt Squid (*Dosidicus gigas*). For example, a large increase in Humboldt Squid abundance as far north as southeast Alaska coinciding with the presence of Pacific Hake, has recently been observed by Pacific Hake fishermen and scientists (Field et al. 2007). The long term impacts on prey abundance with changes in seasonal distribution are a concern.

B.5 ADDITIONAL STRESSORS

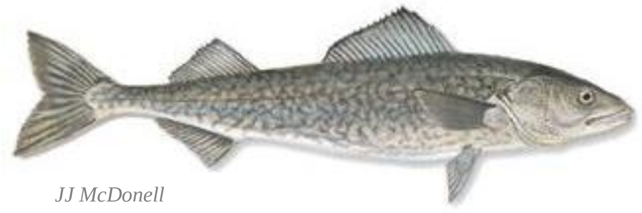
Stressors, either to an individual or to a population can be a result of a changing environmental conditions, be they natural or anthropogenic.

B.6 GAPS AND UNCERTAINTY

Although there has been some speculation as to the impacts of climate change on Pacific Hake, the mechanisms associated with recruitment and distributional changes remain for the most part, unknown. There have been attempts for many years to determine the relationships between environmental effects and recruitment and distribution, with little reconciliation. Examining the interaction between ecology and the fishery within an ecosystem model is believed to be the way forward when attempting to answer questions relating to the impacts of climate on Pacific Hake populations. Focusing efforts on responding to distributional changes rather than continuing with attempts at predicting these changes are recommended.

Table B2. Summary of conceptual impacts, vulnerabilities and opportunities linked to climate-related parameters for migratory Pacific Hake.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Spawning location moves north with warmer SST; Survival is higher during warm ocean years.	Larger feeding range extension in Canadian waters in summer during years with warmer ocean conditions; Spawning location may move northward with warmer water; Possible permanent range expansion into WCVI/North Coast.	Timing of spawning migration may become earlier; Individuals need to match first feeding to beginning of bloom.
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	Eddies (i.e. Juan de Fuca) retain prey and increased prey availability improves larval survival; At shelf break (southern WCVI), currents concentrate prey where Pacific Hake feed.	Increased Davidson Current northward may aid northern feeding migration; Distribution of early life stages to nursery grounds may be impacted by stronger California Current in spring and summer through its effect on advection processes along the coast.	Timing of spawning migration may be impacted by timing and strength of currents.
Stratification	Mid-water species such as hake may be impacted by a change in access to prey items with an increase in Increased stratification. Stratification may reduce primary productivity affecting year-class success.	No information	No information
Upwelling winds	Upwelling concentrates prey at WCVI shelf break front; stronger upwelling increases nutrient enrichment increasing zooplankton productivity; Reduced upwelling and reduced offshore advection favour larval survival (off California).	No information	No information
Dissolved oxygen	No information	No information	No information



JJ McDonell

C. Sablefish
(Anoplopoma fimbria)

Karen Hunter and Joy Wade

KEY POINTS

- Although infrequent, large year classes have been correlated with climate forcing and ocean productivity.
- Differences in movement behaviour of the northern and southern stocks may contribute to contrasting future vulnerability to climate change.
- A generalist diet and preference for deep habitats may allow Sablefish refuge from direct changes in ocean climatology at the surface.

C.1 BIOLOGICAL CHARACTERISTICS

C.1.1 Life cycle, age and growth

Sablefish, also referred to as Black Cod, are a very long-lived species, reaching ages of up to 113 years. The oldest fish recovered from British Columbia was aged at 92 years. Mature females reach an average length of 55 cm fork length in 3 to 5 years. Maximum sizes are reported at ~110 cm fork length. Juvenile Sablefish grow quickly during the first few years then growth slows down. Studies in Alaska have shown that juvenile growth may be affected seasonally with growth slowing during the winter months where they reside in inland waters (Rutecki and Varosi 1997).

Spawning is observed from January to March along the continental shelf at depths greater than 300m (DFO 2010a). Eggs fertilized at approximately 300m depth develop quickly (Hunter et al. 1989) and larvae hatch around the same depth from December to March (King et al. 2001) There is substantial vertical mobility at the larval stage. Larvae descend to 1000m within 18 days of spawning, and within days of descent to 1000m, they begin ascending, feeding on copepod nauplii (Beamish et al. 2008). Larval Sablefish are found in surface waters over the continental shelf and slope in April and May.

Age distribution and growth vary with time, area and depth (Kimura et al. 1998). Growth of Sablefish in Alaskan waters has changed interdecadally, with two distinct growth regimes identified (Echave et al. 2012). Several competing hypotheses for these temporal and spatial differences in growth patterns include geographic differences in food abundance, oceanographic condition, and Sablefish abundance (King et al. 2001; Mackas et al. 2007).

C.1.2 Distribution, habitat and environmental preferences

Sablefish are a deep water species and spend their lives at depths between 200 m and 1500 m depending on life stage. Adult Sablefish inhabit shelf and slope waters to depths greater than

1500 m, from central Baja California to the Bering Sea and Japan. The centre of abundance of Sablefish is located across northern British Columbia to the Gulf of Alaska. In Canadian waters, Sablefish adults are most abundant between 600-800 m (Beamish et al. 2008). Juvenile Sablefish in Pacific LAB are frequently found in shallow waters surveyed in Pacific LAB (Saunders et al. 1997). The wide distribution of ontogenetic stages results in Sablefish presence in most habitats along the Pacific LAB coast and continental shelf waters (DFO 2013c).

High mobility and exchange in Sablefish results in minor genetic differentiation at large spatial scales suggesting that Sablefish form a single biological population throughout their known range in the north east Pacific Ocean (DFO 2013c). Oceanic transport of larvae in upper layers of the ocean and long distance directed movement of juvenile and adult Sablefish are probably important drivers of their widespread distribution, although pathways of movement remain uncertain (DFO 2013c).

In the north east Pacific, coastal fish species having pelagic larvae tend to spawn during winter when surface wind drift is generally directed toward the coast, rather than during the more productive upwelling season. During their early life history, eggs and larvae are prone to drift (Mason et al. 1983; Moser et al. 1994), but is unlikely off WCVI to result in offshore transport (McFarlane and Beamish 1986). Juveniles are highly migratory and feed and grow while moving inshore to rear in near-shore and shelf habitats until they reach between 2 and 5 years of age. It is during this age range that they migrate back offshore (Beamish et al. 2008).

C.1.3 Predators and prey

Though Sablefish are generalist predators, the most important component of their diet is fish. The proportion of fish in stomach contents increases as they mature (DFO 2010a; Laidig et al. 1997). The most important prey items include rockfish, Pacific Herring and squid (Laidig et al. 1997). Stomach content analyses from southern stock Sablefish showed a greater consumption of mid-water prey than northern Sablefish (Laidig et al. 1997). The importance of Sablefish to predators is for the most part unknown (DFO 2010a)

C.1.4 Recruitment

Sablefish exhibit decadal-scale patterns in their relative year class success, with stock production characterized by periods of moderate to relatively low recruitment (King et al. 2000). This variable with periodic year-class strength is believed to be associated with high ocean productivity (McFarlane and Beamish 1992; Ware and Thomson 2005), physical ocean conditions (Schrripa and Colbert 2006) and abundant zooplankton correlated with favourable environmental conditions (DFO 2010a; Mackas et al. 2007). Recruitment is most likely determined as larval fish begin feeding as they drift to the nursery ground. For fish hatching off the west coast of Vancouver Island, favorable oceanic conditions can increase the amount of food available to Sablefish and may be responsible for their strong year classes (McFarlane and Beamish 1992; Mackas et al. 2007).

Reductions in biomass of Sablefish in the 2000's are believed to be related to poor recruitment in the relatively poor productivity regime in the 1990s which is defined by a negative phase of the Pacific Decadal Oscillation (Beamish et al. 2008). Fishery effects on production are likely but can't be teased from environmental forcing (Parma and DeRiso 1996). It is more likely that both fishing and environment interact to determine production (Litzow et al. 2014).

C.2 THE FISHERY

C.2.1 Management

Wide distribution of this species over latitudes and bathymetry make Sablefish the most widely distributed commercial groundfish in the north Pacific (Moser et al. 1994). The first recorded commercial fishery landings of Sablefish date back to 1913. Initially, Sablefish was caught as bycatch by Canadian fishers and later foreign fleets directed effort to Sablefish. Significant foreign fishing that occurred between 1961 and 1981 was gradually phased out after the declaration of the 200-mile Economic Exclusionary Zone in 1977. The modern commercial fishery is primarily a longline fishery using hooks and Korean traps in deepwater. Sablefish are caught in directed fisheries by the long-line trap and hook K-license category sector and the T-license category trawl sector. A smaller amount of fish, up to 8.25% of the annual quota, is captured using trawl nets. The fishery is currently open year round (DFO 2010b).

In 1981 the commercial Sablefish fishery was limited to the existing 48 licenses. The number of commercial Sablefish licenses has remained the same since 1981, thereby halting growth of the fleet. Since 1990, the Canadian Sablefish Association (CSA) and DFO have engaged in annual collaborative agreements to work jointly on assessment, management, and enforcement activities. In 1990, logbooks were made mandatory and an Individual Vessel Quota (IVQ) system was introduced to the commercial Sablefish fishery. This system allocated specific quotas to 48 individually licensed vessels based on their historical catch records. The IVQ system eliminated the short, highly competitive and difficult to monitor derby fishery by allowing year round fishing and provided a management tool to ensure that fishing did not exceed the Total Allowable Catch (TAC).

Sablefish is commercially fished coast wide in British Columbia, in all Groundfish Management Areas (GMAs) except 4B (statistical areas 12-20, 28, and 29). A specific fishery of offshore seamounts occurs and is fished in designated North or South areas for which vessels are chosen by lottery. Seamount areas have specific restrictions including dockside and at-sea monitoring requirements and only trap gear is permitted (DFO 2012b).

Sablefish harvest in Pacific LAB is managed via a coast-wide Total Allowable Catch over a fishing year. Vessels are permitted to harvest other species in addition to Sablefish, but there are restrictions on the amount of other groundfish that may be retained. For example, combined halibut and Sablefish fishing is permitted as long as the appropriate licences are in place and restrictions adhered to (DFO 2012b).

Sablefish are also intercepted by the non-directed groundfish long-line hook fisheries primarily directed at Pacific Halibut, rockfishes, lingcod, and spiny dogfish. Sablefish smaller than 55 cm fork length are released at-sea by regulation (DFO 2012b). The majority of fish in the fishery are age 4 to early 20's (DFO 2012b). Sector caps limited by IVQs have been created to ensure that groundfish harvesters have access to non-directed catch from other sectors.

The reliability of catch monitoring was markedly improved with the implementation of the multi species and multi-gear Commercial Groundfish Integration Program (CGIP) in 2006. The CGIP has achieved the objective of accounting for the catch of all targeted and non-targeted species intercepted by commercial groundfish fisheries. Individual fish harvesters are now accountable for landed catch and catch released at sea. The Pacific groundfish industry has participated fully in developing improved monitoring standards that enable such management practices using an integrated system of fishery logbooks, 100% at-sea observer or video monitoring, and dockside validation of landings. Most importantly, the catch monitoring program has a built-in process for fishery-independent auditing of at-sea catch and release, and subsequent validation of landings that specifies measurable performance targets for catch monitoring accuracy. Prior to the introduction of the CGIP, trap gear was responsible for approximately 80% of the commercial landings; currently about half the non-trawl landings are accounted for by trap gear with the balance landed by the various long-line hook sectors (e.g. the Pacific Halibut fleet, long-line hook K-fleet, and other long-line hook fleets).

C.2.2 Stock assessment

Canadian Sablefish quotas are based on yield recommendations from mark-recapture and catch-age analyses (Haist et a. 1999). Sablefish stock abundance and biological data are provided by a fishery-independent trap survey conducted collaboratively by Fisheries and Oceans and the Sablefish industry. A precautionary harvest decision rule reduces the harvest rate when the abundance of legal-sized Sablefish is estimated to fall below an upper reference point and will proactively reduce commercial harvest to very low levels should stock abundance approach a limit reference point. The research is coordinated by a joint DFO-industry body defined in a collaborative agreement between DFO and the Canadian Sablefish Association (DFO 2012b). The goal of the collaborative agreement is to “produce accurate assessments of the status of the population and to develop fishing strategies that meet Departmental goals of conservation and economic return” (DFO 2012b). Sablefish research surveys and stock assessment surveys are conducted in October and November.

Management systems for Sablefish put in place after 1990 have the capacity to assess changes in stock abundance of Sablefish coast-wide. Monitoring of changes in size and age at maturity occurs in conjunction with fishery management procedures. Climate impacts that affect recruitment may be captured defacto under existing monitoring assessments.

To date, decadal-scale dynamics observed in North Pacific climate–ocean conditions and Sablefish year class success have not been incorporated into the stock assessment process though efforts to introduce such practices have occurred (King et al. 2001).

C.2.3 Catch: Canadian removals

The average BC coast-wide commercial landings from 1978 to 2002 were approximately 4,000 tonnes (Fig. C1; DFO 2005). In recent years, catches have declined as a response to removal from the fishery and reduced total biomass (DFO 2005). Landings declined from 4,620 t in 2005 to 2,350 t in 2010 in response to TAC reductions over the same period. The declines in catch are related to stock assessments that recognize a decline in biomass as indicated by the declining trend in catch per unit effort (DFO 2005). Regardless of the decline, Sablefish continue to be fished at full harvest levels according to the TAC (DFO 2012b).

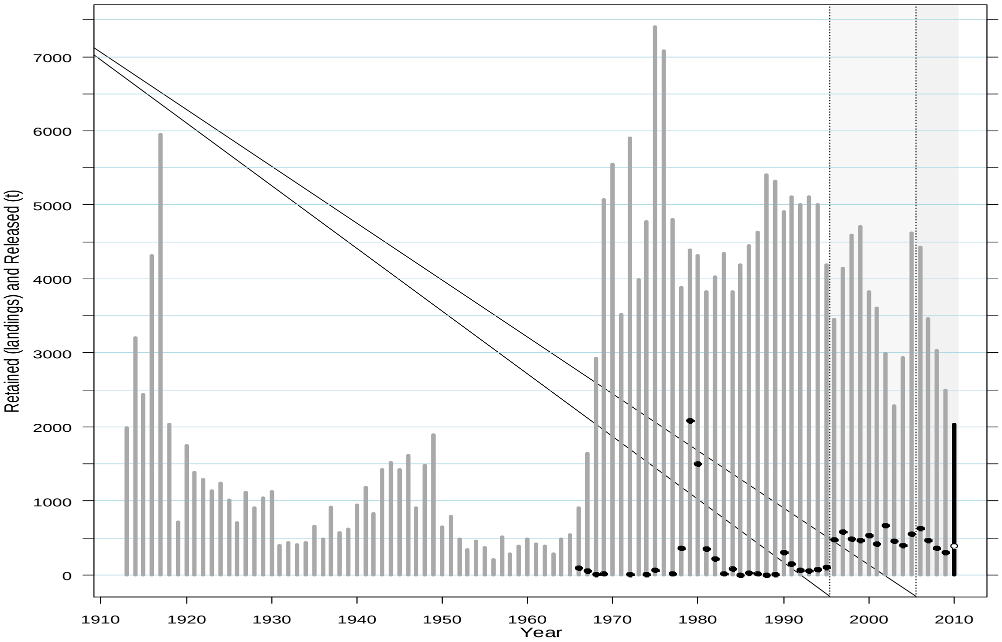


Figure C1. Annual Sablefish retained catch (t) from 1913 to 2010 from commercial sources (gray bars). Annual released catches are shown as reported. Vertical dotted lines demarcate the trawl at-sea observer period from 1996 to 2006 and the start of catch monitoring for all groundfish sectors in 2006. Catch data for 2010 are complete to October 31 for both retained catch (black bar) and released catch (open circle). Figure courtesy of A. Kronlund.

Sablefish are harvested across Pacific LAB in deep regions off WCVI and throughout the North Coast sub-basin. Very little Sablefish is harvested in the Strait of Georgia sub-basin. Harvests (1996-2012) are higher overall in the North Coast sub-basin (Figs. C2, C3). However, catch in WCVI is generally more concentrated (Figs. C2, C3).

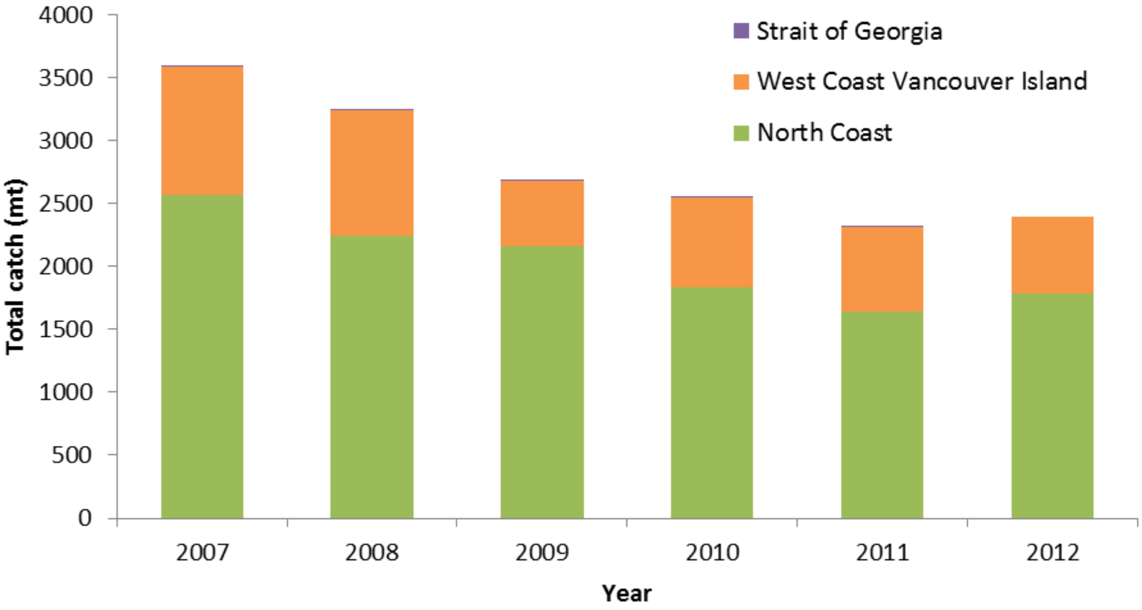
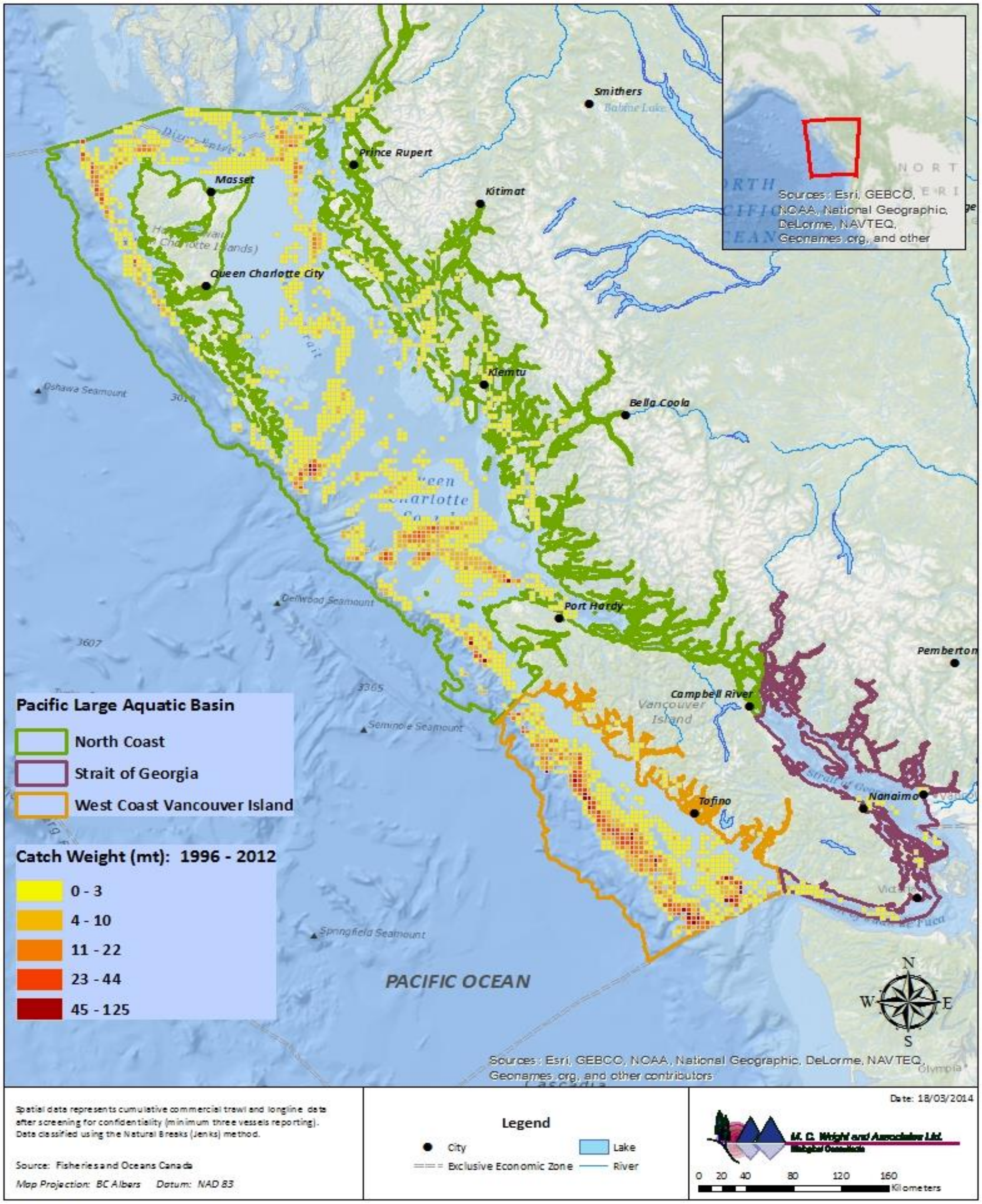


Figure C2. Total catch (mt) of Sablefish (2006-2012) in Strait of Georgia, WCVI and North Coast sub-basins.



Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other

Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

Spatial data represents cumulative commercial trawl and longline data after screening for confidentiality (minimum three vessels reporting). Data classified using the Natural Breaks (Jenks) method.

Source: Fisheries and Oceans Canada

Map Projection: BC Albers Datum: NAD 83

Date: 18/03/2014

Figure C3. Distribution and cumulative catch of Pacific Hake in groundfish trawl fisheries, in Pacific LAB, 1996-2012. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

Sablefish is a high value seafood product for British Columbia. In terms of groundfish, it is second in landed value only to Pacific Halibut. According to the British Columbia Seafood Industry 2011 Year in Review, Sablefish had a landed value of 27.2 million dollars (BC 2012). The Sablefish market is primarily for export to Japan.

C.3 CLIMATE CHANGE AND SABLEFISH

Based on current assessments, there is no known evidence of a direct impact of climate drivers associated with the anthropogenic trend of climate warming on either the northern or southern stocks of Sablefish. However, trends in coast-wide Sablefish production (recruitment and year-class strength) have been related to climate and ocean conditions on the decadal scale (Ware and Thomson 2005).

C.3.1 Abundance

For Sablefish, the number of recruits per spawner is low (i.e. poor larval survival; King et al. 2000), thus impacts on early life stages are important for sustaining populations. Periodic strong year-classes of Sablefish are believed to be associated with high boreal copepod abundance that relate to favourable environmental conditions for young fish (Mackas et al. 2007). El Niño events were shown to retard growth of west coast Sablefish and enhance growth of Alaskan Sablefish (Kimura et al. 1997) demonstrating the importance of ocean climate for fish and fishery dynamics. Observations have suggested that below average temperatures in the subarctic Pacific Ocean and warmer sea surface temperatures experienced as a result of strong Aleutian Lows are attributed to above average year class strength in some groundfish. Cool phases of PDO result in cooling of surface waters along coastal North America and warm in the central North Pacific Ocean. For example, reductions in Sablefish biomass in the 2000’s are attributed to poor recruitment in the poor productivity regime in the 1990s defined by the positive phase of the PDO.

Slow-growing, long-lived demersal species such as Sablefish have a lower degree of variability in abundance and have been classified as having a steady-state population pattern (Caddy and Gulland 1983). Longevity (i.e. lifespan greater than 20 years) and high fecundity benefit species by maintaining a spawning biomass through low productivity regimes and taking advantage of shifts in the environment that are favourable to year class success (Leaman and Beamish 1984; King and McFarlane 2003). However, the period between strong year-classes can be relatively long (up to several decades). In general it is believed that long-lived fish species, such as Sablefish, are able to adapt to prolonged periods of poor recruitment if fishing pressures are not excessive (Beamish et al. 2008). Generalist diet and preference for deep habitats may also allow Sablefish refuge from changes to ocean climate conditions that may be more meaningful at the ocean’s surface (i.e. top 30 m).

A previous synthesis suggested that changes in ocean climate within the next 50 years were not likely to introduce significant impacts on coast-wide adult Sablefish survival or spawning activity that will threaten the dynamics of the population coast-wide (Beamish et al. 2008). They also suggested that if fishing did not harm the spawning stock or genetic age and size structure, there would be occasional strong year classes that could maintain the species across its current distribution.

C.3.2 Distribution

Migration and movement likely play a key role in species susceptibility to changes in ocean climate and productivity. For example, Ware and Thomson (2005) showed fishery yields of commercial resident fish populations are related to primary and secondary productivity on the BC coast. Changes in oceanography impacting primary production in major eco-regions may have minor effects on Sablefish given their propensity for movement and widespread habitat use.

Ocean conditions at depth and latitude impact Sablefish. The preference of adult Sablefish for very deep, relatively constant environments suggests that this species is not likely to be impacted directly by changes in climate occurring at the surface (no temperature change impact projected at depth). The distribution and centre of abundance of Sablefish may be altered should altered frequency of the Aleutian Low and ocean conditions negatively impact southern distributions of Sablefish (i.e. reduced growth, reduced larval survival). Harvests occurring in the WCVI eco-region are therefore more vulnerable to changes in conditions and may be reduced (Beamish et al. 2008). By contrast, the northern distribution, harvested across North Coast, may benefit from strong year classes as a result of more intense Aleutian Lows (Beamish et al. 2008).

Use of and preference for deep water habitat by Sablefish adults and spawning adults may correspond with changes to dissolved oxygen content at depth. Although zones of hypoxia occur in northern areas (Crawford et al. 2007), current data suggest the expansion of hypoxic conditions at depth is a phenomenon affecting southerly waters, including southern areas of WCVI (Christian and Foreman 2013). Species characteristics including use of deep habitat may introduce a vulnerability to life stages (eggs/larvae, adults, spawning adults) that typically reside in deep waters. There has been recent expansion of zones of hypoxia in in coastal waters at depth (800-1000 m) off Washington and Oregon (Peterson et al. 2013). Further growth of this zone in the south, or development of hypoxic zones elsewhere related to changes in ocean conditions introduces vulnerability for groundfish species.

In general, conditions favourable to recruitment may decline in southern Pacific LAB waters, whereas recruitment may improve in North Coast (Beamish et al. 2008), but these general predictions are highly uncertain.

C.3.3 Phenology

Synchronous timing of coast wide spawning suggests that Sablefish do not undergo a spawning migration (Mason et al. 1983). Where conditions for spawning or survival of eggs/larvae are favourable across the distribution, increased recruitment may result for those areas. It has been proposed that southern areas of the distribution of the Alaskan stock will be impacted through reduced recruitment by altered ocean conditions. The west coast (southern) stock has shown the opposite response where under positive PDO conditions, recruitment increased. Greater upwelling was correlated with this covarying trend in Sablefish recruitment along the coast of the North East Pacific Ocean.

Table C1. Summary of conceptual impacts, vulnerabilities and opportunities linked to climate-related parameters for Sablefish.

Physical parameter	Recruitment and abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Impacts of changes in sea surface temperature on zooplankton have been linked to variations in recruitment;	Centre of distribution may shift northward.	Changes in timing of zooplankton peak productivity may affect survival of larvae
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	Changes in currents that assist northward migration of prey and/or predator populations may affect survival of larval and juvenile stages.	Changes to currents may alter transport of larvae to nursery grounds.	No information
Stratification		No information	
Upwelling winds	Possible improved prey productivity off WCVI with positive impact on recruitment	No information	No information
Dissolved oxygen	No information	Possible avoidance of hypoxic areas by adults; seasonal reduction in habitat availability	No information

C.4 ECOSYSTEM LEVEL INTERACTIONS

It is known that there can be coast wide synchrony in strong year class production (Beamish et al. 2008) and it is believed that this phenomenon is linked to trends in high primary and secondary production that relate to favourable ocean conditions for the lower trophic levels.

C.5 ADDITIONAL STRESSORS

Fishing impacts on the population structure are evident in the reduction in the percentage of older fish in the population (Beamish et al. 2008). It can only be presumed that the remaining fish retain the trait of longevity, however the genetic pressures of fishing on the population are unknown (Beamish et al. 2008).

C.6 GAPS AND UNCERTAINTY

Age and growth parameters for Sablefish vary between areas and depths (DFO 2010a). There are generalized hypotheses to explain the mechanisms for this variation (e.g. food resource limitations and physical conditions that impact larval survival), but there is little understanding of direct mechanisms. It is unknown whether substantial differences in the physical and biological oceanography of habitats used by northern and southern Sablefish stocks will be reflected in the species response across its distribution.

Unknown impacts of hypoxic conditions on all stages.

Unknown linkages between habitat use and/or abundance and Sablefish recruitment.

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D. Pacific Herring
(Clupea pallasii)

Jake Schweigert, Jaclyn Cleary and Jennifer Boldt

KEY POINTS

- Based on historic response to both regime shifts and El Niño events, it appears that Pacific Herring are sensitive to changes in the productivity of the local ecosystem resulting in rapid response to changing environmental conditions.
- Pacific Herring populations may be more productive during colder ocean periods compared to warmer periods.

D.1 BIOLOGICAL CHARACTERISTICS

D.1.1 Life cycle, age and growth

The bulk of Pacific Herring (*Clupea pallasii*) spawning on the British Columbia coast occurs during March in the West Coast of Vancouver Island and Strait of Georgia sub-basins; with some spawning in April in the North Coast sub-basin (Fig. 1). The eggs are adhesive and are generally attached to intertidal and subtidal vegetation where they develop and hatch over a period of about two weeks depending on ambient water temperatures (Haegele and Schweigert 1985). Following hatching, the free floating larvae spend almost a month learning to feed and developing scales. After metamorphosis at about 25 mm they form into schools and aggregate in inshore waters where they remain for their first summer (Hourston and Haegele 1980). The juveniles grow rapidly reaching a length of 100 mm and 40 g by the fall. The bulk of the juvenile herring migrate offshore in the fall in the North Coast and West Coast of Vancouver Island areas where they join other schools of immature 1 and 2 year old fish. Many of the juveniles in the Strait of Georgia overwinter and leave the Strait for the feeding grounds on the West Coast of Vancouver Island the following spring. Juvenile Pacific Herring feed primarily on copepods switching to euphausiids as they grow over their first summer. Immature Pacific Herring remain on the offshore feeding grounds for two years migrating back to the spawning grounds in the fall of their third year of life. Pacific Herring spawn primarily at age three although a small number of precocious two year old fish are found. Female Pacific Herring produce 20-40,000 eggs and lay them in small batches of 50-200 eggs in ribbons on kelp and other substrates (Hourston and Haegele 1980). Pacific Herring are repeat spawners and will return to the same general areas to spawn in subsequent years although tagging indicates that some fish will move to other areas up to 1000 km distant. Mature spawning Pacific Herring range in age from 2 to 10 with a small proportion of older fish. Fish in the spawning population range from 130-250 mm in length and 80-225 g in weight. Adult herring feed primarily on euphausiids.

D.1.2 Distribution, habitat and environmental preferences

Pacific Herring are a temperate water species and range as far south as Baja California in North America (Hourston and Haegele 1980). They are distributed widely throughout the three sub-basins within British Columbia (Fig. D1). The majority of herring in all three areas are migratory but there is ongoing debate about the existence and extent of resident or non-migratory populations within these sub-basins (Taylor, 1964). In particular, spawning populations exist within many of the mainland inlets in Johnstone Strait and throughout the North Coast sub-basin. Spawning occurs at or near the heads of the inlets but herring may migrate to the mouths of the inlets to feed. However, to date there has been no evidence that these fish are genetically discrete from the major spawning populations in the area (Beacham et al. 2008).

Pacific Herring are generally restricted to the continental shelf and are normally found in waters 150-200 m deep. They migrate diurnally, likely following the vertical migration of the plankton layer. Pacific Herring spawning and subsequent hatching of larvae is optimized at about 8˚C and timing of spawning is synchronized with the spring warming and subsequent plankton bloom (Alderdice and Hourston 1985; Schweigert et al. 2013).

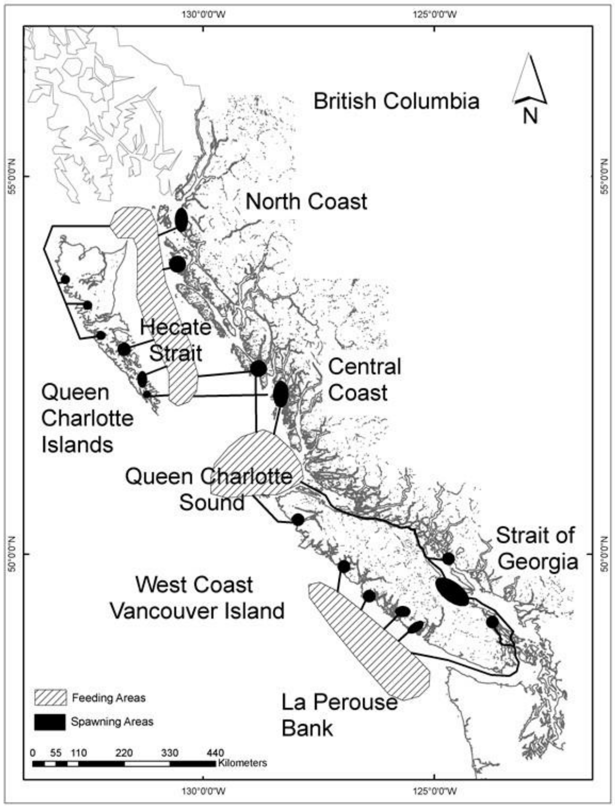


Figure D1. Stylized feeding and spawning areas of Pacific Herring populations in Pacific LAB sub-basins.

D.1.3 Predators and prey

Pacific Herring are planktivorous, feeding primarily on euphausiids, although other plankters such as copepods and amphipods are also consumed (Hourston and Haegele 1980). Herring are consumed by an enormous variety of fish, bird, and marine mammal predators at various stages of their life cycle (Schweigert et al. 2010; Hourston and Haegele 1980). Birds and invertebrates are key predators at the egg and larval stage (Haegele 1993a, b; Bishop and Green 2001; Outram 1958). Subsequently, various species of fish consume the larvae and juveniles (Hourston and Haegele 1980). Juveniles and adults are consumed extensively by marine fish and mammals. The relative importance of herring in each predator's diet varies: for example, Pacific Herring may represent up to 88% of Lingcod diet (Pearsall and Fargo 2007), 40 % of Pacific cod and Pacific Halibut diets (Ware and McFarlane 1986), and 35% - 45% of pinniped diets (Olesiuk et al. 1990; Womble and Sigler 2006; Trites et al. 2007; Olesiuk 2008).

D.1.4 Recruitment

Pacific Herring recruitment is affected by factors determining survival during the first three years of life. Recent analyses suggest that it is likely determined during the first summer (Schweigert et al. 2009) and that it seems to be linked to the timing of spawning in relation to the onset of the spring plankton bloom (Schweigert et al. 2013). It has also been shown that recruitment is inversely related to sea surface temperature in the West Coast of Vancouver Island sub-basin (Ware 1991). However, it is unclear whether this is a result of reduced food supply or increased predation due to key predators migrating north in warm years. It has also been suggested that warm water conditions coincide with a predominance of less lipid-rich southerly plankton prey species.

D.2 THE FISHERY

D.2.1 Management

The commercial Pacific Herring fishery began in British Columbia in 1877 for the local food market, and quickly expanded into a dry salt fishery for the orient. In 1937 a reduction fishery was also established to produce fishmeal and fish oil (Hourston and Haegele 1980). After the collapse of the Pacific Sardine (*Sardinops sagax*) in the late 1940s, Pacific Herring became the major fishery off Canada's Pacific coast, and catches steadily increased to over 200,000 tons in the early 1960s (Hourston 1980). This dramatic increase was unsustainable and by 1965 most of the older fish had been removed from the spawning population by a combination of overfishing and a sequence of weak year-classes attributed to unfavourable environmental conditions and a low spawning biomass. As a result, the commercial fishery collapsed in 1967 and was closed by the federal government to rebuild the stock. Following the fishery closure, a series of above average year-classes in the early 1970s quickly rebuilt the stocks and the fishery was re-opened in 1973 (Hourston 1980).

During the closure from 1967-1971, small fisheries continued locally for food and bait (Hourston and Haegele 1980). At this time there was a growing interest to harvest roe herring for export to Japan. A small experimental roe harvest began in 1971, and limited entry licences were introduced in 1974. This fishery expanded rapidly, and in 1983 fixed quotas were introduced to regulate the catch and to address the difficulty of managing a large fishing fleet. Today most BC Pacific Herring are fished for roe, which is sold in Japan (Stocker 1993). The remainder of the commercial fishery is divided between spawn on kelp production and the food and bait market.

Pacific Herring is ubiquitous along the coast of British Columbia but is managed as five major and two minor populations (Cleary and Schweigert 2011). Major stocks occur in the Strait of Georgia and West Coast of Vancouver Island sub-basins (Fig. D2). A minor stock occurs in Statistical Area 27 in the West Coast of Vancouver Island sub-basin. The Central Coast, Prince Rupert District, and Haida Gwaii major stocks occur in the North Coast sub-basin and Gulf of Alaska sub-basin along with the minor stock in Statistical Area 2W.

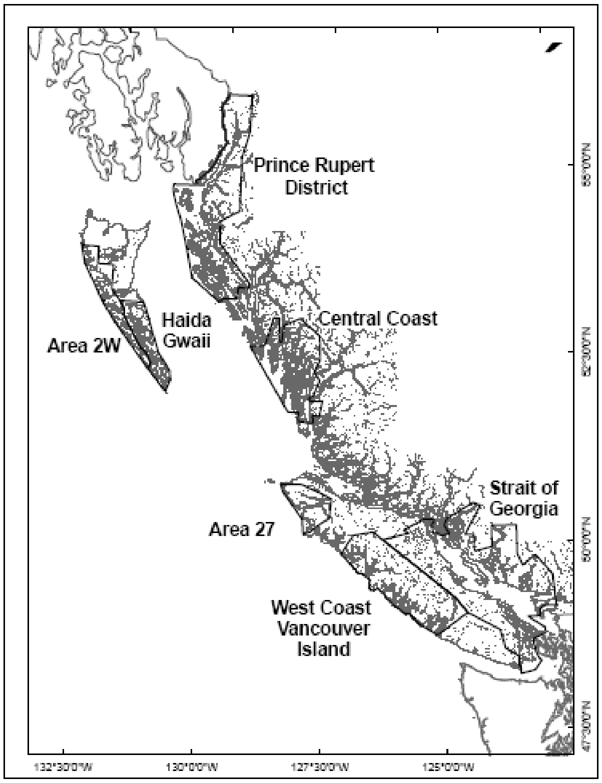


Figure D2. Pacific Herring major stock areas in Pacific LAB: Haida Gwaii, Prince Rupert District, Central Coast, Strait of Georgia, West Coast Vancouver Island, and minor stock areas: Area 2W and Area 27.

The Pacific Herring roe fishery occurs during the spawning period throughout March and April. The focus of this fishery is the female roe that is sold into the Japanese market. The fishery is conducted on or near the spawning grounds using purse seine and gillnet gear. Each of the five major stock areas are licensed separately and the annual total allowable catch is allocated 55% to the seine sector and 45% to the gillnet sector on a coastwide basis as some stock areas are more conducive to seine fisheries and others to gillnets. The roe fishery since 1998 has been managed as a pseudo-IVQ or individual vessel quota fishery with licensees joining into pools for the purpose of catching an aggregate quota. The intent of the pooling is to reduce the fishing rate and increase manageability of the fishery to minimize the possibility of exceeding the annual quota. In addition to the roe fishery, a spawn on kelp fishery occurs in all major areas except the Strait of Georgia. The spawn on kelp fishery is also the primary fishery in the two minor stock areas. The majority of the licensees for the spawn on kelp fishery are First Nations individuals or band councils. The quota for each license is 16,000 pounds of herring eggs and kelp product. The majority of the fishery operates by enclosing fish in pens and hanging *Macrocystis* kelp in the ponds as a spawning substrate. Each license is allocated 100 tons of Pacific Herring to produce the quota. A number of licensees, notably the Heiltsuk tribal council in the Central Coast major stock area operate ‘open’ ponds or wild harvest of spawn on kelp to achieve their quotas. In this case, fish are not entrained in ponds and each license is allocated 35 tons of herring to achieve their quota. A small food and bait fishery operates in the fall, October through February, primarily in the Strait of Georgia major stock area capturing fish on their return migration to the spawning grounds. A number of licenses are also issued for sport bait operators that supply recreational salmon fishermen during the summer months.

D.2.2 Stock assessment

The key component of the Pacific Herring assessment is a survey of the egg or spawn deposition that occurs in the intertidal and upper subtidal zones. Surveys began in 1928 and by the 1950/51 season were conducted routinely throughout the British Columbia coast. Surveys were conducted by fishery officers from the surface at low tide until the mid-1980s when research indicated significant subtidal egg deposition. SCUBA surveys were implemented on a coastwide basis in 1988 and have been conducted with industry contracted dive teams to the present. Additionally, a test fishery is conducted prior to the commercial fishery to monitor roe quality and collect biological samples to support the stock assessment (Stocker 1993). Biomass assessment was based on estimates of total catch and spawn survey information until 1982 when an age structured assessment model was developed and a fixed 20% harvest rate introduced to manage the fishery. In 1986, a fishery threshold or cutoff level was added to allow for fishery closures and stock rebuilding during periods of reduced productivity (Stocker 1993). Annual stock abundance assessments and forecasts are prepared for the five major and two minor stock areas and results reviewed in a scientific forum by the Canadian Science Advisory Secretariat (CSAS). The resulting harvest advice is reviewed with industry and other stakeholders, First Nations, and the public and an integrated fisheries management plan developed prior to the fishing season.

D.2.3 Catch: Canadian removals

The most complete information on catch from the herring fisheries extends from the 1950/51 season for the five major stock areas encompassing the 3 sub-basins in Canada (Table D1). The reduction fishery targeted fish migrating from feeding grounds in the fall to overwintering areas and was primarily conducted with purse or table seines (Stocker 1993). While it focused on the mature component of the population, it also captured younger immature fish. The subsequent roe fishery targets fish at or near their spawning grounds and focuses on the sexually mature component of the population. The food and bait fisheries captured fish in the early fall when they had maximum fat content or in the winter/ early spring as halibut bait. The average landings from the reduction fishery from 1950/51 to 1969/70 for the North Coast, West Coast of Vancouver Island and Strait of Georgia sub-basins were 58700, 21100, and 46200 mt, respectively. The average food and bait landings in the North Coast and Strait of Georgia sub-basins over the entire time period since 1950/51 were 1000 and 2200 mt, respectively, although interest and quota for the food and bait fishery increased in 2011. The average roe fishery landings since its inception in 1970/71 for all three sub-basins were 12500, 9300, and 10200 mt, respectively. In addition, there is likely a small level of bycatch in some of the trawl fisheries, particularly for Pacific Hake (*Merluccius productus*), but the magnitude has not been adequately quantified.

Table D1. Pacific Herring commercial landings (mt) for the three sub-basins within British Columbia. Season includes the period July 1 through June 30 of the following year. Spawn on kelp landings are not presented.

	North Coast			West Coast of Vancouver Island			Strait of Georgia		
Season	Reduction	Food/Bait	Roe	Reduction	Food/Bait	Roe	Reduction	Food/Bait	Roe
1950	90281	890		20772	1049		38283	5515	
1951	94300	1420		26884	124		34993	10892	
1952	693	1940		20			1612	6813	
1953	52823	857		33096	113		61368	4399	
1954	29648	250		6123			65792	2850	
1955	130520	751		17098			70250	1812	
1956	71866	1232		2605	8		58697	912	
1957	24781	738		556			16202	4426	
1958	44053	869		69217	6		49658	367	
1959	21963	550		51522	2389		67819	218	
1960	74131	896		26435			45903	311	
1961	50438	563		23685			64244	1059	
1962	97868	1119		18206			68199	648	
1963	89597	1000		21183	83		76355	526	
1964	94399	930		16046			47238	581	
1965	56429	1095		10838	5		32938	400	
1966	29173	928		15143	2		30132	911	
1967	3386	290					1587	306	
1968								194	
1969		1539					8	236	
1970	1430	5785					69	1630	
1971		2113	15632			6894	103	2651	6058
1973		182	18843			16334		485	3532
1974		172	17992		1	26108		405	5774
1975		939	29894			38825		5069	7168
1976		1132	30750		29	30014		5676	11833

Table D1 continued

	North Coast			West Coast of Vancouver Island			Strait of Georgia		
Season	Reduction	Food/Bait	Roe	Reduction	Food/Bait	Roe	Reduction	Food/Bait	Roe
1978		1865	10410		84	18609		13576	6762
1979		748	6531			3982		2472	3347
1980		1731	9562		2	8088		4907	7147
1981		1873	10259		2	5485		3938	8895
1982		67	11169			8575		824	16394
1983		271	15253			6577		870	10164
1984		297	17767		2	177		773	6257
1985		412	15157		1	203		432	162
1986		155	11792			15934		244	9109
1987		138	12388			9724		756	7459
1988		114	19263			13288		1033	7336
1989		50	19702			9849		233	7886
1990		20	16835			8634		562	10541
1991		230	15832			3713		1216	12480
1992		8	19528			5612		617	13124
1993		1	16865			6037		1032	16706
1994			11642			1947		643	12549
1995			7384			790		541	13572
1996			9161			6656		402	15422
1997			13210			6984		1052	12650
1998			12617			4373		1622	11725
1999			13445			1626		1275	14047
2000			9048					1569	14959
2001		1	8491			821		1465	17285
2002		5	6596			3516		2425	18683
2003		11	7089			4455		1507	12245
2004			7578			4269		2191	16883
2005			5690					2400	16585
2006			1367					1181	9150
2007			1662					1324	8798
2008			2000					603	9622
2009			1484					595	7784
2010			2147					786	4415
2011			1383					4509	7249

D.3 CLIMATE CHANGE AND PACIFIC HERRING

D.3.1 Abundance

It is evident from the response of Pacific Herring to recent strong El Niño events of 1992/93 and 1997/98 that resulted in ocean warming of the three Pacific LAB sub-basins that survival and growth was negatively impacted (Schweigert et al. 2002). There is also a suggestion that Pacific Herring populations were more productive during colder periods, such as the 1940s through to the regime shift in 1977, compared to warmer periods, such as the post -1977 period (Rose et al. 2008; Ware and Schweigert 2002). Ware (1991) found that Pacific Hake predation was a major factor in the natural mortality of Pacific Herring and that it was negatively related to sea surface temperature. It seems likely that during warmer years Pacific Hake migrate further north and as a result would overlap Pacific Herring distribution on the west coast of Vancouver Island to a greater extent increasing the predation rate. One would expect that under warming climate conditions that this effect would be exacerbated.

Pacific Herring are short lived and very responsive to changing environmental conditions. Following the population collapse in the late 1960s, abundance increased rapidly following the closure of the fishery and environmental conditions that favoured survival during the colder regime (Hourston 1980). Following the 1977 regime shift to warmer conditions and the strong 1982/83 El Niño, Pacific Herring productivity declined dramatically particularly in the southern Strait of Georgia and West Coast of Vancouver Island sub-basins (Rose et al. 2008) and has been slow to recover. The rate of recovery may also be affected by increased predation from rebuilding marine mammal populations decimated by earlier harvests or culls. Ware and Thomson (2005) demonstrated that fish production off the West Coast of Vancouver Island and North Coast sub-basins was directly related to primary production, a conclusion Perry and Schweigert (2009) confirmed for Pacific Herring, suggesting that this species is resilient to changes in the productivity of the ocean environment and will take advantage of favourable conditions when they occur.

Based on historic response to both regime shifts and El Niño events, it appears that Pacific Herring are sensitive to changes in the productivity of the local ecosystem resulting in rapid response to changing environmental conditions. Perry and Schweigert (2008) found a positive relationship between primary productivity and Pacific Herring populations at carrying capacity suggesting that local changes in primary productivity will translate directly to changing Pacific Herring productivity.

D.3.2 Distribution

Pacific Herring have optimal egg hatching rates at about 8˚C and it has been shown that there is a relationship between the sea surface temperature and the average latitude of Pacific Herring spawning within the Strait of Georgia sub-basin. In fact, the majority of spawning within this area has moved northward during the past few decades as water temperature has risen (Hay et al. 2009). It has also been noted that Pacific Herring do not rely on the same spawning habitat from year to year and only a small portion of the entire Pacific LAB coast is used annually (Hay et al. 2009) suggesting that habitat is not limiting productivity so that a warming climate may change spawning distribution but should not directly affect spawning conditions and egg survival although it may impact growth rate (Tanasichuk 1997).

D.3.3 Phenology

Production of strong year classes may be dependent upon sufficient food being available during the crucial early feeding period that in turn depends upon climatic conditions that drive zooplankton productivity (McFarlane and Beamish 1992). Timing of spawning is synchronized with spring warming and plankton blooms (Mackas et al. 2007).

Table D2. Summary of potential impacts, vulnerabilities and opportunities from climate change for Pacific Herring.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Recruitment is inversely related to SST off WCVI. Survival and growth are negatively impacted by warm ocean conditions.	As water temperatures have risen in the Strait of Georgia, spawning has moved northward.	Spawning and larval hatching is optimal at 8oC; timing of spawning is synchronized with spring warming and plankton blooms.
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	Possible assisted northward transport of sub-tropical plankton species (lipid-poor) and a key herring predator, Pacific Hake.	No information	No information
Stratification	Increased stratification may inhibit nutrient transfer to the photic zone, thereby limiting primary and, hence secondary production, which in turn may affect the amount of prey available to herring.	No information	No information
Upwelling winds	Increased abundance of significant herring predator, Pacific Hake, may be linked to strength of upwelling	No information	No information
Dissolved oxygen	No information	Pacific herring migrate diurnally and often spend much of the day near bottom. Reduced O2 may restrict their distribution in some of the shallower areas they current inhabit.	No information

D.4 ECOSYSTEM LEVEL INTERACTIONS

Pacific Herring are a significant food source for almost all components of the ecosystems across Pacific LAB so changes in abundance will translate directly through other piscivorous species in the system (Schweigert et al. 2010). During the past two decades Pacific Herring in the outer coast (WCVI and North Coast sub-basins) have been relatively unproductive. It is unclear whether this is due to increased predation pressure from rebuilding marine mammal populations (pinnipeds and cetaceans were heavily hunted until the mid-1960s) or reduced food supply during a period of fishery closures. There is some contrary evidence of pinniped predation pressure on Pacific Herring: the pinniped population in the Strait of Georgia is near carrying capacity, yet the Strait of Georgia Pacific Herring stock biomass is well above estimated unfished levels (DFO 2011a). Schweigert et al. (2010) speculate that the lack of Pacific Herring rebuilding in recent years may be due to competitive interaction with the resurging Pacific Sardine population. Pacific Sardine annually migrate north into the West Coast of Vancouver Island and southern North Coast sub-basins and feed to some extent on euphausiids (McFarlane et al. 2005) thereby impacting the available food supply for herring.

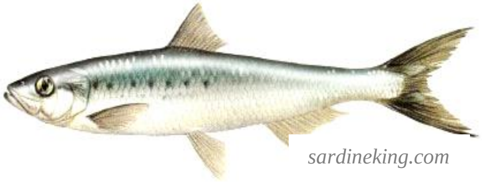
D.5 ADDITIONAL STRESSORS

At the present time, fisheries for Pacific Herring are primarily for roe supplying a niche market in Japan. If the demand for Pacific Herring increased dramatically an increased fishing pressure could impact the rebuilding of currently depressed populations. It is also evident from the experience in Prince William Sound that major anthropogenic impacts such as an oil spill would have significant long term impacts on Pacific Herring populations in all of the sub-basins. Other possible stressors on Pacific Herring are foreshore development that compromises spawning habitat as we have witnessed the disappearance of Pacific Herring from the core of many cities (Vancouver, Seattle, Nanaimo, and Prince Rupert) that supported spawning populations. A recent interest in kelp and seaweed harvest for industrial applications could impact Pacific Herring depending on the extent and timing of the removals. Another possible stressor could be the aquaculture industry and the possible link to disease transmission or sea lice vectors.

D.6 GAPS AND UNCERTAINTY

It is apparent that Pacific Herring would respond to increasing temperature by moving spawning sites northward. How this will affect subsequent survival and growth and ultimately population productivity remains unclear. Pacific Sardine are known to exhibit multi-decadal cycles in abundance. It is unknown whether these cycles will continue under climate change and as a result sardine abundances will remain at moderate to high levels with the resulting potential negative impact on Pacific Herring productivity. There is abundant evidence that marine mammals feed extensively on herring. It is unknown what the overall magnitude of this predation impact is on the herring populations and how mammals as a whole will respond to a changing climate.

Pacific Herring are susceptible to disease pandemics and the extent of baseline infections from Viral Heamorrhagic Septicemia (VHS) and Ichthyophonus are unknown but have been implicated in the non-recovery of the Prince William Sound herring population. In addition to single stressors the cumulative effect of multiple stressors on herring are unknown.



E. Pacific Sardine (*Sardinops sagax*)

Linnea Flostrand, Jake Schweigert and Jennifer Boldt

KEY POINTS

- Migratory patterns are affected by water temperatures, population size and size and age compositions.
- Summer sardine migrations into Pacific LAB waters enable sardine to benefit from the high productivity resulting from extended daylight and nutrient rich waters.
- Juvenile survival is linked to oceanographic factors such as temperature, currents and primary productivity that affect egg and larval survival and distribution.

E.1 BIOLOGICAL CHARACTERISTICS

E.1.1 Life cycle, age and growth

Sardine are oviparous, multiple-batch spawners, with annual fecundity that is indeterminate and age-or size-dependent (Macewicz et al. 1996). For example, mature females ranging from approximately 16 cm to 27 cm may spawn 10,000 to 80,000 eggs in a single batch, with fecundity increasing with fish size. Pacific Sardine spawn in loosely aggregated schools in the upper 50 meters of the water column. Spawning begins in January off northern Baja California, Mexico and southern California, typically peaking off California in April. Eggs are most abundant at sea-surface temperatures of 13 to 15^{o}C, and larvae are most abundant at 13 to 16^{o}C. The spatial and seasonal distribution of spawning and egg hatching is influenced by temperature. During periods of warm water, the center of Pacific Sardine spawning shifts northward and spawning extends over a longer period of time (Butler 1987; Ahlstrom 1960).

Pacific Sardine aged 2 to 4 generally range from 17 to 22 cm, whereas sardines aged 4 to 8 (and older) generally range from 20 to 25 cm (Hill et al. 2012). Pacific Sardine may reach 41 cm in length, but are seldom longer than 30 cm. Year class and recruitment success can vary greatly between years, and a strong year class can comprise a significant proportion of the population for several years, as evidenced by the 2003 year class (Fig. E1). There is evidence for regional variation in size-at-age, with size increasing from south to north and from inshore to offshore (Phillips 1948; Hill 1999). Size- and age-at-maturity may decline with a decrease in biomass, latitude, and temperature (Butler, 1987). At relatively low biomass levels, Pacific Sardine appear to be fully mature at age one, whereas at very high biomass levels only some of the two-year-olds are mature (MacCall 1979).

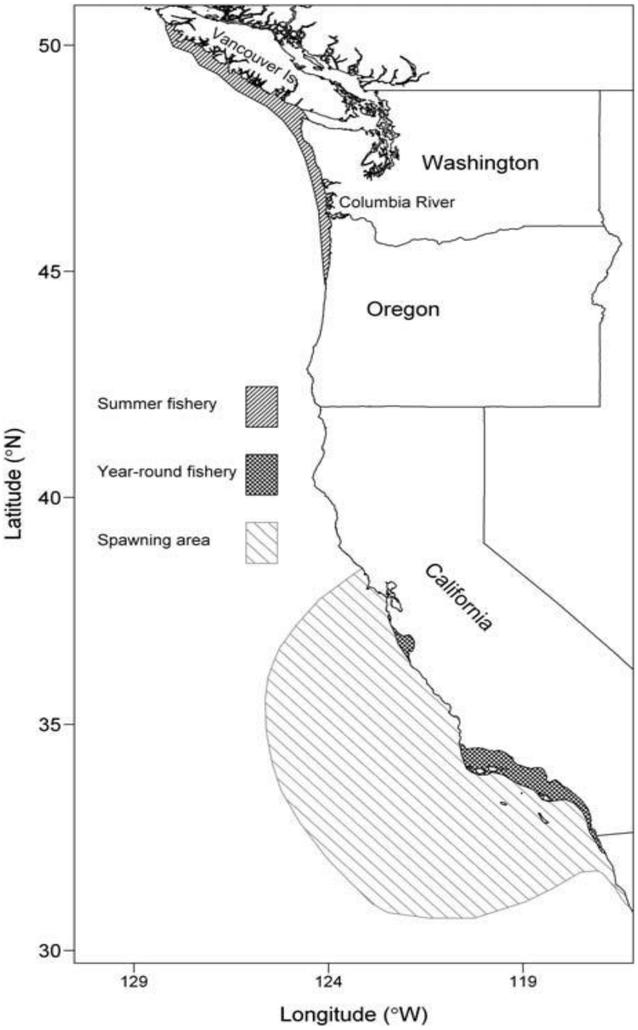


Figure E1. The California Current region, indicating typical locations of spring spawning Pacific Sardine; the summer fishery off Oregon, Washington and Vancouver Island and; the year round fishery off northern Baja California and California. Summer northern migrations (primarily for foraging) can extend to latitudes of 53^o (or more) with wide and varying westward ranges offshore. To date, all commercial BC fishery catch locations have been from waters south of 53^o, within 30 km from shore and caught mainly by purse seine. Figure from Zwolinski et al. 2011.

E.1.2 Distribution, habitat and environmental preferences

Pacific Sardine migrate extensively when abundance is high and marine conditions are favourable, moving north as far as British Columbia in the summer and returning to southern California and northern Baja California in the fall (Fig. 1). Based on observations of egg and larval distributions as well as spawning aggregations, the northern Pacific Sardine subpopulation mostly spawns in south-central California between January and April (Lo et al. 2005; Song et al. 2012), however larvae and juveniles have been observed off Oregon and Washington (Emmett et al. 2005). During the 1950s to 1970s, a period of reduced stock size and unfavorably cold sea surface temperatures apparently caused the stock to abandon the northern portion of its range. In recent decades, the combination of increased stock size and warmer sea surface temperatures has resulted in the stock re-occupying areas off central California, Oregon, Washington, and British Columbia, as well as distant offshore areas off California.

Resumption of seasonal movement patterns between the southern spawning habitat and the northern feeding habitat has been measured through spring and summer research surveys (Emmett et al. 2005; McFarlane et al. 2005; Lo et al. 2010; Flostrand et al. 2011; Demer et al. 2012). Length and age sample data and tagging studies indicate that the older and larger fish move farther north (Janssen 1938; Clark and Janssen 1945; Lo et al. 2010; Hill et al. 2012). Seasonal trends in geographic distribution and biological data (length, age, parasite and historic tagging data) show that regional connectivity in the population is complex. Seasonal migrations are also complex, with timing and extent of movements affected by population size and structure and oceanographic factors (Ware and Thompson 1991; McFarlane et al. 2002; Emmett et al. 2005; McFarlane et al. 2005; Demer et al. 2012) and the northward migration appears to be constrained by the 12^{o}C isotherm (Ware 2001; Emmett et al. 2005).

Pacific Sardines filter feed on phytoplankton and zooplankton and summer migrations into BC enable them to benefit from the marine productivity resulting from extended daylight and nutrient rich waters from oceanic upwelling and coastal run-off during times when water temperatures offer favourable habitat (McFarlane et al. 2005).Seasonal occurrence of sardine off the west coast of Vancouver Island is greater than in other areas of the BC coast because those waters are migratory pathways as well as terminal foraging grounds for Pacific Sardine.

E.1.3 Predators and prey

Pacific Sardine are frequently the most abundant forage fish in the California Current system and their seasonal migrations into BC (especially the west coast of Vancouver Island) overlap with the occurrence of several predator species of fish, marine mammals and sea birds (Emmett et al. 2005; Irvine and Crawford 2012). In particular, their seasonal distribution in BC corresponds with the return of adult Coho and Chinook salmon and humpback whale foraging and migrating seasons. Other predator species observed to feed on Pacific Sardine include dogfish sharks, Pacific Hake, jack mackerel, seals, sea lions and dolphins. From the 1950s to 1980s, the Pacific Sardine population was severely reduced at a time when coastal British Columbia had relatively low levels of marine mammals (resulting mainly from hunting activities). Pacific Sardine may have had an important role in supporting the recovery of marine mammal populations, especially given the variability in abundance of other forage species off the west coast of Vancouver Island, such as Pacific Herring (Schweigert et al. 2010).

Pacific Sardine are omnivorous fish, that filter feed on many species of phytoplankton and zooplankton and are likely well adapted to varying species compositions in plankton communities because of their opportunistic foraging habits (McFarlane et al. 2005).

E.1.4 Recruitment

Pacific Sardine recruitment is highly variable (Fig. E2); analyses of the stock recruitment relationships have been controversial with some studies showing a strong density-dependent relationship (production of young sardine declining at high levels of spawning biomass) and others finding no such relationship (Clark and Marr 1955; Murphy 1966; MacCall 1979). More recently, there is strong evidence supporting improved quality of spawning and rearing habitat during El Niño conditions, especially during transition periods between La Niña and El Niño that maintain Pacific Sardine ichthyoplankton concentrations relatively near shore (Song et al. 2012).

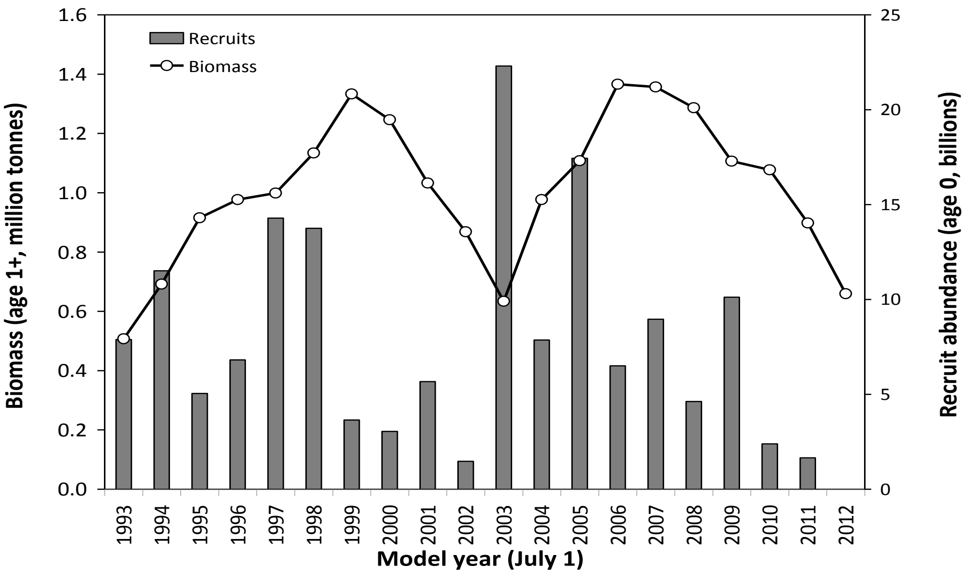


Figure E2. Estimates of Pacific Sardine population abundance for age 1 and older (1+) biomass (millions of tonnes) and year class strength of age 0 recruits (billions of fish) from Stock Synthesis population model "X6e" (from Hill et al. 2012).

E.2 THE FISHERY

Pacific Sardines associated with the California Current are primarily caught in near-shore surface waters by purse seine gear from all regions of the population's distribution. Since the population's resurgence over the last 20 years, the Pacific LAB sardine fishery has also grown. In 1995, experimental fishing off the west coast of Vancouver Island was initiated and in 2002, following de-listing by COSEWIC (Committee on the status of endangered wildlife in Canada), the fishery became a full commercial fishery (DFO 2012b). In recent years, the fishing season has opened June 1st and extends to February 9th of the following calendar year; however, no or few sardine licenses have fished between December and February, largely due to absence of sardine in Pacific LAB during winter months. Most Pacific LAB marine areas have been open to commercial Pacific Sardine fishing except where there are permanent fishing closures or salmon bycatch concerns.

The fishery operates under an Individual Quota system and currently there are 50 licensed quotas (25 allocated to First Nations and 25 to non-natives), each is allocated a percentage of the annual Total Allowable Catch (TAC) and quotas are fully transferable within the sector (DFO 2012b). All Pacific Sardine landings in BC since 1995 have had 100% third party dockside validation and varying proportions of the fleet have been required to have at-sea observers.

It is generally accepted that Pacific Sardine (*Sardinops sagax)* off the west coast of North America consist of three subpopulations or stocks. The northern subpopulation linked to the California Current (northern Baja California to Alaska), the southern subpopulation (outer coastal Baja California to southern California), and the Gulf of California subpopulation were distinguished on the basis of serological techniques (Vrooman 1964) and in a study of temperature-at-capture (Felix-Uraga et al. 2004; 2005). An electrophoretic study (Hedgecock et al. 1989) however, showed no genetic variation among sardine from central and southern

California, the Pacific coast of Baja California, or the Gulf of California. Although the ranges of the northern and southern subpopulations overlap, the adult spawning stocks may move north and south in synchrony but do not overlap significantly. The northern California Current subpopulation is exploited by fisheries off Canada, the US and northern Baja and has undergone long-term fluctuations in abundance for at least 2000 years (Baumgartner et al. 1992).

Large abundances of Pacific Sardine occurred throughout the California Current population's range from the early 1900s to the late 1940s. Following that period, abundance declined and the geographic distribution contracted to small pockets off southern California and Ensenada Mexico. The population has gradually rebuilt since the 1980s. As the population has increased in size, so has the northern extent of its distribution. A resurgence of sardine distribution into British Columbia waters has been observed since 1992 (Hargreaves et al. 1994).

E.2.1 Management

No formal agreements exist between Canadian, US and Mexican governing agencies on coordinated approaches to assessment or management. Both population level age 1 and older biomass estimates from a US led annual assessment and Pacific LAB regional observations have been used to track Pacific Sardine productivity trends for use in setting fishing levels in Pacific LAB (DFO 2012c).

E.2.2 Stock assessment

The US led annual assessment of the California Current Pacific Sardine population incorporates fishery catch data (regional landings and biological data) and research survey data (from acoustic-trawl, aerial. and ichthyoplankton-trawl surveys) into an age structured Stock Synthesis model which is formally reviewed every two to four years. Hill et al. (2012) summarizes the data and results of the most recent population assessment. Figure 24 offers an example of the variation in age 1 and older biomass estimates as well as estimates of recruitment year class strength.

Since 1997, an index of the biomass of the migratory component of the Pacific Sardine population has been determined from an annual summer surface trawl survey off the west coast of Vancouver Island. The index is based on average sardine densities observed for the region. In addition to survey observations, Pacific Sardine fishery catch locations have been considered to represent potential sardine habitat in unsurveyed areas. Schweigert et al. (2010) and Flostrand et al. (2011) describe estimation methods used to characterize survey observations.

Length and age data from fishery and research surveys are important for describing population and fishery dynamics. Spatial and seasonal availability of Pacific Sardine size and age classes varies throughout the geographic range. One important characteristic of the population evident from survey and fishery catch samples is that, on average, within and between seasons, younger and smaller sardines are predominant in near shore fisheries off California and Ensenada compared with older and larger Pacific Sardines observed further offshore (e.g. >50 km) or in more northern waters, such as off of Oregon, Washington and BC (Hill et al. 2012).

E.2.3 Catch: Canadian removals

From 2002 to 2012, landings of the California Current Pacific Sardine population have averaged approximately 150,000 mt (Table E1). The Pacific LAB fishery averaged approximately 6% of the total landings from 2002 to 2012 and approximately 12% since 2008, whereas the US fishery averaged approximately 60% of the total landings from 2002 to 2012 and approximately 50% since 2008 (Table E1; Fig. E3).

Table E1. Annual landings (mt) of Pacific Sardine from the California Current subpopulation. Legend: BC=British Columbia; WA=Washington state; OR= Oregon state; CCA=central California; SCA=southern California; ENS=Ensenada (Baja Mexico). *Landings for 2012 are preliminary*.

Year	ENS	SCA	CCA	OR	WA	BC	Total
2002	46,845	49,366	14,078	22,711	15,212	822	148,952
2003	41,342	30,289	7,448	25,258	11,604	1,006	116,919
2004	41,897	32,393	15,308	36,112	8,799	4,259	138,948
2005	55,323	30,253	7,940	45,008	6,929	3,266	148,684
2006	57,237	33,286	17,743	35,648	4,099	1,558	149,588
2007	36,847	46,199	34,782	42,052	4,663	1,507	166,065
2008	66,866	31,089	26,711	22,940	6,435	10,435	164,466
2009	55,911	12,561	25,015	21,482	8,025	15,334	138,328
2010	56,821	29,352	4,306	20,852	12,381	22,223	145,935
2011	70,337	17,642	10,072	11,023	8,008	20,719	137,801
2012	*61,023*	*18,814*	*4,220*	*41,476*	*35,041*	*19,129*	*179,703*

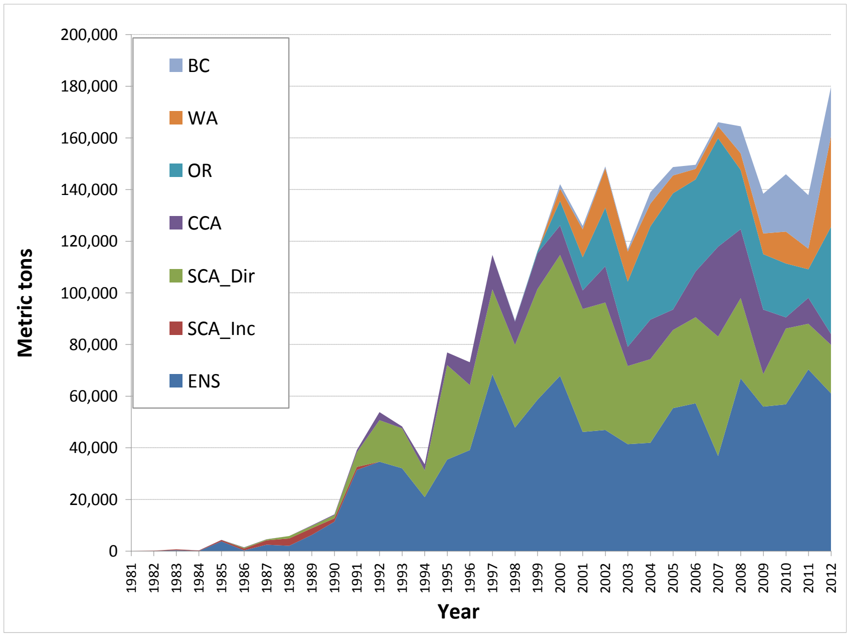


Figure E3. Pacific Sardine landings by fishing region and calendar year (from Hill et al. 2012 Figure 23). Legend: BC=British Columbia; WA=Washington state; OR= Oregon state; CCA=central California; SCA-Dir and SCA-Inc= southern California directed and incidental fishing respectively; ENS=Ensenada (Baja Mexico). *Landings for 2012 are preliminary.*

Since 2002, the Pacific Sardine fishery in Canada has developed and grown under varying markets and management conditions which have improved fishery feasibility. Three management changes which have affected the feasibility of the fishery since 2007 are: 1) increases in annual TACs; 2) the allowance for transferability of licensed quotas; and 3) a reduction in at sea observer coverage and related fees. Fishing locations have included the Queen Charlotte Strait and the Queen Charlotte Sound but most harvests have been from the west coast of Vancouver Island (Table E2; Fig. E4, E5). Fishing effort has varied between coastal locations over time because of changing seasonal availability of sardine; desire to minimize vessel travel costs between fishing and landing sites and variability in buyers and landings ports.

Table E2. Recent BC commercial Pacific Sardine individual licence quota (IQ), total allowable catch (TAC) and landings for west coast of Vancouver Island (WCVI DFO Fishery Management Areas 20-27, 121-127); North Coast, (DFO Pacific Fishery Management Areas 6-12).

YEAR	TAC (mt)	% of TAC	IQ (mt)	WCVI landings (mt)	North Coast landings (mt)	Total landings (mt)
2002	5,000	16	180	480	340	822
2003	9,000	11	180	1,006	0	1,006
2004	15,000	28	300	4,179	80	4,259
2005	15,200	21	304	595	2670	3,266
2006	13,500	12	270	0	1,558	1,558
2007	19,800	8	396	275	1,232	1,507
2008	12,491	84	250	5,670	4,765	10,435
2009	18,196	84	364	8,073	7,262	15,334
2010	23,166	96	463	18,911	3,312	22,223
2011	21,917	95	438	20,718	0	20,719
2012	27,279	70	546	19,129	0	19,129

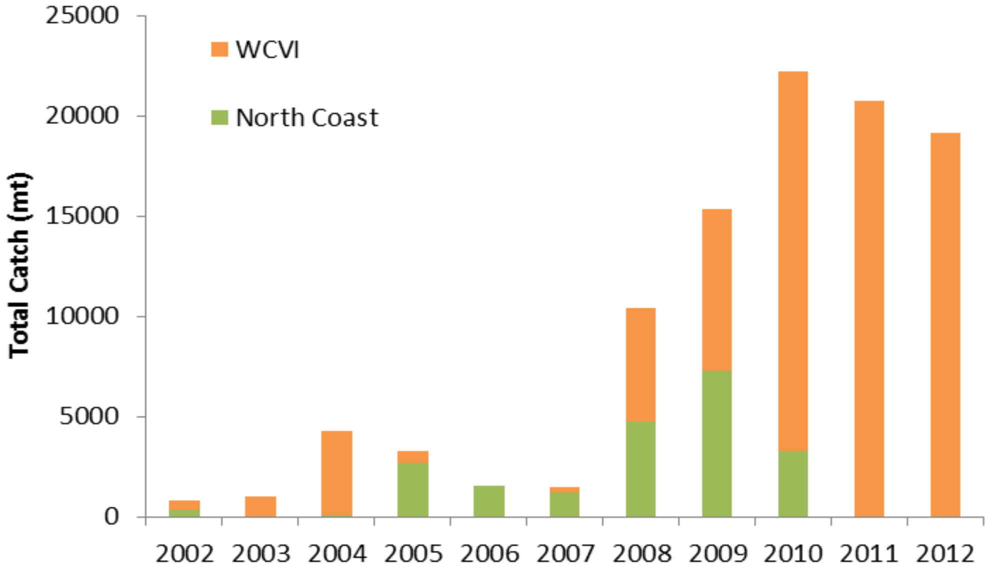
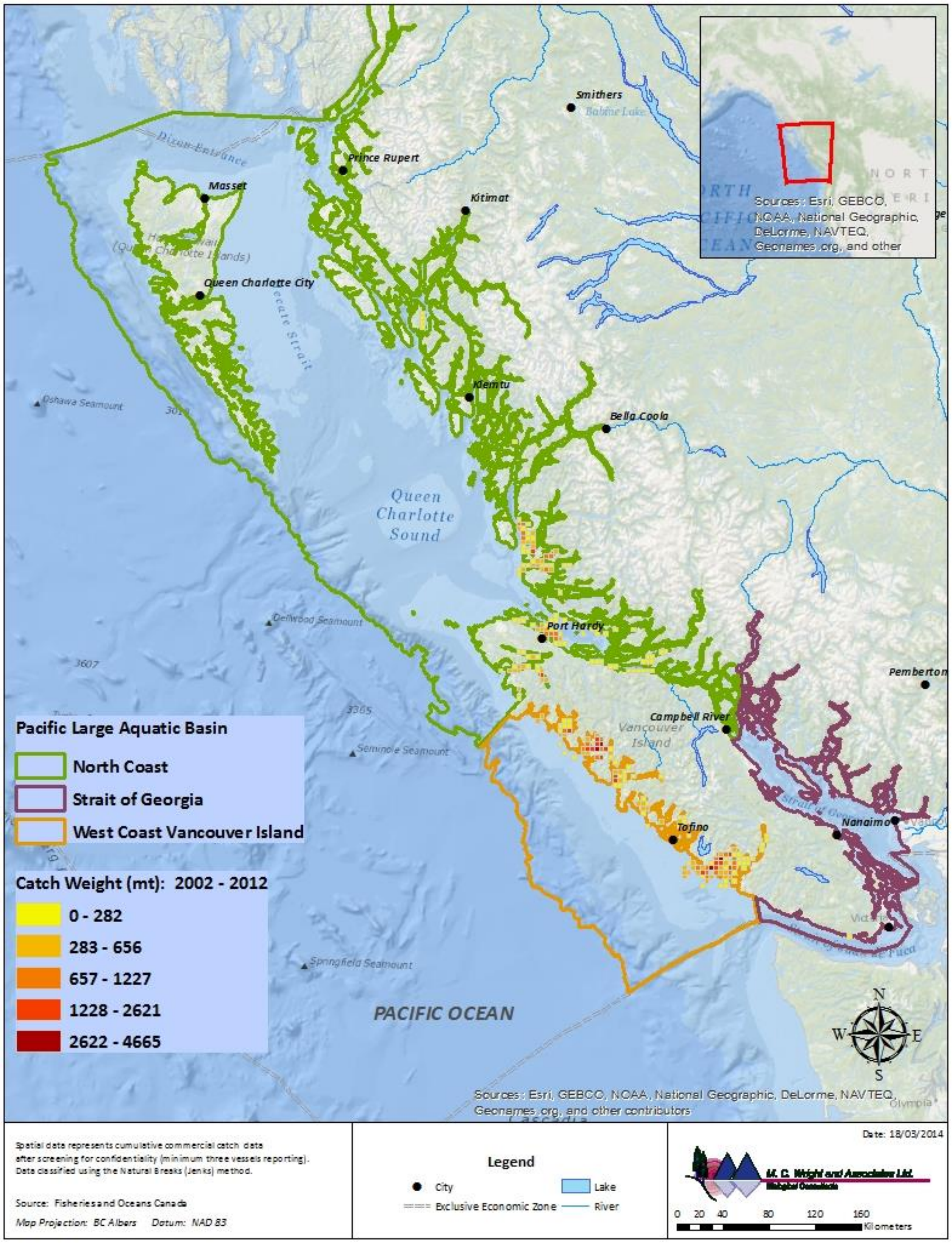


Figure E4. Total catch (mt) of Pacific Sardine (2002-2012) in Strait of Georgia, WCVI and North Coast sub-basins. Unpublished records report no sardines caught in BC in 2013.



Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other

Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

Spatial data represents cumulative commercial catch data after screening for confidentiality (minimum three vessels reporting). Data classified using the Natural Breaks (Jenks) method.

Source: Fisheries and Oceans Canada

Map Projection: BC Albers Datum: NAD 83

Date: 18/03/2014

Figure E5. Distribution and cumulative retained catch of Pacific Sardine in Pacific LAB, 2002-2012. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

E.3 CLIMATE CHANGE AND PACIFIC SARDINE

E.3.1 Abundance and Phenology

The timing and quality of marine conditions conducive to Pacific Sardine spawning success and recruitment are subject to climate change (Song et al. 2012). Marine currents and temperatures affecting and egg and larvae survival and dispersal to favorable rearing habitat are believed to be what governs recruitment success, which is at the base of the population's production and stock dynamics.

E.3.2 Distribution

The spatial and seasonal distribution of spawning is influenced by temperature. Pacific Sardine are known to migrate farther north during the summer in relatively "warm" water years (McFarlane et al. 2005; Demer et al. 2012). During periods of warm water, the center of sardine spawning also shifts northward and spawning extends over a longer period of time (Ahlstrom 1960; Butler 1987). Thus, spawning and rearing of sardine may be expected to occur further north as a response to temperature increases. To date, the majority of spawning activity has been concentrated in the region offshore and slightly north of Point Conception, California (Lo et al. 1996, 2005; Song et al. 2012).

Based on past observations, it is expected that during El Niño events when the subpopulation is at relatively moderate or high abundance levels, that a larger proportion of the northern stock will migrate into Pacific LAB.

Table E3. Conceptual pathways linking physical features and productivity processes to migratory Pacific Sardine biology and population dynamics.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	During warm water years the centre of spawning abundance shifts northward and extends over a longer time period. Spawning and rearing are occurring further north as a response to temperature increases.	Increased stock size combined with warmer sea surface temperatures results in greater northward range extension.	Timing of spawning and larval rearing during favourable plankton production affect recruitment success
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	Recruitment success is governed by water currents and temperatures affecting egg and larval dispersal to favourable rearing habitats.	Stronger northward flowing currents in spring augment northward migration.	Dispersal of eggs and larvae to favourable rearing habitats affect recruitment success
Stratification	Increased stratification may inhibit nutrient transfer to the photic zone, thereby limiting primary and, hence secondary production, which in turn may affect the amount of prey available to sardine.	May affect migratory forage behaviour and seasonal distribution.	Concentrates prey for first feeding larvae, June/July in northern California Current Ecosystem
Upwelling winds	Increased upwelling may lead to higher seasonal productivity that supports sardine growth. However, increased upwelling will push colder water farther offshore and may move sardines in the warmer plume into less nutrient rich offshore waters.	No information	No information
Dissolved oxygen	No information	No information	No information

E.4 ECOSYSTEM LEVEL INTERACTIONS

The role of Pacific Sardine in the ecosystem varies significantly depending on environmental conditions and population abundance and size and age compositions. See predators and prey Section 1.3.

E.5 ADDITIONAL STRESSORS

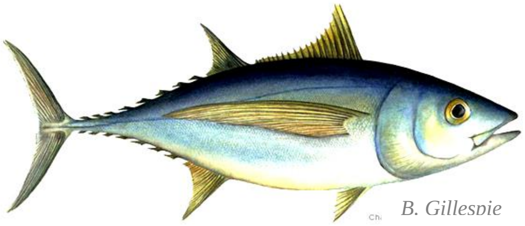
In the past, Pacific Sardine and Pacific Anchovy have shown an inverse cycle in abundance. Warming may result in a northward expansion of the Pacific Anchovy population that may negatively impact Pacific Sardine feeding in WCVI waters (Chavez et al. 2011).

E.6 GAPS AND UNCERTAINTY

It is clear that sardine go through long term cycles that may correspond to PDO cycles and they definitely show up farther north in major El Niño events. Climate change would be expected to exacerbate these effects. However, Pacific Sardine stock responses in BC waters to climate change may be difficult to detect, due to possible confounding factors such as uncertainty and variability in natural mortality and fishing mortality of the different regions; changes in population abundance and stock composition (age and size classes); changes in BC survey effort, and changes in fishery management. Pacific Sardine is a seasonally migratory forage species with a population abundance that can greatly fluctuate on decadal scales; therefore there are unknown long-term effects on ecosystem dynamics.

Because Canada, the US and Mexico independently set harvest levels; there has been significant debate as to the potential cumulative impacts of removals on the population. Associated concerns include unknown effects on stock structure and reproductive capacity resulting from the targeting of younger components of the population in the south (e.g. from southern California) versus older components in the north (e.g. from Washington, Oregon and BC).

There is a high level of uncertainty associated with biomass estimates for BC waters because Pacific Sardine distribution and density observations can be greatly confounded by in-season movements, particularly related to ocean conditions.



F. North Pacific Albacore Tuna
(Thunnus alalunga)

John Holmes, Joy Wade and Karen Hunter

KEY POINTS

- Distribution of North Pacific Albacore Tuna (henceforth Albacore Tuna) is influenced by oceanic conditions including temperature and productivity fronts in the Pacific ocean.
- It is not clear if co-variation among environmental conditions and other factors such as spatial changes in fishery operational areas or targeting behaviour drive recruitment trends.

F.1 BIOLOGICAL CHARACTERISTICS

F.1.1 Life cycle, age and growth

Approximately 50% of Albacore Tuna mature at 5 years of age (85 cm) and all Albacore Tuna aged 6 and older are mature (Ueyanagi 1957). Spawning occurs in tropical and subtropical waters between 10 and 25^{o}N in the central and western Pacific Ocean from Hawaii to Taiwan/Philippine Islands (ISC 2013). Spawning peaks in March-April in the western Pacific Ocean (Chen et al. 2010) and may peak between June and August in the central Pacific near Hawaii (Otsu and Uchida 1959), although recent information on spawning in the central Pacific Ocean is not available. Females release eggs at depths exceeding 90 m where they are fertilized by the males (Ueyanagi 1957, 1969; Otsu and Uchida 1959; Yoshida 1968; Chen et al. 2010). Eggs develop very quickly in surface waters and hatch within 24-48 hours post fertilization (NOAA 2011). Fecundity ranges between 0.17 and 2.6 million eggs per batch and is dependent on female size (Ueyanagi 1957; Otsu and Uchida 1959; Chen et al. 2010). Female Albacore Tuna mature at lengths ranging from 83 cm fork length (FL) in the western Pacific (Chen et al. 2010) to 90 cm in the central Pacific (Ueyanagi 1957), and 93 cm north of Hawaii (Otsu and Uchida 1959).

Growth is rapid for immature Albacore Tuna and slows at maturity and through the adult period of the life history. Growth in the first year of life is uncertain because these young fish are rarely captured in any of the active fisheries in the North Pacific Ocean. However, juvenile Albacore Tuna recruit into intensive surface fisheries by age 2 in both the Eastern Pacific Ocean and the Western Pacific Ocean; as a result, much better size-at-age and growth information is available. Estimated size at age-1 in Albacore Tuna ranges from 45 to 64 cm (Clemens 1961; Chen et al. 2010; Wells et al. 2011). Albacore Tuna are ~ 60 cm FL at age 2 when they recruit into surface fisheries and growth slows to about 10 cm per year for ages 2-4 and becomes even slower after 5-6 years of age when Albacore Tuna are mature (Clemens 1961; Otsu and Uchida 1959; Yabuta and Yukinawa 1963; Chen et al. 2010; Wells et al. 2011). Growth is sexually dimorphic in adult albacore, with males living longer and achieving larger size-at-age than females (Chen et al. 2012). Maximum measured size of Albacore Tuna is 128 cm (Otsu and Uchida 1959; Clemens 1961) and the maximum recorded age is 15 years (Wells et al. 2011).

All species of tuna swim constantly in order to oxygenate their tissues. Consequently, tuna have up to 30 times the gill surface of other fishes enabling them to extract almost half the oxygen available in the water flowing over their gills (FAO 2006-2013). Tuna also have a counter-current exchange system (rete mirabile) in order to maintain the body core temperature several degrees above ambient to increase muscle efficiency, only tunas and some sharks possess this ability. The rete mirabile consists of small arteries and veins in close proximity with blood flows in opposite (counter-current) directions. Their arterial blood is warmed by the venous blood travelling through the highly energetic red muscle tissues enabling the retention of 70 to 99% of the energy produced by the red muscle fibres.

F.1.2 Distribution, habitat and environmental preferences

Albacore Tuna is a highly migratory species found in tropical, subtropical and temperate waters of the Atlantic, Pacific and Indian oceans as well as the Mediterranean Sea (DFO 2011b). There are two distinct, non-mixing, stocks of Albacore Tuna in the Pacific Ocean, a North Pacific stock and a South Pacific stock separated at the equator. There is no evidence of structure within the North Pacific stock, i.e. subgroups or further stock differentiation.

Albacore Tuna that appear in the coastal waters of North America from California to British Columbia are juveniles living primarily in epipelagic waters above the thermocline, although daily excursions to depths of 300-400 m occur, particularly during migrations (Childers et al. 2011). Adult Albacore Tuna occupy the mesopelagic zone in tropical and subtropical areas of the central and western Pacific Ocean (Fig. F1; FAO 2006-2013). Juvenile Albacore Tuna are strongly associated with warm water transition zone chlorophyll fronts as these areas have high primary production which attracts prey species (Polovina et al. 2001; Zainuddin et al. 2008; Childers et al. 2011).

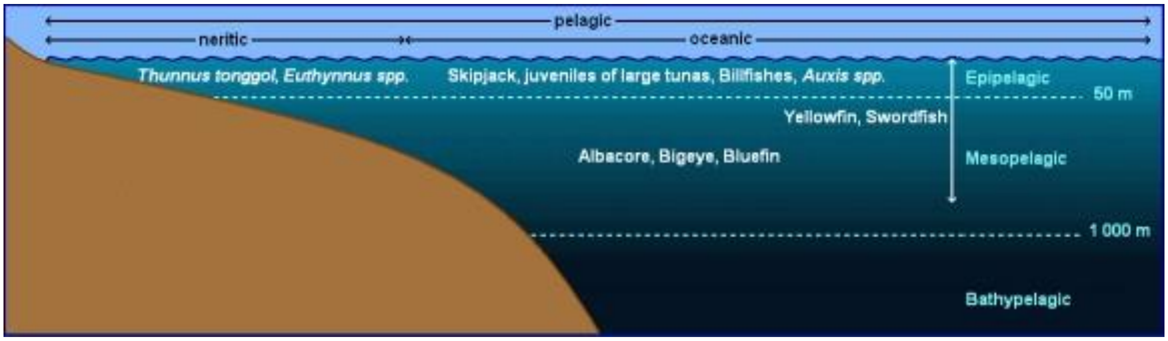


Figure F1. Distribution of tuna and tuna-like species (reproduced from FAO, 2006-2013)

Albacore Tuna undergo both seasonal and ontogentic migrations and these movements are influenced by oceanic conditions (e.g. Polovina et al. 2001; Zainuddin et al. 2006, 2008). The majority of the migrating population is believed to be composed of juvenile fish (i.e., immature animals that are less than 5 years old and 85 cm FL) and these movements are seasonal (Ichinokawa et al. 2008; Childers et al. 2011). Extensive tagging data support the hypothesis that there are two groups of juvenile fish that move into the eastern and western Pacific Ocean in the spring and early summer, returning to the central Pacific Ocean in the late fall and winter where mixing among the eastern and western components of the stock probably occurs (Otsu and Uchida 1963; Ichinokawa et al. 2008). Some juvenile Albacore Tuna undergo a trans-Pacific movement from the western Pacific to the eastern Pacific annually to join the eastern component of the stock (Childers et al. 2011). Recent estimates of seasonal migration rates show that westward movements are more frequent than eastward movements, which corresponds to the recruitment of juvenile fish into fisheries in the western and eastern Pacific Oceans followed by a gradual movement of maturing juveniles and mature fish to low latitude spawning grounds in the central and western Pacific Oceans (Ichinokawa et al. 2008).

Trans-Pacific movements of juvenile Albacore Tuna from west to east track the position of the transition zone chlorophyll front, a zone of sharp temperature fronts combined with high productivity between the sub-arctic and sub-tropical gyres, which is known to be an important migratory pathway for Albacore Tuna and other species (Polovina et al. 2001; Zainuddin et al. 2006, 2008). Kimura et al. (1997) noted that ENSO events and large eastward extensions of the Kuroshio Current meanders affect Albacore Tuna migration patterns, particularly trans-Pacific migration rates to the EPO through disruptions in prey distribution. The migration rate increases when large meanders in the Kuroshio Current are evident because of increased prey availability in the transition zone.

F.1.3 Predators and prey

Albacore Tuna undergo a size-related shift in diet as they grow, switching from microplankton to macroplankton, fish, and squids (Young and Davis 1990; Watanabe et al. 2004; Pusineri et al. 2005; Consoli et al. 2008). Juvenile and adult Albacore Tuna are top predators and forage in epipelagic and mesopelagic waters where they feed primarily on small schooling pelagic fish species such as Pacific Sardine, Northern Anchovy, Pacific Saury, Pacific Herring, and species of mackerel and squids in the eastern Pacific Ocean (Iversen 1962; Pinkas et al. 1971; Watanabe et al. 2004; Glasser 2010). Although squids can be a common item in Albacore Tuna diets, their importance in terms of numbers and weight varies with location and even season (Iversen 1962; Watanabe et al. 2004). Albacore Tuna are occasionally preyed upon by marine mammals, sharks and billfish (DFO 2012d), but most commonly by humans.

F.1.4 Recruitment

Population dynamics of the Albacore Tuna stock is considered to be recruitment-driven, but absolute estimates of recruitment are highly uncertain as they are based on model estimates and lack corroboration from fishery-independent observations of spawning biomass or larval fish production. The stock is modeled assuming a Beverton-Holt stock-recruitment relationship and a steepness value of h = 0.9, which means that recruitment is influenced by both changes in environmental conditions and spawning biomass (ALBWG 2014). The 2014 assessment results show that recruitment has been “about average” from 2005 to 2012 with lower interannual variability in recruitment relative to variability in earlier periods, and the total female spawning biomass was estimated to be about 110,101 t in 2012 (ALBWG 2014). Although absolute estimates of recruitment and biomass are uncertain, trends in both quantities are more robust and the range of uncertainty in these quantities has been reduced relative to the show periods of high, low, and average recruitment coupled with high interannual variability since 1966; stock projections utilize an average annual recruitment of 48 million fish (DFO 2012d).

F.2 THE FISHERY

F.2.1 Management

Albacore Tuna is one of many highly migratory species in the Pacific Ocean and is managed internationally by two regional fisheries management organizations (RFMOs) to which Canada is a member: the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC). The IATTC is responsible for Pacific waters east of 150°W longitude between 50°N and 50°S and the WCPFC is responsible for waters west of this longitude (Fig. F2). There is overlap in the convention areas of these RFMOs between 5 and 40°S and 130-150°W, corresponding to EEZ of French Polynesia, that is managed by the WCPFC. Scientific advice on stock status and conservation of North Pacific highly migratory stocks is provided to the IATTC and the WCPFC by the International Scientific Committee for tuna and tuna-like Species in the North Pacific Ocean (ISC) (DFO 2010c). Canada is a member of the ISC and currently chairs the ISC's Albacore Working Group.

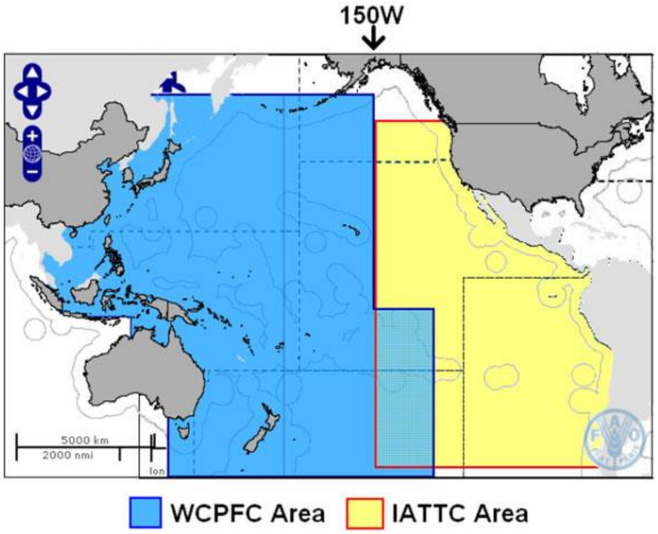


Figure F2. WCPFC and IATTC convention areas (http://www.pac.dfo-mpo.gc.ca/fm-gp/commercial/pelagic-pelagique/tuna-thon/form/map-carte-eng.htm). Canada is a member of both organizations. Note the overlap in convention areas in the South Pacific Ocean around the islands of French Polynesia. This area is managed by the WCPFC by agreement with the IATTC.

The Canada-US Pacific Albacore Tuna Treaty is a bilateral agreement providing access to the EEZ waters and specified ports of each country. The majority of effort and catch in the Canadian fishery historically has occurred within the exclusive economic zone of the United States. The most recent access regime permitted 45 Canadian vessels to access US waters from June 15 to September 15 for the 2013 fishing season. This regime was subsequently extended for three years (2014-2016) by the Governments in Canada and the United States in negotiations that concluded in April 2014. Although the terms of the bi-lateral agreement are probably the most important factors governing the performance of the Canadian albacore fishery, the Canadian fleet must also adhere to the requirements of the WCPFC and IATTC as Canada is a member of these organizations and they are responsible for maintaining sustainable tuna stocks in the Pacific Ocean. These obligations include the requirement to carry and complete daily logbooks of catch, effort, and location and to report these data as well as size composition data from the catch to the RFMOs annually.

The Canadian fishery has operated using vessel-based licences with Schedule II privileges up to 2012. A licence with Schedule II privileges was required for access to Albacore Tuna in the Canadian and US EEZs. In addition, vessels accessing albacore in the US zone must be on the eligibility list compiled in 2005 and have a Section 68 (USA) licence. The new fishing regime in the Canada/US PAT specifies that only vessels 1 through 45 on the eligibility list will be permitted to fish in United States waters. Vessels fishing on the high seas only do not require Schedule II privileges but must have a Section 68 (High Seas) licence (DFO 2012d). Because both the coastal and offshore fleets are under the same licencing scheme it was difficult for DFO to meet international and domestic obligations to better define the fleet for effective management. As a result, a CT licence for tuna only was introduced in 2013 as an interim measure in the move towards a standalone tuna licence. Discussions with industry concerning the type of licence (vessel-based or party-based), eligibility rules, and other components of a stand-alone licence are continuing and final decisions have not been made at present.

There are a number of international agreements which directly impact the responsible management of the Albacore Tuna resource in addition to the Canada/US PAT. The most important is the United Nations Straddling Fish Stocks and Highly Migratory Fish Stocks Agreement (UNFSA), ratified in 2001 (DFO 2012d). Under this Agreement, Canada has an obligation to ensure that any vessel flying its flag on the high seas complies with the conservation and management measures (CMMs) of the relevant Regional Fisheries Management Organizations (RFMO) namely, the IATTC and WCPFC, for Pacific Albacore Tuna (DFO 2012d). These RFMOs are in place to ensure the long-term conservation and sustainable use of highly migratory fish stocks (DFO 2012d).

F.2.2 Stock assessment

The most recent stock assessment based on data from 1966 through 2012 was completed in 2014 by the Albacore Working Group. This assessment used an age-, length-, and sex-structured Stock Synthesis (SS Version 3.24f) model fitted to time series of standardized catch-per-unit-effort and size composition data. Sex-specific growth curves were used because there is evidence of sexually dimorphic growth in adults and the assumed value of the steepness parameter in the Beverton-Holt stock-recruitment relationship was h = 0.9, based on two separate external estimates of this parameter. The assessment model was fitted to the abundance indices and size composition data in a likelihood-based statistical framework and maximum likelihood estimates of model parameters, derived outputs, and their variances were used to characterize stock status. The base case model shows a long term decline in total stock biomass (age-1 and older) and female spawning biomass from the early 1970s to 1990 followed by a recovery through the 1990s and subsequent levelling off and fluctuations without trend in the 2000s (Figure 3). Female spawning biomass was estimated to be 110,101 t in 2012 and stock depletion was 35.8%

of unfished biomass while estimated recruitment has averaged 42.8 million fish annually from 1966 to 2012 (ALBWG 2014). Current fishing mortality ($F_{2010-2012}$) is estimated to be below $F_{2002-2004}$, which had led previously to the implementation of conservation and management measures (CMMs) for the north Pacific albacore stock by the IATTC and the WCPFC. The point estimate (± SD) of maximum sustainable yield (MSY) is 105,571 ± 14,759 t and the point estimate of spawning biomass to produce MSY (SSB_{MSY}, adult female biomass) is 49,680 ± 6,739 t.

Biological reference points were computed with the base case model and stock status in relation to MSY-based and MSY proxy reference points was assessed. Based on an evaluation of the estimated current F ($F_{2010-2012}$) against various F-based reference points, the north Pacific albacore stock is not currently experiencing overfishing since the ratios for most reasonable candidate reference points, except F_{MED} and $F_{50\%}$, are below 1.0 (ALBWG 2014). Biomass-based reference points have not been developed for this stock, but there is little evidence from this assessment that fishing has reduced SSB below reasonable candidate biomass-based reference points, so the stock is likely not in an overfished condition at present (2014). Although there is uncertainty in absolute estimates of biomass and recruitment, stock status and conservation advice are relatively insensitive to these uncertainties as trends in both quantities are robust to the different plausible assumptions that were tested.

Projections in the 2014 assessment to evaluate the impact of different harvest and recruitment scenarios on stock status in the future led the ALBWG to conclude that the north Pacific albacore stock is healthy and that current productivity is sufficient to sustain recent exploitation levels, assuming average historical recruitment continues. It was noted that there is no evidence that fishing has reduced SSB below thresholds associated with the majority of biomass-based reference points that might be chosen and that population dynamics in the north Pacific albacore stock are largely driven by recruitment, which is affected by both environmental changes and the stock-recruitment relationship. Since recruitment is a key driver of the dynamics in this stock, a more pessimistic recruitment scenario, which is within historical variability for this stock, increases the probability that current management objectives for the stock will not be achieved.

F.2.3 Catch: Canadian removals

The majority of the Canadian fishery targets the North Pacific stock in the eastern Pacific Ocean, and has a landed valued of approximately $30 million annually (DFO 2010c). According to the British Columbia Seafood Industry 2011 Year in Review, the landed value of tuna in BC was 28.7 million dollars in 2011. The Canadian albacore fishery is seasonal, occurring primarily in the 3rd quarter of the year, and highly lucrative. The fishery uses troll gear and jigs to catch Albacore Tuna with an average weight of 20 lbs (9kg) and average value to the fishermen of $2.37/lb (DFO 2012d).

Canadian fishermen access the Albacore Tuna stock within Canadian, US, and international waters. A small number of vessels also accessed the South Pacific Albacore Tuna stock historically, although there have been no reported catches or landings since 2007 (DFO 2012d). Approximately three-quarters of the annual catch and effort by the Canadian fishery for Albacore Tuna occurred in US waters between 2000 and 2011 under access provisions in the bilateral Canada-United States Pacific Albacore Tuna Treaty (PAT). A further 16% of the catch and 20%

of the effort occurred in Canadian waters during this period and the remainder occurred in international waters. The 2012 fishery was marked by the absence of a reciprocal fishing regime in the PAT, which prevented access to US waters and resulted in a redistribution of effort to Canadian and international waters and a 55% reduction in catch relative to the average for 2000-2011. A new fishing regime was negotiated for 2013 with reduced access provisions (fewer vessels, shorter period), resulting in a redistribution of catch and effort in the Canadian fishery: while catch increased to 5,090 t in 2013, 59% of this catch and 66% of the effort occurred in Canadian waters, 31% of the catch and 24% of the effort occurred in US waters, while the remaining catch and effort occurred in adjacent high seas waters.

The Canadian fishery for Albacore Tuna is a hook-and-line fishery using troll gear at the surface with artificial jigs (DFO 2012d) trolled at approximately 6 knots. This fishery targets juvenile Albacore Tuna inhabiting the upper 50 m of the water column. Albacore Tuna are harvested by the three major gear types in the North Pacific Ocean, including longline (37% of catch), pole-and-line (35% of catch), and troll (23% of catch). These three gear types accounted for 95% of the total reported catch across 2008-2012. Albacore Tuna is harvested primarily by Japan which accounts for 64% of the catch, the US (18% of the catch), Canada (7% of the catch), Chinese Taipei (4% of the catch), and China (3% of the catch) (ISC 2014). Other countries including Korea, Mexico, Tonga, Vanuatu, Cook Islands, and Ecuador harvest minor amounts of Albacore Tuna annually. Pole-and-line and troll gears fish in the surface waters and harvest immature juvenile Albacore Tuna while long line gear fishes deeper in the water column and harvests sexually mature adult Albacore Tuna (DFO 2012d). Most longline fleets target the more valuable Bigeye Tuna (*T. obsesus*), but retain Albacore Tuna as a secondary species of value (ALBWG 2011)**.**

Approximately 2,500 vessel-based licences with Schedule II privileges attached permit Canadian fishermen to retain Albacore Tuna, but only 100-200 vessels participate in the fishery annually and harvest fish in the coastal waters of BC, the US, and the high seas international waters of the north and South Pacific Oceans (DFO 2010d). A new "CT" licence was implemented in 2013 to better define the Canadian fleet and is seen as an interim step in the development of an independent tuna licence for Canadians. A coastal fleet and an offshore fleet participate in the Canadian fishery (DFO 2012d) and vessels from these fleets may intermix operationally during the fishing season; coastal vessels are primarily salmon troll vessels and approximately 11-18 m in length while the offshore vessels are generally larger than 18 m but fewer in number than the coastal vessels.

The coastal fleet operates in Canadian and US waters from Haida Gwaii to Cape Blanco on the southern coast of Oregon (DFO 2010d). The timing of the inshore fishery is dependent on migration timing of the species, fuel costs, market prices and weather conditions (DFO 2010d). Access to US waters is based on provisions outlined in the PAT. A number of factors affect the amount and distribution of fishing effort annually, including ocean conditions, and tuna availability (DFO 2013d). Catch from coastal vessels is sold as blast-frozen product for loining or the sashimi markets (DFO 2013d).

The larger offshore fishing vessels can remain at sea for longer periods than the smaller coastal vessels and they fish the area from west of the dateline to the Canadian zone in the North Pacific and some have fished in the South Pacific Ocean historically (DFO 2013d). Depending on weather conditions and abundance of fish, the offshore fishery takes place from June to late fall, fishing toward the coast of North America. Offshore catch is almost exclusively sold to the blast-frozen sashimi market (DFO 2013d).

In addition to the commercial offshore and coastal fisheries, recreational fishing for Albacore Tuna is permitted with a licence in British Columbia, a daily catch limit of 20 fish and a possession limit of 40 fish. First Nations also have access to communal licences to fish for food, social and ceremonial purposes. Anecdotal reports of a developing recreational fishery at the continental shelf edge along the west coast of Vancouver Island prompted DFO to initiate data collection efforts in 2014 aimed at characterizing the amount and distribution of catch and effort in this sector.

The Canadian fishery began in 1939 as fishery off the BC and, probably, the Washington coastlines. This fishery was fairly small and never registered more than a few hundred tonnes of landings until the mid-1990s when catch and effort ramped up substantially and developed into the present fishery. Fishery effort and the operational area of the fishery likely began increasing in the 1980s but there are few records available to confirm these changes. Since the 1980s South Pacific Albacore Tuna also have been harvested by Canadian vessels, but there are no reported catches in the South Pacific since 2007 (DFO 2012d). Total catches of Albacore Tuna (Pacific-wide) since the 1950s have ranged from 37,000 to 126,000 tonnes/year (DFO 2012d). Catches by Canadian fleet have changed in recent years with a shift in effort from offshore areas to coastal waters. From 1996 to 2011 approximately 70% of the average annual catch and effort by the Canadian fleet occurred within the US EEZ (DFO 2012d). Since the 1996, the Canadian fleet in the north Pacific fishery harvested from a low of 2,734 tonnes in 1999 to a high of 7,856 tonnes in 2004, with an average of 5,378 tonnes (DFO 2012d). In recent years, catch has declined to less than 2,000 tonnes per year, except in 2010 (Table F1).

Table F1. Catch (tonnes) of Albacore Tuna, 2006-2011.

Area	2006	2007	2008	2009	2010	2011	2012	2013
British Columbia	1,082	1,297	248	406	2,340	670	2,033	3,007
Washington	2,246	1,410	1,844	2,430	803	1,230	0	296
Oregon	1,812	3,287	2,870	2,773	2,512	3,144	0	1,210
California	22	43	5	1	26	265	0	94
High Seas	660	5	496	88	845	106	465	483
Total	5,834	6,042	5,463	5,698	6,526	5,415	2,498	5,090

Total catches throughout the North Pacific Ocean from 2008-2012, averaged 77,438 tonnes. Japan accounted for 64% of the harvest; the USA 18%; Canada 7% Chinese Taipei 4%, and China 3% during this period (ISC 2014). Estimated Canadian catches from 1939 to 2013 are presented in Figure F3, annual catches of Albacore Tuna by all countries throughout the North Pacific Ocean are provided in Figure F4. Figure F5 shows distribution and cumulative catch across Pacific LAB.

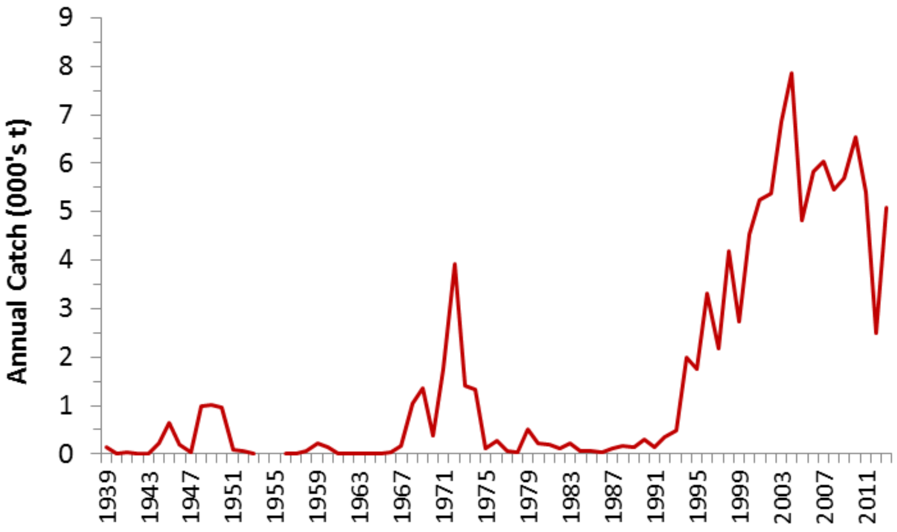


Figure F3. Estimated annual catches (metric ton) of Albacore Tuna by the Canadian fishery from 1939 to 2013 (ISC 2014) in all zones (Canada, USA and highseas).

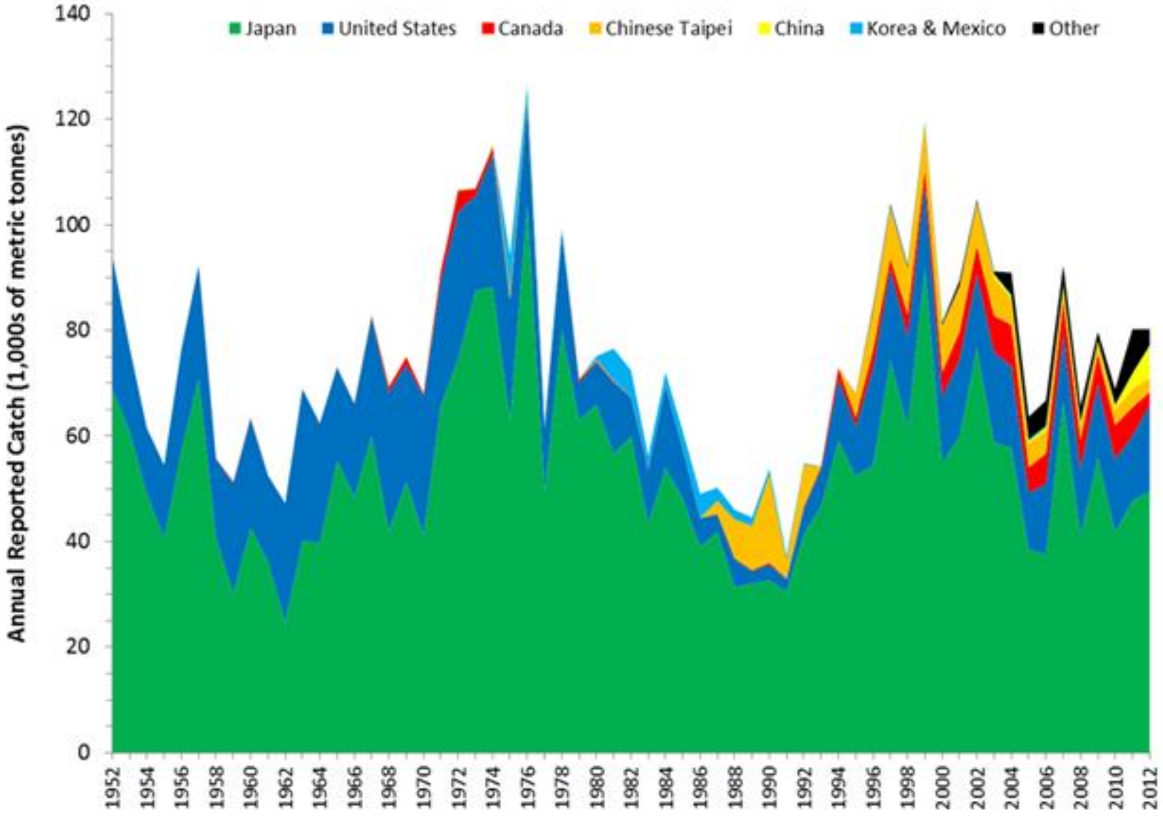


Figure F4. Total annual catches of Albacore Tuna by all countries fishing the stock from 1952-2012 (ISC 2014). The other category includes catches by Vanuatu, Cook Islands, Ecuador, and Belize.

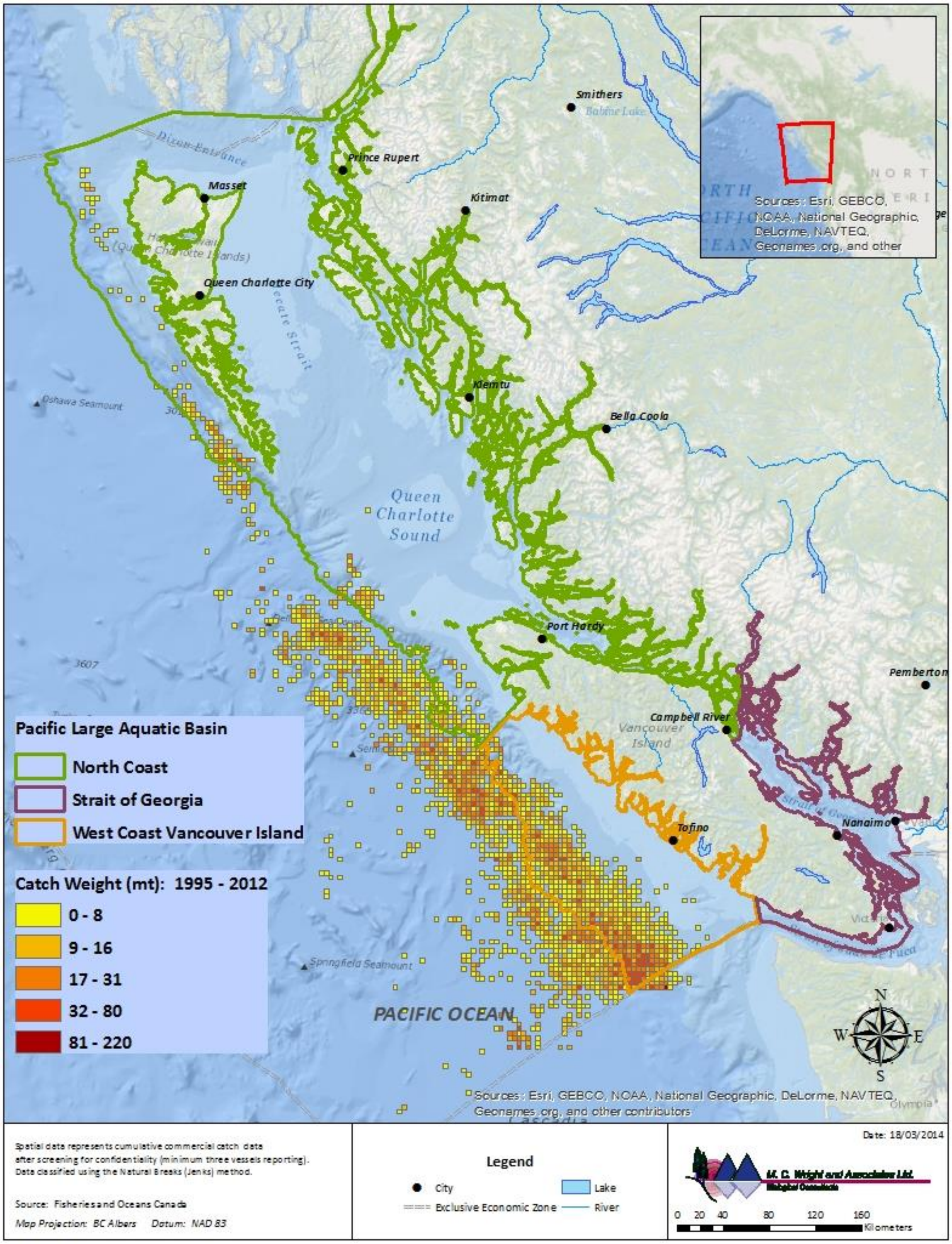


Figure F5. Distribution and cumulative catches of Albacore Tuna in and around Pacific LAB, 1995-2012. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

F.3 CLIMATE CHANGE AND ALBACORE TUNA

F.3.1 Abundance

Based on current assessments, there is no known evidence of a direct impact of climate drivers associated with the anthropogenic trend of climate warming on Albacore Tuna in BC waters. There have however been instances of oceanic changes such as warmer water temperatures and regime shifts affecting Albacore Tuna. For example, recent research results provide some evidence of changes in Albacore Tuna recruitment levels (high, low, average) that coincide with documented regime shifts in the North Pacific Ocean (Kiyofuji 2013, see Appendix 12.1). These results are not conclusive regarding environmental influence(s) on the recruitment level because it is not clear if co-variation with other factors such as spatial changes in fishery operational areas or targeting behaviour, are driving these results. Nonetheless, the evidence of coincident shifts is sufficiently compelling that the relationship between recruitment and variables such as the Pacific Decadal Oscillation (PDO; Appendix 12.1) cannot be neglected in future. For example, periods of high Albacore Tuna recruitment tend to be correlated with negative PDO values in the winter months. Negative PDO values are associated with a warming of the western Pacific Ocean and cooling of eastern Pacific waters. The major Albacore Tuna spawning and recruitment areas are in the western Pacific Ocean. Although climate change could result in enhanced Albacore Tuna recruitment, the effects on Albacore Tuna availability in Canadian waters are uncertain as interactions between migration pathways and other factors related to availability are not fully understood at present. Collaborative research involving US and Canadian scientists is underway to address this issue in the eastern Pacific Ocean.

F.3.2 Distribution

Albacore are a highly migratory species and are only present seasonally in BC waters. The Canadian fleet has changed in recent years with a shift in effort from offshore areas to coastal waters of both Canada and the US.

There have been periodic shifts in distribution noted in the US fishery. Historically there were periods of 25 to 30 years in which the fishery was confined to the coastal waters of California followed by 15-20 years where the fishery shifted to Oregon/Washington/BC (Brock 1943; Clemens and Craig 1965; Clark et al. 1975 in Childers et al. 2011). Indeed, the signing of the original Canada/United States Pacific Albacore Tuna Treaty in 1981 was precipitated by a shift in the distribution of Albacore Tuna primarily into Canadian waters in the late 1970s and the desire of the American fleet to follow the fish.

It is known that Albacore Tuna aggregate (and therefore are fished) in association with specific sea surface temperatures, particularly at sharp gradients or fronts. This phenomenon has been investigated by many researchers throughout the range of the species. Clemens (1961) and Laurs et al. (1984) have noted that in the US, cold fingers of water along the margins of currents and eddies (15.6-18.3^{o}C) range far offshore and are isolated at this boundary by either warmer or cooler water. These fish appeared to be cut off from the main migration, concentrating the fish as the pools of water became smaller, making them easier to catch.

Albacore Tuna hot spots in the North Pacific Ocean have been identified using multi-sensor satellite sensing. These areas are linked to hydrographic features, frontal zones and eddy fields, it is believed these physical features control the primary productivity levels (Zainuddin et al. 2006).

F.3.3 Phenology

Climate change is likely to influence the timing and spatial distribution of feeding migrations to productive areas.

Table F2. Conceptual pathways linking physical features and productivity processes to migratory Albacore Tuna biology and population dynamics.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	High recruitment tends to be correlated with negative PDO values in the winter, which are associated with cooling of the eastern Pacific Ocean	Higher abundance in BC waters occurs in response to increased overlap in time and/or space with specific 'warmer' sea surface temperatures. Trans-Pacific juvenile movement occurs in high productivity zones with sharp temperature fronts.	No information
Sea surface salinity	No information	Juveniles concentrate in lower salinity waters nearshore, believed to be due to food availability	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents		Juvenile migration rates increase when there are large meanders in the Kuroshio current providing increased prey availability	No information
Stratification	No information	No information	No information
Upwelling winds	No information	No information	No information
Dissolved oxygen	No information	No information	No information

F.4 ECOSYSTEM LEVEL INTERACTIONS

Trolling operations are carried out at or close to the surface of the ocean and catches of non-target fish species and turtles, marine mammals and seabirds are generally negligible in troll fisheries world-wide. Trolling gear does not make contact with the seabed and contact with the epipelagic zone is minimal because of the nominal dimensions of the fishing gear.

Incidental catch reported in the Canadian Albacore Tuna fishery includes Skipjack Tuna (*Katsuwonus pelamis*), Pacific Bluefin Tuna (*Thunnus orientalis*), Dolphinfish or Mahi-Mahi (*Coryphaena hippurus*), Yellowtail (*Seriola lalandi*), Blue Shark (*Prionace glauca),* and Shortfin Mako Shark *(Isurus oxyrinchus*). Species with no commercial value may be returned to the sea alive immediately after hooking, as fish are caught individually and barbless hooks are commonly used, so stress and injuries can be kept to a minimum. Canadian vessels with a Section 68 (USA) licence and operating in US waters under the terms of the Can/US PAT are only permitted to retain Albacore Tuna. All other species must be released regardless of their commercial value.

Conservation and management measures to maintain effort were adopted in 2005 by the IATTC and the WCPFC. They were as follows (DFO 2012d): 1) no increase in fishing effort of Albacore Tuna in the eastern or western Pacific Oceans beyond current levels (the current level has never been defined in the eastern Pacific Ocean, but the average of 2002-2004 is used by the WCPFC); 2) each country must take measures to ensure their fleet is not increasing fishing effort; and 3) each country will report catch by gear type to both RFMOs every 6 months.

F.5 ADDITIONAL STRESSORS

Important environmental parameters for Albacore Tuna in the coastal waters of North America include sea surface temperature and salinity. The lower thermal boundary for temperate tunas such as albacore is approximately 10^{o}C (FAO 2006-2013). Juveniles exhibit a preference for fresher water, but this may be in response to the high productivity associated with the Columbia River discharge and the resulting concentration of prey species.

F.6 GAPS AND UNCERTAINTY

Currently, there is no in-season monitoring of catch or effort by the Canadian fleet, although efforts are underway to implement an electronic logbook system which would permit the in-season compilation of this information. Initial estimates of catch and effort are compiled about a month after the fishing season is completed (31 October) and logbooks are returned (deadline is 11 Nov each year). The primary axes of uncertainty in the stock assessment include age and growth (two plausible alternatives), spatial dynamics (the model does not explicitly account for movement patterns), and life history parameter estimates (important parameters such as natural mortality and maturity have not been updated in more than 40 years).

G. Dungeness Crab
(***Metacarcinus magister***)

Karen Hunter and Joy Wade

KEY POINTS

- Climate change is anticipated to affect Dungeness Crab through every life history phase.
- Larval stages are most vulnerable from the effects of increasing sea surface temperature and changes in productivity on abundance, as well as disruptions in their transport to settlement areas with impacts on recruitment.
- Inshore areas of the coast could experience significant change from the combination of increasing sea level, ocean acidification, and intermittent hypoxia affecting important adult and sub-adult crab habitat.

G.1 BIOLOGICAL CHARACTERISTICS

G.1.1 Life cycle, age and growth

Four distinct phases exist in the life history with each strongly linked to habitat and behaviour. Phases include offshore-associated zoeae (larvae) and megalopae (0+ year class) phases, and nearshore and continental shelf-associated subadult (1+ to 3+ year class) and adult (>3+ year class) phases. To initiate mating, adults move inshore in the spring into more shallow water where mating takes place. In late summer and early winter, both sexes move back into deeper water. Though protracted across the entire species distribution (Rasmuson 2013), mating is generally synchronous coast-wide in BC, normally occurring in the late spring (April/May). Eggs begin hatching in late winter and early spring when water temperature is appropriate for spring plankton blooms (Park et al. 2007). Early ocean-going larval stages or zoeae transition through five stages before metamorphosing to megalopae. By April/May, megalopae can be found in large concentrations in nearshore areas throughout the summer (Tasto 1983). Megalopae are crab-like and strong swimmers that seek out favourable benthic habitats for metamorphosis to sub-adult. It takes at least 2 years or 10 moults for a newly settled sub-adult to reach sexual maturity, after which animals move into deeper habitat.

Because crab have hard exoskeletons, they can only grow by shedding their shell. Moulting occurs more frequently in the first 2 years of life, allowing individuals to grow rapidly (Tasto 1983). Though growth can be limited by density dependent factors in this species (Shanks et al. 2010), by the end of their first summer, growth rate of juveniles from Oregon populations in warmer estuaries is generally faster than for juveniles that settle on the continental shelf (Gunderson et al. 1990). Sexually mature crab can moult yearly, but may “skip-moult”. The maximum size of a Dungeness Crab male is approximately 215 mm and females 165 mm carapace width. Longevity is between 6 and 9 years (Rasmuson 2013).

G.1.2 Distribution, habitat and environmental preferences

Dungeness Crabs inhabit in coastal regions from California to Alaska including the continental shelf, coastal estuaries and inland fjords at water depths ranging from the intertidal to approximately 230 m (Jensen 1995). Depending on the life stage, they occupy several different types of habitat. The larval phase occurs in open waters and can disperse long distances (>1,500 km) (Park et al. 2007). After migrating off the shelf, zoea develop into megalopae that must settle in the nearshore habitat (Jamieson and Phillips 1988). Advection of megalopae from continental shelf to shelf waters and consequently back to a settlement location in the nearshore environment is not completely understood. In the California Current ecosystem, physical oceanographic processes influence the dispersal of early life stages across-shelf and along-shelf (Shanks 2009), but do not predetermine settlement location. For example, while over the continental shelf, larvae will be transported northwards by the Davidson Current, but as they migrate off the shelf, they may enter the California Current (depending on the distance of southward flow from shore) and be transported southward (McDonald and Armstrong 2013). The influence of larval behavior on dispersal is partly known (e.g. Moloney et al. 1994), but is likely secondary to the effects of seasonally predominant ocean currents and wind stress (McDonald and Armstrong 2013). However, preference of megalopae for the upper 25 m of the water column is a behaviour that apparently fosters beneficial transport by advection to the nearshore off Vancouver Island (Jamieson et al. 1989). In the California Current Ecosystem, most megalopae settle on the continental shelf; however, some migrate into estuaries to settle (Miller and Shanks 2004).

Larvae from Dungeness Crab populations within the Strait of Georgia occur in an estuarine circulation pattern, where surface water (<100 m) flows outward through the Strait of Juan de Fuca and is replaced by an influx of saltier water at depth (Jamieson and Phillips 1993). Daily vertical migrations of about 160 m by Strait of Georgia larvae act to effectively retain larvae within the Strait. Preference for out-flowing surface waters by outer coast megalopae inhibit mixing of these populations (Jamieson and Phillips 1993). Information on the movement of crab larvae in other enclosed waters (e.g. inland fjords) and the north flowing Alaska Current is too sparse to provide a description of the dispersal of larvae in those areas.

Sub-adult and adult crabs are generally more sedentary, inhabiting subtidal substrates such as sand or mud often associated with estuaries and shelf areas; sub-adults prefer littoral habitats (Sweetnam et al. 2010). As adults, critical cross-shore movements from deeper to inshore shallow waters occur for mating (Rasmuson 2013).

G.1.3 Predators and prey

Dungeness Crabs are opportunistic, generalist feeders. Across life stages, bivalves appear to be the most important food source (see references in Rasmuson 2013). Larval stages feed on zooplankton and phytoplankton in the water column. Juveniles forage in littoral habitats for clams, mussels, other molluscs, small fish, shrimp and other crab species. Adults prey upon bivalves, crustaceans, worms and fish.

As prey, Dungeness Crab are a resource for many species (Reilly 1983). Planktonic stages and megalopae are eaten by many fish species, whales and other predators (DFO 2013e). Juvenile stages are preyed upon by demersal fishes, as well as birds (Butler 1954). Adults are food for many fish species including Cabezon, Wolf Eel, Pacific Halibut, rockfish, dogfish, sculpin, sturgeon, and other crabs (DFO 2013e).

G.1.4 Recruitment

Since larvae originate over large areas, recruitment is difficult to predict in Dungeness Crab populations. Significant fluctuations on a yearly basis with periods of high and low abundance in metapopulations across the species distribution are affected by differences in hydrography and ecology of enclosed, open, inshore or offshore areas. Potential impacts on recruitment in the California Current Ecosystem were compiled by McDonald and Armstrong (2013) and include elevated temperatures (Wild et al. 1983), nemertean worm predation on incubating eggs (Wickham 1979), salmon predation on larvae (Thomas 1985), and various cyclic phenomena (cannibalism, upwelling, wind stress, geostrophic flow, fishing effort; see reviews by Botsford et al. 1989, Jamieson et al. 1989, McConnaughey et al. 1994, Orensanz et al. 1998). Along the North Coast, long-term stability in abundance may result from the retention of larvae in an important current gyre (Fig. 2; Crawford and Jamieson 1996) and recruitment to adjacent fishery-supporting bottom habitat.

There is general agreement that recruitment variation is impacted by marine environmental conditions, at least in southern production areas (Shanks and Roegner 2007; Shanks et al. 2010). Shanks et al. (2010) reported a negative correlation between recruitment and the Pacific Decadal Oscillation index. They suggest that enhanced southward transport in the California Current during negative PDO years (i.e. cool years) may be the cause of the increased recruitment in US waters. Additionally, there appears to be a positive correlation between recruitment and the amount of upwelling that occurs along the Oregon-Washington coast following the spring transition (Shanks 2013).

Off the southern continental shelf, survival is reported to be highest in more complex intertidal habitats such as eelgrass and oyster shell (Armstrong et al. 2010). Influenced by hydrodynamics and circulation, recruitment in fjord systems in Alaska has shown both regional (>300 km) and small scale (2–6 km) variations among locations (Herter and Eckert 2008). Additional research is needed to understand the movements and/or retention of larvae in enclosed basins, including the Strait of Georgia.

G.2 THE FISHERY

G.2.1 Management

Dungeness Crab is harvested coastwide in First Nation food, social, ceremonial fisheries as well as recreational and commercial fisheries. The first commercial landings along the Pacific coast were recorded in 1885 (Butler 1954). Because of fluctuations in populations, the crab fishery is not managed to a total allowable catch (TAC). The commercial fishery is managed using a minimum harvestable size limit, limited commercial licensing, area licensing, trap limits, soak limits, sex restrictions, soft-shell restrictions, and gear restrictions. Stock management has focused on protecting the breeding component of the population - only hard-shell males about 4+

years old (155 mm carapace width, notch-to-notch) are legal in the commercial fishery. Females cannot be harvested but may suffer fishery effects nevertheless (DFO 2013e).

Traps must comply with regulations such as mesh size, type of line, biodegradable escape mechanisms such as rot cord, size, buoys and labelling. Trap limits are specific to the crab management area and vessel size. Haul restrictions are also specific to the crab management area as well as time of year and time of day (DFO 2013e). The fishery is also managed through opening restrictions. In general, it is open year round; however there are restrictions on certain areas depending on the season, protected areas or other restrictions (DFO 2013e). The commercial fishery allots 221 commercial (R) or communal commercial (FR) single vessel licences per year. These are distributed over seven management areas coast wide (DFO 2013e).

The minimum size limit and non-retention of females applies also to First Nations and recreational crab fishers. First Nations can fish for crabs using communal licences for food, social and ceremonial purposes. Nations fishing effort for an FSC domestic purpose has not been limited by catch quantity, except in those Nations where the Council or fisheries program has established their own catch limits for band members, or where allocated under treaty. The number of First Nations harvesters is unknown.

All recreational fishing for crab requires a BC Tidal Waters Sport Fishing licence and fishing limitations include trap and bag limits. The recreational fishery is an open entry fishery open all year round in most areas. Management measures include female non retention, size limits, specific buoy and trap regulations, and area specific daily and possession limits. There are also additional regulations within select areas.

G.2.2 Stock assessment

Individual Dungeness Crab populations are sustained by larvae originating over a large geographical area resulting in a wide range of potential donors to the larval pool at any location. Consequently, no stock assessment model is applied to this species because a stock/recruitment relationship is difficult to demonstrate. To monitor this fishery, biological data are collected by DFO, various Service Providers, the Area A Crab Association and several First Nations groups across the species distribution with special focus on important fishing areas. DFO has been conducting research surveys using standardized traps on the Fraser River Delta (Areas I and J) since the 1990s in order to better understand this population before and after the fishery takes place (Fig. G1; DFO 2013e). During these surveys, the sampling protocol collects biological data such as sex, shell condition, injuries, and size as well as catch per unit effort (CPUE) (DFO 2013e). Service providers collect crab biological data from commercial vessels during the fishing season and harvests are reported by commercial fishers in log books (DFO 2013e). The Area A Crab Association conducts its own soft shell monitoring program to determine the timing of the male moult. Certain First Nations interested in crab resources in their traditional territories conduct their own biological sampling programs in collaboration with DFO.

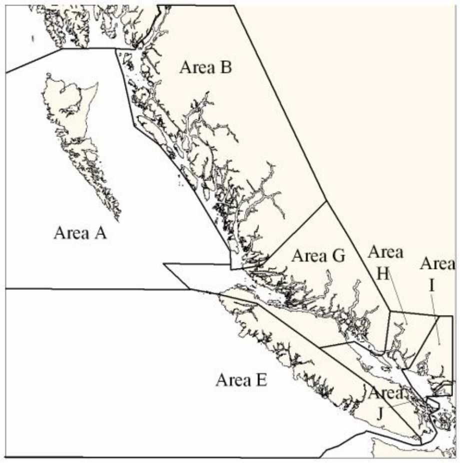


Figure G1. Dungeness Crab management areas on the Pacific coast of Canada.

G.2.3 Catch: Canadian removals

Dungeness Crab is commercially exploited throughout its distribution (Fig. G2). Most exploitation in the US occurs from winter through spring, while in Canada, it is during the spring and summer. Populations harvested off California, Oregon and Washington regularly cycle in abundance (Johnson et al. 1986). The North Coast (mainly Area A) generally contributes the largest proportion of the catch in BC (Fig. G2; G3).

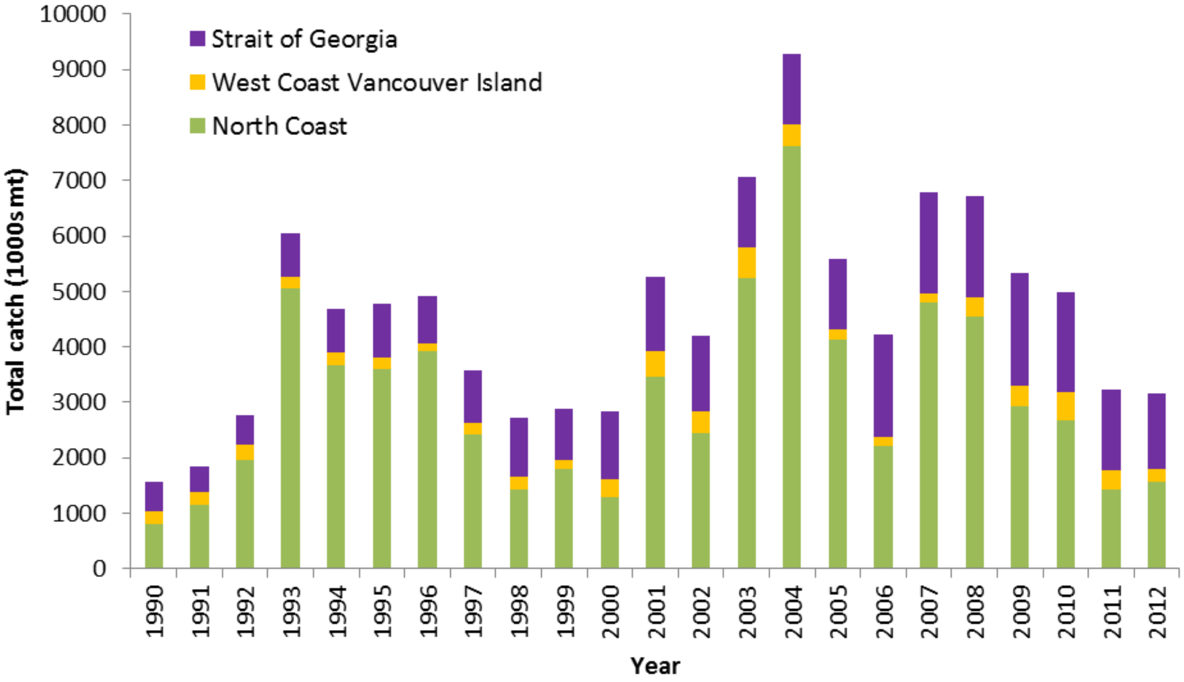
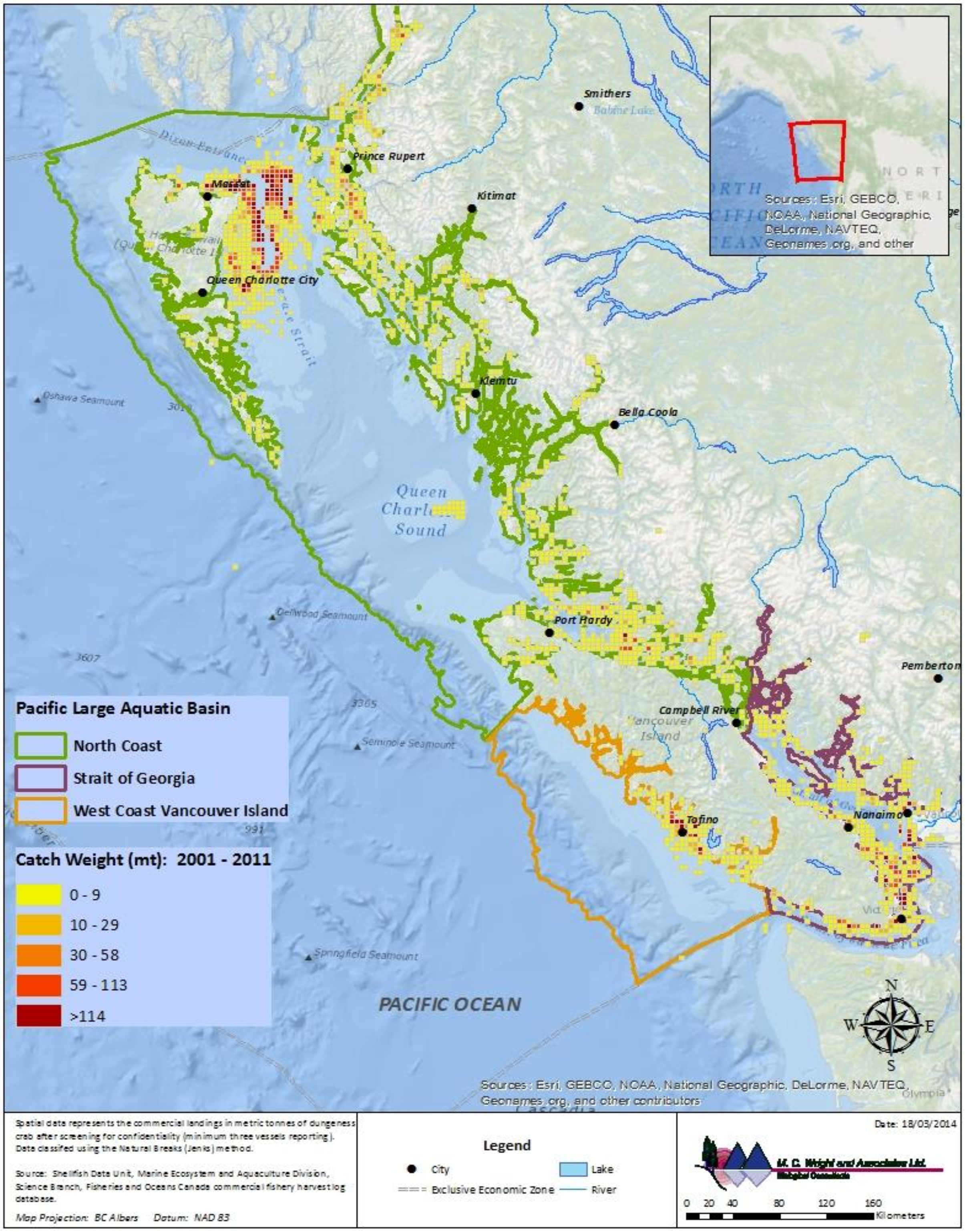


Figure G2. Total catch (mt) of Dungeness Crab (1990-2012) in Strait of Georgia, WCVI and North Coast sub-basins.

The landed value of the commercial crab harvest in BC was 32.5 million dollars in 2011 (BC 2012). In 2011, Dungeness Crab had the third highest landed value of shellfish; Geoduck clam had the highest landed value at 41.3 million dollars, and prawns were second at 40 million dollars. To achieve this landed value, the Dungeness Crab fishery (2011: 5000 mt) requires about twice the harvest as prawns (2800 mt) and three times that of Geoduck (1600 mt).

Recreational fishing for Dungeness Crab is significant in BC. According to DFO (2012a), in 2005, tidal water anglers in BC harvested approximately 363 mt of crab which was more than half the total recreational shellfish harvest in BC. Further, interest in shellfish has increased, with 18% of resident anglers indicating crabs as preferred species (DFO 2012a). The same survey shows that fishing days spent on recreational shellfish harvesting increased by 13% from 2005 to 2010.The spatial distribution of this activity is not known, but presumably the majority occurs close to major population centres.

There is little catch and effort reporting for First Nations FSC crab fisheries and as a result, the Department has limited information upon which to assess the fishery.



Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

Spatial data represents the commercial landings in metric tonnes of dungeness crab after screening for confidentiality (minimum three vessels reporting). Data classifed using the Natural Breaks (Jenks) method.

Source: Shellfish Data Unit, Marine Ecosystem and Aquaculture Division, Science Branch, Fisheries and Oceans Canada commercial fishery harvest log database.

Map Projection: BC Albers Datum: NAD 83

Date: 18/03/2014

Figure G3. Distribution and cumulative catch of Dungeness Crab in Pacific LAB, 2001-2011. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

G.3 CLIMATE CHANGE AND DUNGENESS CRAB

The plasticity of current populations resulting from adaptation to living in variable, shallow, nearshore areas may make Dungeness Crab relatively resilient to a changing climate. However, several important considerations on the effects of habitat alteration and loss associated with climate change may be important for the Canadian portion of its distribution. A summary of the main pathways of effects of aquatic climate projections on crab life stages across Pacific LAB sub-basins is presented in Table G1.

G.3.1 Abundance

Armstrong et al. (2010) stated that the most significant climate-related bottom-up processes affecting crab populations correspond to the food quality and quantity for pelagic larval stages. Variation in the productivity of offshore waters influences abundance of planktonic prey available in environments where early life stages are distributed and settle. These early life stages lack mechanisms to avoid unproductive waters because their distribution during that time is determined mainly by currents, leaving populations vulnerable to variability in ocean conditions.

Strong effects on larval survival and subsequent numbers of juvenile crab result from variability in ocean conditions. High winter sea surface temperature (SST) associated with El Niño negatively affect abundance of Dungeness Crab larvae (Botsford 2001). Sensitivity of planktonic larval stages is also relatively high because of temperature effects on egg hatching success (Wild 1983; Moloney et al. 1994). Unfavourable current patterns have also been correlated with high SST (Shanks and Roegner 2007). Therefore, it is suspected that if the future climate resembles conditions associated with climate modes such as El Niño, then conditions for larval Dungeness Crab may be of lower quality. Shanks (2013) suggested that improved Dungeness Crab recruitment along the West Coast of the USA is correlated to the negative PDO phase (cool). Given that greater warming is projected for all ocean waters along the Pacific LAB coast (Christian and Foreman 2013), the benefits of cooler years experienced by crab populations may be dampened or become irrelevant should their frequency diminish. In interior/coastal waters, populations are adapted to different climatology and may be more able to cope with warming.

Whether a ubiquitous 3^{0}C projected increase in sea surface temperature along the BC coast (Christian and Foreman 2013) is sufficient to alter the determinants of crab survival is not known. The cumulative response to several factors may surmount any direct effects of an altered temperature regime. For older life stages, increased water temperature may affect critical energetic processes including relationships among of prey consumption, prey assimilation and growth (Holsman et al. 2003). Ecological changes that impact growth of this species, a particularly important prey item, may cascade through local food webs. For example, increased prey consumption needed to correspond to increases in temperature-facilitated growth may decrease carrying capacity of crabs in affected habitats (i.e. shallower areas such as estuaries; McDonald and Armstrong 2013).

Ocean acidification has been identified as a significant threat to crustaceans as it is correlated with an inability to produce calcareous structures, thus inhibiting proper development (Feely et al. 2004). However, while preliminary results of ongoing studies in Washington state suggest some deleterious effects of acidification on larvae (McDonald and Armstrong 2013), adult

Dungeness Crab are known to have a greater capacity to regulate extracellular pH (Pane and Barry 2007). Other calcifying organisms, (i.e. oysters), whose shells provide important habitat to juvenile Dungeness Crab may be more sensitive to changes in ocean pH. Reduced calcification of oyster shells with increasing *p*CO2 (Gazeau et al. 2007) will likely negatively affect oyster contributions to inshore habitat structure. Already, negative impacts of acidic waters include recruitment failures of oysters in Pacific coast estuaries that overlap with areas considered to be important nursery areas for Dungeness Crab (Gunderson et al. 1990). Other impacts of decreased pH in marine areas are uncertain, and almost nothing is known about cumulative impacts of synergistic/antagonistic climate drivers.

G.3.2 Distribution

Environmental forcing plays an important role in the distribution of early life stages of Dungeness Crab. Distribution of larvae to offshore foraging areas relies on upwelling that drive surface waters away from shore (Jamieson and Phillips 1993). Changes in hydrographic conditions that act on the extended larval duration of this species may disrupt larval transport across the continental shelf and affect access to settlement habitats. Projected increased upwelling (Foreman et al. 2013) overlapping during egg hatch may inhibit shallow water settlement if early life stagers are moved too far from shore. The influence of freshwater systems can also impact Dungeness Crab in nearshore marine environments where strong river plume dynamics of larger freshwater sources, such as the Fraser, Skeena and Nass rivers, have the potential to disrupt the essential shoreward transport of zoeae and megalopae to settlement habitat.

Estuaries are critical nursery areas for juvenile Dungeness Crab, and provide critical forage, rearing habitat and refuge grounds for subadult crab (Gunderson et al. 1990; Rasmuson 2013). Rising sea levels and increased seasonal freshwater discharge may change the availability and quality of intertidal habitat in some estuaries (Bornhold and Thomson 2013). Change to intertidal habitat due to sea level rise in some Strait of Georgia and North Coast areas (Bornhold and Thomson 2013) would alter conditions of these refuges and possibly result in habitat loss. Typically used by Dungeness Crabs for foraging at adult and sub-adult life stage, changes to nearshore habitat may impel populations to inhabit greater water depths (McConnaughey and Armstrong 1995) with unknown consequences on survival. Changes in salinity profile linked to sea surface freshening may also have dramatic consequences for overall estuarine production (Holsman et al. 2003) and crab recruitment (Armstrong et al. 2003).

Distribution of adult crab is influenced by quality and quantity of benthic habitat. At depth, access to habitat may be further limited in places where hypoxic conditions establish regularly or become permanent bottom because crabs likely avoid strongly hypoxic conditions (Bernatis et al. 2007; Curtis and McGaw 2008). Where hypoxia was experienced for longer duration off the coast of Oregon, there was higher crab mortality and/or migration away from the impacted area (Chan et al. 2008). Avoidance of hypoxic habitat by crab is likely to affect catch if hypoxic conditions overlap with traditionally abundant areas (Keller et al. 2010). In BC, the majority of the harvest occurs in North Coast waters (Fig. 2) where ocean conditions at depth are currently not monitored sufficiently to understand trends in conditions of bottom habitat.

Intensity and seasonality of streamflow of important rivers may be affected in Pacific LAB (Morrison et al. 2013). Larvae originating in estuarine systems are typically advected by buoyant freshwater river plumes (e.g. Reilly 1983) so changes to the timing and magnitude of these plumes may areas affect cross-shelf patterns of distribution.

G.3.3 Phenology

Delayed upwelling/spring transition may translate to increased mortality of crab larvae (Moloney et al. 1994; Shanks and Roegner 2007) and continued northward movement of southern generated larval stages as the presence of the Davidson current is prolonged along the coast (McDonald and Armstrong 2013; Shanks 2013). In contrast, projected increased intensity of upwelling off Vancouver Island (Foreman et al. 2013) may encumber survival and transport of larval life stages along the coast.

Table G1. Summary of the potential impacts, vulnerabilities and opportunities from climate change for Dungeness Crab.

Physical parameter	Recruitment and abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Eggs incubate faster in warmer water but with higher mortality	No information	Molt timing is impacted by warmer water temperatures.
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Increased ocean acidification may lead to an inability to produce calcareous structures; Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	No information	Hydrographic processes drive the dispersal/retention of pelagic larvae.	Larval success is affected by spring transition time which is influenced by currents
Stratification	Potential effects on food availability for early life stages.	No information	No information
Upwelling winds	No information	No information	No information
Dissolved oxygen	Potential effects on survival.	Potential effects on distribution.	No information

G.4 ECOSYSTEM INTERACTIONS

Dungeness Crab occupy ecological niches in both marine and estuarine waters. The compounding effects of a changing climate on an individual species cannot be fully appreciated without understanding the ecosystem level interactions including both the physical as well as biological parameters.

There are concerns about sea otter predation on Dungeness Crabs now that otters have been successfully re-introduced to the west coast of Vancouver Island (DFO 2013e).

G.5 ADDITIONAL STRESSORS

For Dungeness Crab, as with many other commercially fished species, stressors may include: overfishing; pathogens; pollution and; habitat loss or destruction. Any combination of these potential stressors may range in severity from short-term to long-term stress of an individual or population. Short-term stress events may for example affect the immune system and pathogen susceptibility, behavioural changes such as predator avoidance or the ability to capture prey. Consequences of long-term stress to an individual may include for example, mortality, morbidity, disruption of reproductive capacity, migratory behaviour etc.

The effects of pot fishing on crap populations in BC are unknown. Current practices are regulated to ensure that only males large enough to have spawned at least once are taken out of the fishery. Effects of unreported catch and bycatch of female crabs are not known. It has been stated that fishing pressure does not affect population size structure (Armstrong et al. 2010). However, the cumulative effects of fishing practices in a changing environment are unknown.

There are a number of pathogens to which Dungeness Crab are susceptible which have been identified by Bower (2010). None currently represent significant threats to crab populations.

G.6 GAPS AND UNCERTAINTY

Although many Dungeness Crab settle on the continental shelf (within 10–15 km of shore), most available information is on the settlement and biology of juvenile crabs inside estuaries. Further, this species is abundant in both open ocean and inland fjord habitats, yet much of our understanding of this species focuses on the offshore component of the species distribution.

It is not known if undersized, female and soft-shell crab are being harvested illegally or succumbing to incidental mortality due to intensive fishing practices (DFO 2013e). Because catch is the only indication of abundance in the crab fishery, poor catch reporting is a significant concern. As of 2006, electronic monitoring (EM) or 100% at-sea observer coverage became a requirement (DFO 2013e). These efforts help gather data on legal sized animals however a data gap remains for animals which are returned. Beyond the data collection issue, the effects of excessive handling and high discard rates in areas where fishing intensity is high remain a concern on a localized level (DFO 2013e). In addition to these issues with data collection, there is little data collection on recreational and First Nations catches.

It has also been identified that improved understanding of moulting, growth, recruitment and movements are necessary to better understand the impacts of fishing (DFO 2013e), not excluding the impacts and interactions of climate change.

H. Spot Prawn
(*Pandalus platyceros*)

Karen Hunter and Joy Wade

KEY POINTS

- Inshore Spot Prawn populations that are subject to the majority of fishing pressure in BC have shown stability in recruitment over time.
- Impacts of climate drivers on survival of different life history stages are unknown. This may be particularly important because life stages are characterized by sex, as well as size and age in this hermaphroditic species.
- Changes in water chemistry (oxygen, pH) associated with increased water temperature and CO_2 absorption of the ocean are likely the largest unknowns and largest risks facing Spot Prawn populations in BC coastal waters in a changing climate.

H.1 BIOLOGICAL CHARACTERISTICS

H.1.1 Life cycle, age and growth

Spot Prawn is the largest of the north eastern Pacific pandalid shrimp species (Butler 1980). Pandalid shrimp have a very plastic life history, and have been shown to have highly variable size and age at maturity and, at sex change (Charnov and Anderson 1989; Bergstroem 2000). Animals are short-lived with life span generally presumed to be about 4 to 5 years (Butler 1970). However, more recent tagging studies suggest a longer life span of up to 7 years (Sunada 1984, Kimker et al. 1996). Pandalid shrimp first mature as males then undergo a sexual transformation to become female. This life history is referred to as protandric hermaphroditism.

The only reliable estimate of Spot Prawn fecundity was reported by Butler (1970). Fecundity varies with female size, ranging from 1400 to 5000 eggs at first spawning and declining to 1000 eggs the second spawning (Lowry 2007). Females carry the developing eggs under their bodies for 5-6 months. Spawning occurs in the fall or early winter (September-October) in deeper water (Butler 1980). Each animal spawns first as a male (18-30 months old), then as a female. Sex reversal occurs during winter and spring when prawns are between 2.5 and 3.5 years (33-38 mm CL). The prawns mature as females in time to mate for the first time in the late summer. Mature females are 3.5 years and older (>42 mm; Butler 1980).

It is believed that females are unlikely to survive to a second spawning event (DFO 2013f). Butler (1964) states “following hatching of eggs in the spring, practically all females evidently leave these (rocky) grounds, and the conclusion is that most die”. This assertion has been widely interpreted as a definition of maximum age as no more than 4 years, implying that Spot Prawns only breed once as females during their lives and led to their being treated as a semelparous species in management in British Columbia. However, Rensel and Prentice (1977) observed multiple breeding events for prawns in captivity. Further evidence of iteroparity is discussed in Lowry (2007).

Eggs hatch and larvae are released into the water column in March-April (Butler 1980). Larvae remain free swimming for approximately 3 months while they grow and develop. The amount of time the larvae spend as plankton before settlement has not yet been accurately determined in the wild.

Settlement of larvae out of the plankton occurs in shallow water. The juveniles remain in this shallow water habitat until shortly before they mature. In male form, juvenile prawns follow a well established pattern of migration from shallow nursery areas into deeper water (Butler 1970; Sunada 1984). Marliave and Roth (1995) observed post-larval prawns in shallow (10-15m) water Agarum kelp beds in May and June in British Columbia; similar observations are reported at shallow depth for juveniles (Barr 1973; Sunada 1984). It is not known if larval prawns actively swim to seek out settlement habitat or if their movement from deep to shallow water is driven by wind and tides. It other marine taxa, ecological, behavioural and physiological data are being combined to build a picture of pre-settlement in which larvae/early life stages are much more actively involved in habitat selection than has previously been assumed (Montgomery et al. 2001).

Growth in crustaceans is limited by molting. Growth rate depends on the frequency of molting and the amount of growth at each molt. In Spot Prawns, there is a wide variation in growth rates across the range with size at each life stage reflecting variations in growth rate (Koeller 2006). Growth rate in other Pandalid shrimp has been shown to be closely linked to water temperature (Hansen and Aschan 2000; Wieland 2004), so a latitudinal gradient in growth rates can be expected. Spot Prawn growth rates appear to be faster in more temperate environments (Butler 1980). In the northern part of the range, each life stage may be reached a year or more later than in more southerly areas (Lowry 2007).

H.1.2 Distribution, habitat and environmental preferences

The species ranges in the North East Pacific from central Baja California to the Aleutian Islands. The northern limit of the Spot Prawn range is not currently confirmed (Lowry 2007). However, the northern limit for fisheries has moved south in the recent past, and the range of the species may also have contracted over the last few decades (Lowry 2007).

The species has a wide bathymetric range (Butler 1970) with distribution in the water column being a function of developmental stage as well as temperature and salinity. Immature shrimp can tolerate greater ranges of salinity and temperature and are found shallower than adults (Lowry 2007). Adult Spot Prawns are typically found much deeper, between 198 and 234 m. However, they are known to use the intertidal to nearly 500 m depth (Lowry 2007). As juveniles, Spot Prawns occupy shallow inshore areas less than 90 m in depth, migrating offshore as they mature (DFO 2013f). The length of the time in shallow water and the depth of the adult grounds vary depending on latitude and habitat availability. Free-swimming larvae may be affected by tides and currents (Boutillier and Bond 1999).

Spot Prawns occur in both protected waters and in open coasts, and there appear to be some ecological differences between these two types of populations (Lowry 2007). Open ocean stocks in Alaska and BC have not been extensively explored. Adults of open coast populations are often found around the shelf break, or at the heads of submarine canyons. They tend to be deeper than protected water populations at similar latitude, and there is a similar change in depth with latitude as seen in inshore populations. In protected waters they are found in channels, sounds and fjords on rocky or hard substrates including reefs, coral or glass-sponge beds and the edges of marine canyons (Butler 1980; Lowry 2007). Schlining (1999) showed that prawns were not usually associated with barren sediments, but appeared to actively seek out habitats that are more complex, including habitat provided by drifting macroalgae (Britton-Simmons et al. 2012).

In the northern part of the range, mature adult Spot Prawns are most abundant between 45-140 m, with the depth range increasing to the south, to 100–165 m in southern British Columbia and Washington. Adults occurring in protected waters appear to have a diel migratory pattern moving up and down in the water column (Butler 1980; Lowry 2007). Indicators such as parasite load and some tagging studies suggest that once the animal settles on the bottom, little horizontal movement occurs (Bower and Boutillier 1990; Bower et al. 1996; Kimker et al. 1996; Boutillier and Bond 1999).

Information regarding population structure for this species is lacking. One hypothesis is that the sedentary behaviour of adults creates many small populations (Kimker et al. 1996; Boutillier and Bond 2000). Whether these populations are connected by the dispersal of larvae, or if each population is dependent on its own larval production, is unknown. Isolated patches of Spot Prawns may result from single recruitment events, which live out their entire lives in one area without migrating to nearby habitat which is apparently suitable (Boutillier and Bond 1999).

H.1.3 Predators and prey

Spot Prawn are generalist scavengers, eating a wide array of dead or moribund organic material including worms, algae, sponges, small molluscs and other shrimp. Recent work on abundance of Spot Prawns in concentrations macroalgae drift suggests a trophic connection that occurs because the prawns aggregate to deeper habitats where macrophyte detritus is concentrated by currents (Britton-Simmons et al. 2012).

Natural predators of settled Spot Prawn are octopus and fish such as Pacific Halibut, Walleye Pollock, Lingcod, Pacific Spiny Dogfish, Pacific cod, flounders, rockfish, and skates (Bergstrom 2000). The effect of predation and predator abundance on the abundance of other related pandalid species suggests Spot Prawn may be subject to similar consequences. For example, Pacific Hake impacted the stock of pink shrimp off Oregon (Hannah 1995). Mortality from predation is believed to be high during prawn larval and juvenile stages but is reduced after animals settle out of the water column (Wargo et al. 2013).

H.1.4 Recruitment

Little information is available on recruitment in Spot Prawn stocks. Understanding the processes, factors and relationships between year classes/recruitment and populations (or meta-populations) has proven difficult. Success of Spot Prawn reproduction and recruitment are believed to be affected by many factors including reduction in food supply, increased levels of suspended organic or mineral materials, alterations to intertidal areas or benthic habitat, variation in preferred water temperatures, pH, and/or dissolved oxygen concentrations (ADFG 1985).

Spot Prawn fecundity is naturally very low. The species reproductive potential to create large year classes is therefore limited. This is particularly significant for management because the fishery tends to target larger animals; i.e. females. Spot Prawn can also transition to become female at an earlier age and therefore smaller size. Smaller female size correlates with reduced fecundity (eggs per female) and reduced stock productivity. Availability of quality habitat to juvenile Spot Prawn may play a significant role in overall survival and population abundance (Lowry 2007).

Barr (1973) reported a six fold difference between years in the abundance of juveniles in Auke Bay, Alaska. Larson (2001) reported strong recruitment of Spot Prawns in California associated with the 1997 El Niño event, although this was not noted in other areas. Boutillier and Bond (2000) fitted a Ricker spawner-recruit relationship to data from an experimentally monitored population of Spot Prawns in Howe Sound, BC. This suggested that there was a density dependent mechanism operating in this area, which resulted in slightly lower recruitment at high spawning stock levels. Howe Sound is a semi-enclosed fjord, so the dynamics that operate may be different in more open areas (Lowry 2007).

H.2 THE FISHERY

H.2.1 Management

Current assessment and management frameworks in BC do not rely on estimates of abundance for prawns. Rather, populations are assessed and managed to ensure that a sufficient number of female Spot Prawn escape the commercial fishery and survive to reproduce. Assessment and management occur at a small spatial scale, on an area by area basis. For each area, a spawner index has been determined, which is an index that represents the minimum number of spawning (i.e. reproductive) females needed to maintain healthy populations. The number of spawners is measured throughout the fishing season by the commercial catch rate of only those females that will contribute to the spawning population in that year. When the average catch rate of potential female spawners approaches the target spawner index in a given area, the fishery in that area is closed for the remainder of the year (DFO 2013f). Fishery-independent surveys are also conducted in the major fishing areas in the fall, prior to the winter spawning season to ensure spawner indexes are being met. Spawner indexes have been met for most areas in most years (DFO 2013f). This monitoring strategy does not allow for estimates of total abundance of Spot Prawn. However, since the target reproductive goals are being met the fishery is considered to be sustainable. Additionally, this fishery has been operating since the late 1970s under this management strategy (DFO 2013f). Commercial landings are considered a reasonable proxy of overall stock abundance.

The BC Spot Prawn fishery is presently managed to meet two biological objectives: 1) prevention of growth overfishing; and 2) prevention of recruitment overfishing. Overfishing is controlled through legal size limits, trap escapement modifications, and the timing of season openings. Implementation and refinement of the fixed escapement manages recruitment overfishing. During the fishing season, as commercial fishing efforts reach the monthly fixed escapement, seasonal closures are implemented. Areas remain closed to the commercial fishery until the next year in order to protect the remaining gravid females from fishing mortality to the end of the egg hatching period, and thus take account of recruitment variation. In order to reduce overcapitalization of the fishery, a limited-entry system was established in 1990.

The commercial fishery currently has 250 available licences. Fifty-five of these are communal licences for First Nations. Licences are regulated through the use of seasonal closures, area closures, gear limits and marking requirements, trap mesh size requirements, size limits, fishing time restrictions and daily single haul limit. It is illegal to retain berried females and fishermen are required to sort their catch on a trap by trap basis to return berried females and undersized prawns to the water. Each licence entitles the holder to fish a maximum of 300 traps on 6 groundlines.

H.2.2 Stock assessment

The fishery is assessed using a fixed escapement model termed the Spawner Index Model (Boutillier and Bond 2000). The SIM is a standardized catch per unit effort model based on ensuring a minimum number of female spawners are available at the time of egg hatch. Growth and mortality parameters for the model are obtained through semi-annual fishery independent surveys conducted in the fall to monitor stock status prior to the onset of spawning. In-season monitoring of catch is also performed on a sub-set of commercial traps by independent observers. On-ground monitors conduct sampling for in-season spawner index estimates as well as gear inspection and rockfish by-catch information.

H.2.3 Catch

Generally under current conditions the productivity of areas for Spot Prawns decreases moving north with the effective limit for commercial fishing being around Yakutat, Alaska. The bulk of commercial landings have come from the Strait of Georgia and North Coast (Figs. H1 and H2); the remainder are caught off West Coast Vancouver Island. Most of the fleet fish the waters inside Vancouver Island, which includes Queen Charlotte Strait, Johnstone Strait, Georgia Strait, and the bordering mainland inlets (Fig. H2). Spot Prawns are landed incidentally in offshore fisheries for black cod, shrimp, and groundfish indicating presence in open areas off the BC coast. However, given the distance, short commercial fishing season, and unknown abundance, the incentive to trap offshore is mainly prohibitive.

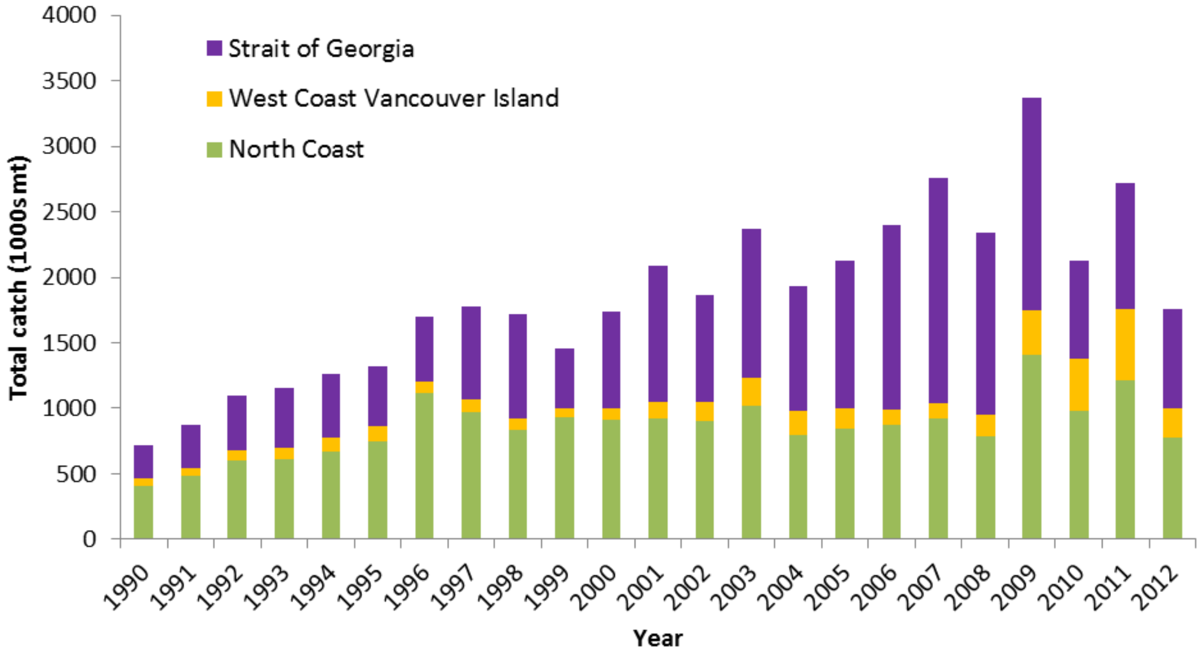
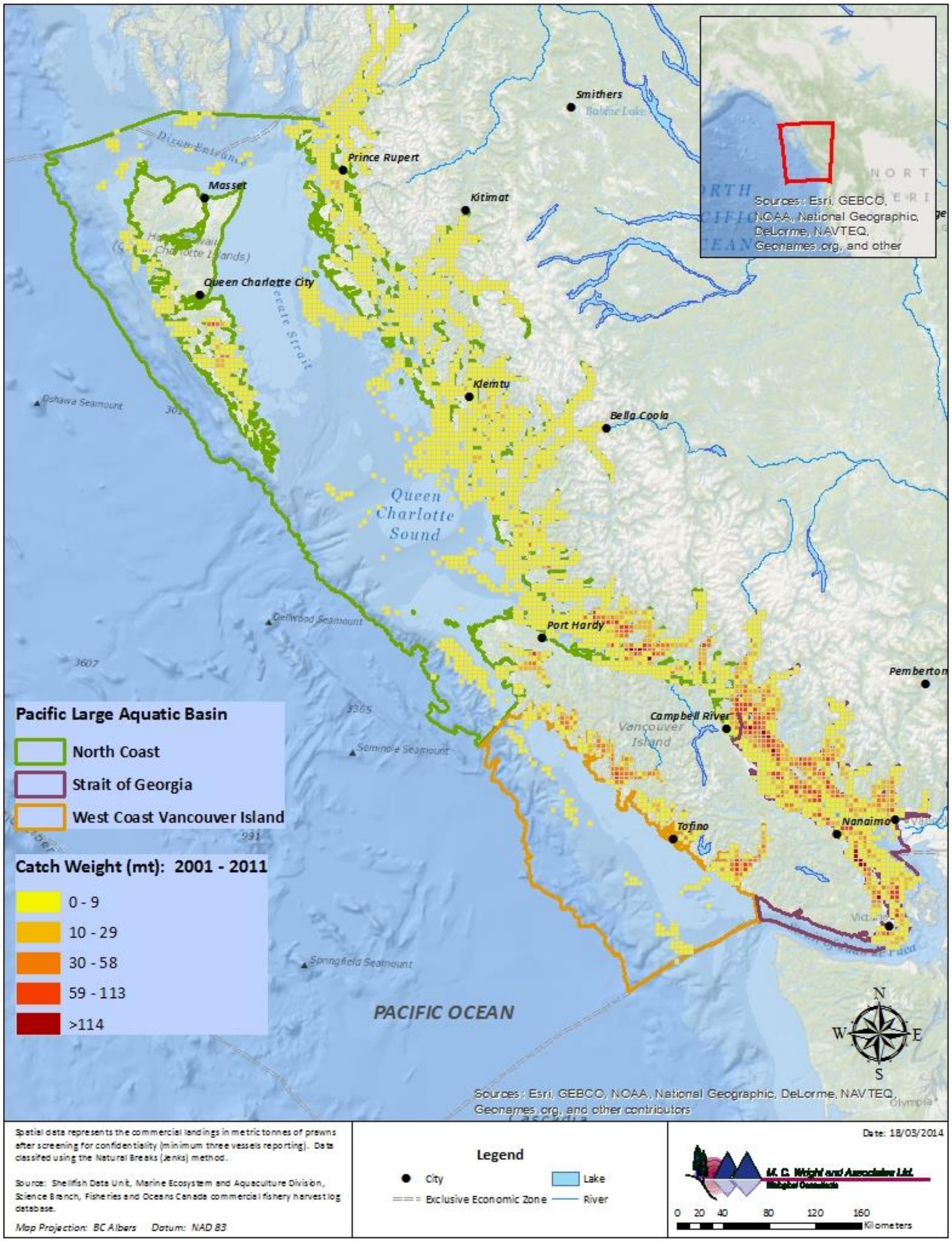


Figure H1. Total catch (mt) of Spot Prawn (1990-2012) in Strait of Georgia, WCVI and North Coast sub-basins.

The Spot Prawn fishery takes place mainly in nearshore areas between 40 and 100m depth. There is an active trap fishery for prawns, *P. platyceros*, and retention in the shrimp trawl fishery is restricted to minor, incidental landings. Over 90% of the catch is prawns, with a small amount of Coonstripe and Humpback Shrimp making up the remainder of the trap fishery harvests. The commercial trap fishery accounts for 98% of Spot Prawn landings.



Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

Spatial data represents the commercial landings in metric tonnes of prawns after screening for confidentiality (minimum three vessels reporting). Data classifed using the Natural Breaks (Jenks) method.

Source: Shellfish Data Unit, Marine Ecosystem and Aquaculture Division, Science Branch, Fisheries and Oceans Canada commercial fishery harvest log database.

Map Projection: BC Albers Datum: NAD 83

Figure H2. Distribution and cumulative catch of the Spot Prawn fishery in Pacific LAB, 2001-2011. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

The commercial trap fishery began in Howe Sound around 1914. In the 1950s trapping began in Kingcome and Knight inlets. There was a large increase in growth of the fishery between 1979 and 1989 after exploratory surveys were conducted to expand harvests in the north and central coast.

Annual landings showed an increasing trend from the development of the fishery to 2009, since then catches have been inconsistent. There was a decrease in catch in 2010 followed by a high catch in 2011 and what is estimated, based on preliminary data, to be the lowest catches since 1999 occurring in 2012. Causal factors in landing fluctuations have not been positively determined. The following factors have been offered as potential explanations for the declines:

- a return to normal levels following higher recruitment levels in recent years;
- surplus stocks in newly fished areas being fished down;
- environmental changes resulting in abnormal water temperatures and reduced levels of plankton;
- low surface-water salinity affecting the 1999 year-class;
- reduced prawn predator (e.g. rockfish and lingcod) population levels in the mid-1990s, and increased abundance of other predators, such as hake, in the late 1990s

Prawn and shrimp fisheries were originally an export market. Commonly more than ¾ of landings are frozen and packaged at sea or on shore and exported to Japan (DFO 2013f). There has been some diversification of the industry and now live and fresh prawns can be found locally. According to the British Columbia Seafood Industry 2011 Year in Review (BC 2012), the landed value of Spot Prawns in 2011 was $40 million, $24 million in 2010 and $33 million in 2009. The value of each of these annual harvests exceeded the landed value of Chinook, Chum, Coho and Pink salmon combined in the same years.

H.2.4 Recreational and First Nations harvests

The Pacific Region prawn and shrimp by trap fisheries include commercial, recreational and First Nations fisheries under communal commercial licences and for food, social and ceremonial purposes. The total catches in First Nations fisheries is not known (DFO 2013f). Though some detail is provided here, readers are directed to the Integrated Fishery Management Plan for Spot Prawn (DFO 2013f) for detailed information on recreational and First Nations harvests for this species.

Anecdotal reports of Spot Prawn fishing are sparse but suggest many anglers set traps while participating in other fisheries. The recreational fishery takes place in near-shore areas in depths of 40 to 100 m mainly within proximity to population centres. Most of the recreational prawn catch comes from the Strait of Georgia (66%) and West Coast Vancouver Island (20%; DFO 2013f). The recreational fishery is open for most of the coast throughout the year. Local winter recreational closures may be implemented on a year by year basis during the spawning cycle (January to March) when female prawn abundance is low in fall. Special measures are in place in three high use recreational fishing areas.

First Nations’ communal licences and harvest documents identify the location where First Nations may fish for food, social and ceremonial harvest. Harvesting has generally taken place in areas fronting or adjacent to reserves. First Nations fishing effort for FSC purposes is currently not limited by catch quantity, except in those Nations where the Council or fisheries program has established their own catch limits for band members, or where allocated under treaty.

The level of Aboriginal harvest is not known. It is believed to be low relative to commercial harvests but increasing. Nine First Nations organizations reported prawn landing in annual reports between 2003 and 2008. In 2011 licence conditions were introduced on commercial vessels to prohibit recreational or FSC catch being on-board during the commercial fishing season. Under consideration are restriction on the FSC including, trap limits, and increased monitoring and reporting.

H.3 CLIMATE CHANGE AND SPOT PRAWN

Inside waters of the Strait of Georgia and North Coast are known to be the most productive areas for Spot Prawn in BC. Known projections of important climate drivers for these sub-basins may affect this species mainly through changes to its abundance at the nearshore.

H.3.1 Abundance

Oceanographic forcing appears important for recruitment of pandalid shrimp in offshore open ocean regions of the eastern Pacific Ocean. Declines in Spot Prawn populations in Alaska are thought to be primarily due to unfavorable ocean conditions (Anderson and Piatt 1999). However, strong year classes of several groundfishes in the late 1970s may have resulted in decreased shrimp abundance through predation and/or competition (PICES 1998). Negative effects on recruitment leading to abundance fluctuations in the offshore fisheries for pink shrimp (*P. jordani*) in Canadian and US waters have been linked to environmental variation (Perry et al. 2000), including ENSO events (Hannah 1993) and ocean decadal-scale oscillations (Anderson 2000). Importantly, stocks in the inshore, protected regions have not experienced the same abundance fluctuations as have the offshore open water stocks (Otto and Jamieson 2001).

It is known that abundance of berried females, growth rates, rates of development, larval production and larval survival of Spot Prawn are influenced by water temperature (Lowry 2007; Amberg et al. 2013). Where temperature reaches beyond the preferred range impacts on adult life stages may include delays in the timing of spawning, reduced numbers of reproducing females (Nunes and Nishiyama 1984), and reduced female size at maturity/lower egg production (Koeller et al. 2006). Similar impacts on reproductive ecology may emerge under more acidic ocean conditions, but these impacts may be less important than temperature (Amberg et al. 2013). Growth and survival of early life stages may be severely compromised should unsuitable water chemistry properties become wide spread.

Hypoxia may impact the abundance of Spot Prawn by altering physiologic requirements and prawn behaviour. To date, direct impacts of low oxygen conditions occurring off the Vancouver Island shelf on offshore populations of Spot Prawn are not known. Some anecdotal evidence in nearshore environments subject to low oxygen stress in summer, i.e. Saanich Inlet, suggests that predation risk from amphipod spp. increases because prawns become sluggish in low oxygen conditions (J. Boutillier, PBS, Nanaimo, pers. comm.).

H.3.2 Distribution

The combined effects of winds, tides and water-mass changes may affect the local spatial distributions of prawn by impacting the density of aggregations across space (Lowry 2007). Changes in use of the water column by shrimp (mediated by habitat conditions) and locally induced exchanges of water, and shrimp, will also impact their distribution.

Changes to water chemistry at the habitat scale would have consequences for the supply of prawn habitat, but it is uncertain if the species latitudinal distribution would be altered.

H.3.3 Phenology

Many invertebrate species have low mobility and are hypothetically less able to adjust their distribution relative to productivity or other conditions affecting growth and/or survival (PICES 1998). Delays in the timing of spawning by Spot Prawn occur at temperatures outside their preferred range (Nunes and Nishiyama 1984). Changes in the timing of spawning and length of spawning events may lead to variations in larval survival of Spot Prawn. For example, in the North Atlantic, Koeller et al. (2009) compared egg hatching times of pink shrimp to phytoplankton blooms derived from satellite images across large spatial and temporal scales. They found that spring phytoplankton blooms were correlated to egg hatching with different populations adapting hatch timing to localized bottom temperatures. Future latitudinal shifts in plankton bloom timing to earlier in the year linked to warmer sea surface temperatures may result in a mismatch in food availability and shrimp hatch (Kruse 2007).

The strength and timing of the spring transition of the eastern Pacific Ocean, i.e. the change between downwelling dominated winter conditions and upwelling dominated summer conditions, is thought to be a major driver of productivity off Canada’s Pacific coast. Late transition has been shown to impact successive recruitment of pink shrimp off Oregon (Hannah 1993). It is hypothesized that mismatch in food availability is at play at this location when the timing of this major seasonal event is altered. The projected increase in the upwelling strength off Vancouver Island could potentially improve productivity so long as the region’s phenological relationships are maintained.

Table H.1. Summary of potential impacts, vulnerabilities and opportunities from climate change for Spot Prawn.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Populations adapt to localized temperatures matched to egg hatch and phytoplankton bloom timing.	No information	Sea surface temperature affects the timing of egg hatch and availability of phytoplankton/zooplankton.
Sea surface salinity	No information	No information	No information
Freshwater discharge	No information	No information	No information
Sea level change	No information	No information	No information
Ocean acidification	Reproduction and recruitment may be negatively impacted by a decrease in pH via impacts on shell development and growth; Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	Stronger currents could affect movements of larval prawn from deep to shallow water, possibly impacting survival.	Onshore movements of larvae to nursery areas in spring may be altered by changes to key coastal currents affecting WCVI and North Coast regions	Ocean currents affect the timing of egg hatch and availability of phytoplankton/zooplankton. Mismatch between larval hatch and plankton abundance may result in poor year classes.
Stratification	No information	No information	No information
Upwelling winds	No information	Increased upwelling will influence offshore advection. Settlement and distribution of juveniles/adults could be impacted if transport to nearshore nurseries is affected.	No information
Dissolved oxygen	Possible increased rate of predation from hypoxia tolerant animals	Altered habitat distribution; limited nearshore nursery areas	No information

H.4 ECOSYSTEM LEVEL INTERACTIONS

Species-specific ecosystem linkages are difficult to identify owing to the multivariate nature of ecosystem function. However, prawn larvae are likely prey items for other pelagic and planktonic marine organisms as reported on the northern shrimp (Parsons 2005). Once prawns have settled to the bottom and have found suitable protective habitat, mortality is likely reduced. At this stage they are preyed upon by bottom fish and octopus (Bergstrom, 2000). Long-lived predators that can endure climate perturbations that may have longer term ecological effects on more sessile prey organisms such as Spot Prawn (PICES 1998).

Fishing effects on benthic communities have been reviewed (DFO 2010e). It was determined that gear can pose an entanglement issue for sea turtles, sharks and whales. Trawling effects on habitat structures such as hexactinellid sponge reefs could reduce the carrying capacity of an area for Spot Prawns (and other species), and may take decades to recover. Overfishing has also severely reduced populations of rockfish, likely a major predator of the Spot Prawn. As rockfish stocks rebuild, they could have substantial impacts on Spot Prawn fisheries.

H.5 ADDITIONAL STRESSORS

There are several potential stressors associated with fishing activity including bycatch of Spot Prawn in trawl fisheries, inaccurate measurements the size of prawns or not measuring at all and possible impacts of pot hauling on benthic habitat structure.

The survival rates for released undersize and berried prawns are not known. There is concern about releasing into the warmer surface waters and to areas with lower salinity.

There is a parasitic barnacle (*Sylon* sp.) which is present in prawns in northern waters. This parasite is currently not found in southern prawn populations. Barnacle larvae may be discharged through transport water thereby introducing this stressor to southern areas.

H.6 GAPS AND UNCERTAINTY

Vulnerability of inshore vs offshore stocks presents are relatively large gap in knowledge for this species.

The life history of Spot Prawns is not particularly well understood. There are gaps in the details of early life history, most notably the length of the planktonic larval phase. There is also disagreement in the published literature about the maximum age which the species reaches, how fast they grow, and whether they are iterparous or semelparous. Knowledge gaps still exist, especially regarding location, form and function of nursery areas and other principal factors controlling recruitment. There is also little understanding of prawn ecosystem function.

Although important commercial and recreational fisheries for this species are found throughout its range, it has been comparatively little studied, and management is somewhat ad hoc in many jurisdictions. Many of the fisheries have a fairly short history, and gaps in knowledge of the Spot Prawn’s basic biology complicate management efforts.

Fisheries impacts as they relate to prawns and prawn harvest are not known. There is limited information on the amount of prawn being harvested by the recreational fishery.

sustainablesushi.

I. Geoduck Clam
(*Panopea generosa*)

Karen Hunter and Joy Wade

KEY POINTS

- Inter-regional coherence in recruitment and growth of Geoduck Clam (henceforth Geoduck) has been correlated to elevated sea-surface temperature and positive phases of the Pacific Decadal Oscillation, respectively.
- Because of their longevity, Geoduck shells provide a record of climate; Geoduck shell chronologies have been annually resolved and relate to local to regional-scale sea surface temperature.
- Geoduck have shells composed of aragonite which may make them sensitive to changing ocean chemistry.

I.1 BIOLOGICAL CHARACTERISTICS

I.1.1 Life cycle, age and growth

Geoduck are among the longest lived animals in the world (oldest recorded age is 168 years; Bureau et al. 2002). This species is also among the largest clams. Growth continues in the first 10 to 15 years and generally reaches slows by age 20 (Bureau et al. 2002). Sexual maturity can occur as early as 2 years of age (Campbell and Ming 2003). Males become sexually mature at younger ages than females (Goodwin and Pease 1989). Some Geoduck can be large enough to enter the fishery at age 4 and are generally fully recruited by age 6 to 12 (Harbo et al. 1983).

While remaining buried into over a meter of substrate, broadcast spawning of eggs and sperm typically occurs from June to July. During each event, 7 to 10 million eggs are released into the water to be fertilized externally. Laboratory studies have reported that spawning in captivity was triggered by a slow increase in water temperature (initial temp. 9-12^{o}C) and the addition of culture phytoplankton to the spawning tank (Goodwin and Pease 1989). Fertilized eggs develop in the water column as they are negatively buoyant in sea water at 14^{o}C and 29 ppt (Goodwin and Pease 1989). Developing larvae drift in the current; drift zones for Geoduck are large (Brickey et al. 2012). The long pelagic larval period potentially results in distribution over large distances from the spawning area and thus a poor relationship between spawning stock in a given bed and subsequent recruitment.

Settlement occurs 40 to 50 days post fertilization, post-larvae settle on the bottom (Goodwin et al. 1979). Postlarvae settle and move on the seafloor surface for several weeks until metamorphosis and the start of suspension feeding (King 1986). There is some indication that metamorphosis is triggered by a chemical cue produced by several species of polychaetes worm commonly found in areas where Geoduck adults are abundant, suggesting that there is some selection of suitable habitat by metamorphosing animals (Cooper and Pease 1988). Development of the siphon occurs concurrently as the animal burrows deeper into the sediment. Only the tip of the siphon is exposed at the surface for feeding and oxygenation. Eventually, Geoduck cannot move laterally in the sediment, only vertically by extending or retracting the siphon. The end of the burrowing stage is marked by the beginning of the reproductive phase which begins as early 2 years of age.

Geoduck are slow-growing after an initial phase of fast growth during the first 10 years of life, and growth rate and maximum size varies along environmental gradients and between geographic regions (Hoffman et al. 2000, Bureau et al. 2002). For example, average size of Puget Sound Geoduck is larger in northern vs southern areas and deeper vs shallow water (Goodwin and Pease 1991).

I.1.2 Distribution and environmental preferences

The Geoduck is an infaunal bivalve that aggregates in dense coastal beds at the intertidal to 110 m (Jamieson et al. 1984) from Gulf of California to Japan. Once Geoduck settle, they remain buried up to a meter deep in silt, sand, gravel and other soft substrates (DFO 2012f).

Laboratory studies have shown that Geoduck embryos have a narrow tolerance for salinity and temperature. It was shown that for 70% of individuals, normal embryo development required salinities between 27.5 and 32.5 ppt and temperatures between 6 and 16^{o}C (Goodwin 1973). Davis et al. (1999) tested the burrowing success of various seed (juvenile clam) sizes and it was found that all seed size classes had maximum burrowing rates at 11, 14 and 17^{o}C and 26, 28 and 30 ppt. In culture operations, avoiding extreme temperatures and salinities less than 26 ppt even for short period of time is suggested to significantly increase overall seed success (Fischer and Mueller 2007).

I.1.3 Predators and prey

Examinations of gut contents of these filter feeders from Puget Sound showed only phytoplankton, specifically flagellates and diatoms (Goodwin and Pease 1989). Geoduck which live below the photic zone are hypothesized to feed on live phytoplankton carried by wind-driven or tidal currents or dead plankton and bacteria (Goodwin and Pease 1989).

As with many other broadcast spawners, Geoduck produce a large number of eggs (millions) which are broadcast into the water column. Mortality rates are initially very high, slow during the juvenile stage and are presumed very low when animals are adults (Goodwin and Pease 1989). The same authors assume that planktonic larvae are consumed by fish, other plankton or suspension-feeding invertebrates. At the early benthic stage, Geoduck have a very thin shell which does not fully close, making them highly vulnerable to predators. Hatchery reared seed broadcast over the sea bed must dig in to the sediment quickly, else they fall prey to Sunflower Star, Basket Whelk, Coonstripe Shrimp, Red Rock Crab, Graceful Crab, Starry Flounder, English Sole, Rock Sole, Sand Sole and Pile Perch (Goodwin and Pease 1989). Animals that don't burrow as deeply into the substrate can be dug up by starfishes (Sloan and Robinson 1984). Older Geoduck can also suffer from siphon grazing which does not necessarily result in death. Geoduck siphons have been found in the stomach contents of Pacific Spiny Dogfish, Cabezon and Pacific Halibut (Goodwin and Pease 1989). However, once they are fully burrowed into the sediment there are only a two predators of concern, humans and sea otters. Geoduck are a significant prey item for sea otters. Off the west coast of Vancouver Island where sea otters have recently re-colonized, predation is believed to be impacting the harvest quota (DFO 2012e).

I.1.4 Recruitment

Recruitment of Geoduck is highly episodic (Zhang and Hand 2007; Black et al. 2008). Back-calculation of historical recruitment rates showed declines between the 1950s and mid 1980s (Orensanz et al. 2004; Zhang and Hand 2007), followed by an increase in recruitment rate in recent years (Oresanz et al. 2004; Zhang and Hand 2007).

Calculations by Zhang and Hand (2007) show that recruitment appears to have been strong in recent years throughout the BC coast, likely because of some favourable environmental conditions prevailing in these years (Valero et al. 2004). Overall historic recruitment trends appear to be similar across sub-basins, suggesting that Geoduck recruitment may be strongly influenced by trends in ocean climate. However, within each geographic region, recruitment variation is large meaning that local 'bed-level' regulation occurs across the distribution.

Geoduck are fully recruited to fisheries in BC at age 6 (Zhang and Hand 2007). The magnitude and frequency of recruitment determines productivity since growth in body weight is negligible beyond age 10 (Zhang and Hand 2007).

I.2 THE FISHERY

I.2.1 Management

The Pacific LAB fishery for Geoduck is managed through a combination of limited entry and individual quotas (Heizer 2000). In 1976, the commercial Geoduck fishery was opened as an "open access" fishery without catch limits (DFO 2013g). In 1979, entry was limited to 55 licences and total allowable catch (TAC) was introduced to help regulate the industry (DFO 2012e). Quotas were reduced in 1987 with improved scientific data as they were deemed too high for a sustainable fishery. Quotas have remained at approximately 3.4 million pounds over the last few years. An Individual Vessel Quota (IVQ) system was introduced in 1989 where the TAC was split equally among 55 licences. In 2011, a pilot quota block transfer system was introduced where the TAC was split into 550 blocks which can be transferred between Geoduck licences on a temporary or permanent basis. Geoduck Licence Holders form the Underwater Harvester Association (UHA).

The fishery is open year round along the coast in stipulated Geoduck Management Areas (DFO 2013g). Licence Area and Geoduck Management Area are not the same. There are 3 Licence areas and more than 100 Geoduck Management Areas (GMAs). A GMA is a group or sometimes a portion of some subareas that are used in the management of the fishery on the grounds because in some cases the PFM Sub Area boundaries do not work well to manage Geoduck. Geoduck licences are allocated to one of three geographic regions; North Coast, West Coast of Vancouver Island or Inside Waters. From 2007 to 2012, 40 of the 55 licences have been for the North Coast area; the Inside Waters area was allocated between 6 and 7 licences and; West Coast Vancouver Island area was allocated 8-9 licences (DFO 2012e).

The North Coast and Inside Water are divided into three sub-units, with approximately equal harvest areas which are harvested on a 3 year rotation to reduce the number of landing ports and facilitate monitoring. The WCVI is harvested annually due to sea otter predation pressures. Regions under three year rotation are fished at 3x the annual exploitation rate of 1.8% (5.4%) once every three years (Bureau et al. 2012).

Geoduck are individually harvested by hand, by divers using a "stinger", a water jet which loosens the substrate around the clam so that they can be gently lifted out. Although animals inhabit depths up to 110 m, the commercial harvest typically only occurs down to 20 m. All Geoduck harvested in BC are processed in Vancouver and almost exclusively shipped live to the Asian market.

Because of the significant value of Geoduck, there is concern over illegal harvest. To help mitigate this, a monitoring system consisting of On-Grounds Monitors and 100% docks-side validation of landings is in place and tightly regulated transport and unloading of landings enables complete traceability.

Geoduck aquaculture in BC started in the 1990's and has been limited to the Strait of Georgia (Hand and Marcus 2004). To date, 411 ha have been tenured for subtidal Geoduck aquaculture between 17 sites, of which 215 ha (3% of IW) fall on existing Geoduck beds. There is considerable interest from the aquaculture industry to expand intertidal and subtidal Geoduck aquaculture in BC. Aquaculture tenure applications have been received for an additional 361 ha, of which 193 ha overlap existing Geoduck beds. Furthermore, applications have been made to include Geoduck on existing licenses, representing approximately 100 ha of seabed.

I.2.2 Stock assessment

Geoduck stocks form metapopulations. There is no stock-recruitment relationship in the traditional sense, as recruitment to one location is unlikely associated with the reproductive capacity in the same location (Orensanz et al. 2004). Unless and until we can model the larval movement, we are not able to link recruitment in one spot to stock biomass in another. Current population models assume that recruitment in the future will reflect what has occurred in the past (Zhang and Hand 2007).

The TAC is calculated by estimating the current biomass for each Geoduck bed and applying regional exploitation rates, ranging from 1.2 to 1.8%, to the biomass estimates (Bureau et al. 2012). Harvestable biomass is estimated as the product of harvestable Geoduck bed area, Geoduck density and mean weight of Geoduck for each bed (Bureau et al. 2012). Bed area is estimated from harvest locations; substrate mapping; dive surveys; on-grounds monitors; harvester information and; logbook questionnaires (DFO 2013g). Density is estimated by dive surveys, and mean weight is estimated from landings data (Bureau et al. 2012). Biomass on unsurveyed beds is estimated by extrapolating from surveyed beds and using density categories. Harvest rate is multiplied by the biomass to provide harvest options (Bureau et al. 2012).

The TAC was constant for many years at 3.4 million pounds. In 2012 it was decreased by 4% to 3.3 million pounds as a result of stock assessments and increasingly conservative management strategies (DFO 2013g).

I.2.3 Catch

Though the North Coast sub-basin supports greater abundances of Geoduck for harvest (Fig. I1), the species is commercially exploited throughout Pacific LAB (Fig. I2).

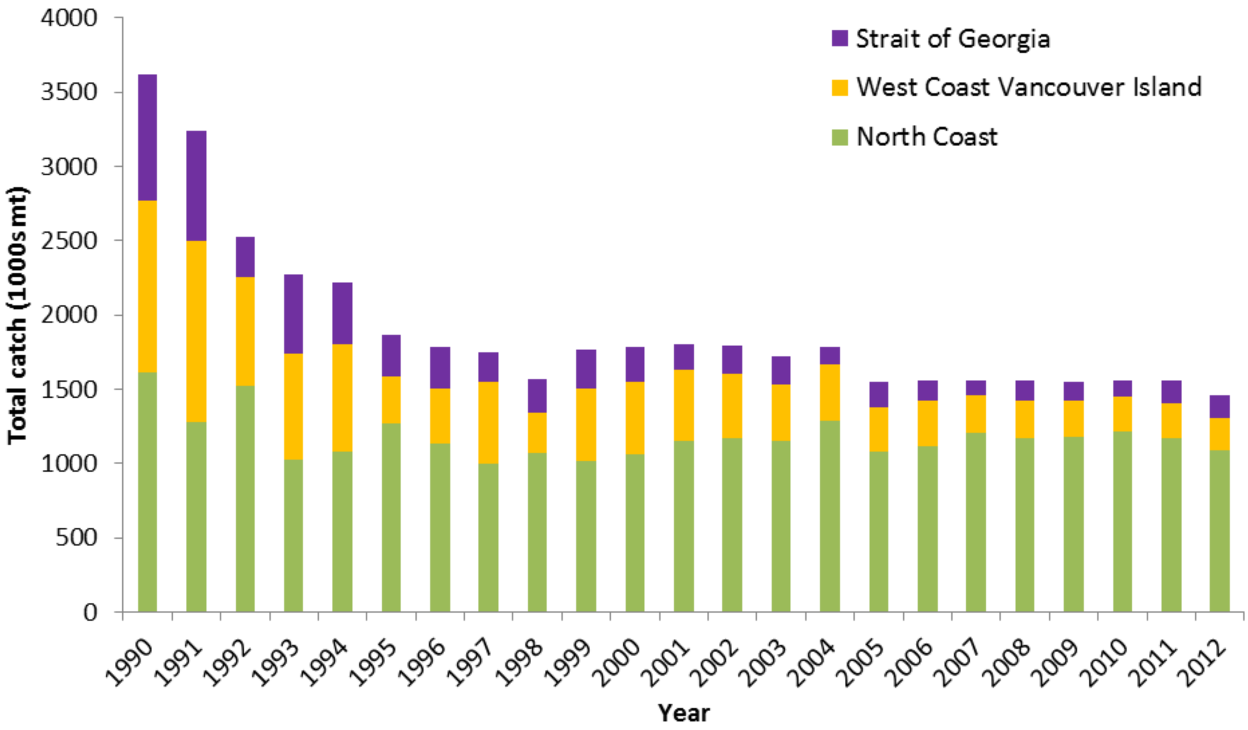
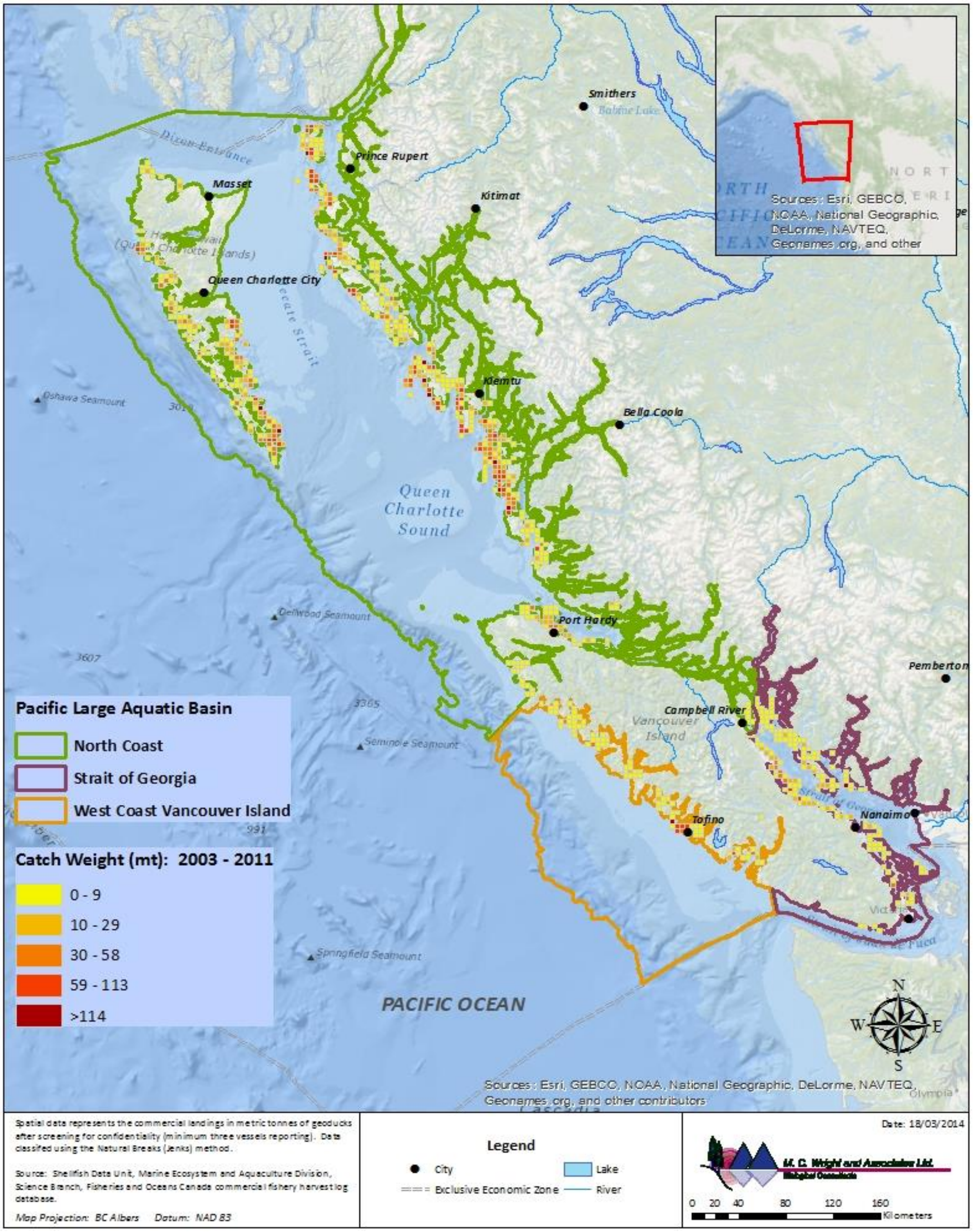


Figure I1. Total catch (mt) of Geoduck (1990-2012) in Strait of Georgia, WCVI and North Coast sub-basins.



Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other

Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

Spatial data represents the commercial landings in metric tonnes of geoducks after screening for confidentiality (minimum three vessels reporting). Data classifed using the Natural Breaks (Jenks) method.

Source: Shellfish Data Unit, Marine Ecosystem and Aquaculture Division, Science Branch, Fisheries and Oceans Canada commercial fishery harvest log database.

Map Projection: BC Albers Datum: NAD 83

Date: 18/03/2014

Figure I.2. Distribution and cumulative catch of the Geoduck fishery in Pacific LAB, 2003-2012. Data shown meet public confidentiality requirements, which state that no information resulting from the activities of fewer than 3 vessels can be released for any given space/time interval.

Geoduck populations support very lucrative dive fisheries in BC and Washington. According to the British Columbia Seafood Industry 2012 Year in Review, in 2011, the landed value of Geoduck was $41.3 million dollars.

The British Columbia Geoduck aquaculture industry began around 1995 (DFO 2013g). Culture of the Geoduck is now poised to move forward into commercial development and expansion. Hatchery capacity to produce Geoduck seed will have to increase to promote the growth of a culture industry. British Columbia companies have risen to meet this need with at least three hatcheries now capable of producing Geoduck seed animals.

There is also a coast-wide, year round recreational fishery for Geoduck which is restricted by daily limits, possession and gear limits (DFO 2013g). The number of animals taken by the recreational fishery is unknown although believed to be low.

I.3 CLIMATE CHANGE AND GEODUCK

I.3.1 Abundance

Research to determine the biological impacts of climate change on Geoduck populations has focused on growth and recruitment of these sessile animals. Coherence in recruitment patterns across BC and Washington across the latter half of the last century revealed that climate forcing has played a role in growth and recruitment in the North East Pacific Ocean (Valero et al. 2004; Nielsen et al. 2008).

Hydrodynamics, salinity, temperature, food availability and food composition all affect the growth of individual Geoduck (Nielsen and Nielsen 2009). Increased sea surface temperatures have been correlated with gains in Geoduck growth. Because of their longevity, Geoduck shells provide a record of climate (Strom 2005; Black et al. 2009) and Geoduck shell chronologies have been annually resolved and relate to local to regional-scale SST (Black et al. 2009). Nielsen et al. (2008) suggested that juvenile growth is most sensitive to conditions at the beginning of the growing season, and that early conditions set the stage for annual growth. This corroborates existing correlations between shell growth and climate modes and sea surface temperature observed across the species distribution (Nielsen et al. 2008; Black et al. 2009), though microhabitat impacts on growth should not been dismissed (Nielsen et al. 2008). There is variation in growth that is attributed to greater stratification in the water column, reduced upwelling, and lower nutrient content that accompany warmer conditions along the Pacific LAB coast (Strom et. al. 2004). Because increased temperature could result in decreasing food sources or increased predation on Geoduck, the benefits of increased growth under warming may not be realized at the population level.

Valero et al. (2004) suggested that recruitment in BC is correlated with coastal environment indexes, such as river discharges (negatively) and coastal sea-surface temperature (positively). Delayed spawning during cold years or larval flushing off coastal environments during years of strong river discharge could possible affect Geoduck year-class strength. The effects of wind, upwelling and primary productivity on recruitment have not been investigated. It is also recognized that recruitment is likely related to the geographic and oceanic features in the immediate area. For instance, recruitment is higher in locations where water currents are of medium velocity (Goodwin 1990; Bureau et al. 2002). While trends thus far demonstrate that Geoduck have not declined under warmer ocean conditions, and may in fact increase. Much is still left unknown about how Geoduck will physiologically respond to persistent warming and greater variation in temperature extremes as temperatures linked to El Niño and the PDO superimpose on ambient conditions. Trends in abundance can be perceived only by examining long time series of data and understood only if placed in the context of long-term trends of climatic change (Valero et al. 2004).

The percentage of Geoduck showing their siphon (feeding) varies with different environmental and physiological conditions (Campbell et al. 2004; Lochead et al. 2012). The percentage of shows has been reported to be reduced from 80% to 65% after a storm in a wave exposed area (Campbell et al. 1996). Tidal currents also have an effect on the amount of Geoduck showing above the surface (Goodwin 1977; Brinkhoff et al. 1983). Sedimentation rate and substrate consistency may affect the growth of some populations of Geoduck. It is known that high winds lower the frequency that siphons are seen above the substrate surface, which is also related to turbidity and sea bottom topography. It is believed that wind-induced storm disturbance resulting in wave action causes Geoduck to retract their siphon. With increased high energy weather events the frequency of "showing" may be reduced resulting in a reduction in feeding.

Geoduck have shells composed of aragonite, a calcium carbonate compound. This compound reacts with carbonic acid, which increases as the ocean acidifies (Brickey et. al. 2012). Some scientists project that the observed rise in ocean acidity will have large effects on aragonite-shelled organisms, such as Geoduck. However, Geoduck larvae may have higher survival rates in waters with lower pH (Bascom unpublished).

I.3.2 Distribution

Increasing sea surface temperatures could extend Geoduck thermal habitat range farther north (Brickey et. al. 2012). It is probable that because larval drift zones are large, larvae produced in an area of optimal temperature and salinity could drift to an area less favourable. Fluctuating water temperatures will have an effect on larval development and dispersion (Brickey et al. 2012).

Juvenile and adult stages of Geoduck are sessile; abrupt changes in sedimentation, food availability and quality may affect survival and distribution. Although Geoduck live in the sediment in deeper water, tidal fluctuations and freshwater inputs from rivers and precipitation may occur in these areas (Herlinveaux and Tully 1961; Vadopalas et al. 2004; Goman et al. 2008).

Table I.1. Summary of potential impacts, vulnerabilities and opportunities from climate change for Geoduck.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Recruitment is positively correlated with sea-surface temperature; Growth rates are correlated with sea surface temperature;	No information	No information
Sea surface salinity	Larvae produced in an area of optimal temperature and salinity may drift to areas less favourable for development	No information	No information
Freshwater discharge	Recruitment is negatively correlated with increased river discharge	No information	No information
Sea level change		No information	No information
Ocean acidification	Shells composed of aragonite are susceptible to changes in saturation state; Potential to disrupt cascading food web linkages.	No information	No information
Ocean Currents	No information	Larval drift is affected by oceanic conditions; Larvae produced in an area of optimal temperature and salinity may drift to areas less favourable for development	No information
Stratification		No information	No information
Upwelling winds	High winds lower frequency of siphon shows and may result in reduced feeding and growth	No information	No information
Dissolved oxygen	No information	No information	No information

I.4 ECOSYSTEM INTERACTIONS

Sea otters (*Enhydra lutris*) are a natural predator of Geoduck and are impacting populations as the range and population of sea otters expand in the Central Coast, WCVI and recently in the northeast of Vancouver Island. Sea otter predation on Geoduck has led to the closure of most

Geoduck beds on the WCVI north of Estevan Point. Coastwide to date, sea otters have impacted 2,401 ha of Geoduck bed area (11% of total bed area), 1,803 ha on WCVI (33% of WCVI area) and 598 ha in the Central Coast (28% of Central Coast area). The Geoduck quota for WCVI has decreased by 56% between 2001 and 2012 from 497 t (1,095,000 lbs) to 217 t (480,000 lbs), with an accompanying decrease in the number of licences fished from 15 to 8. As the range and population size of sea otters grow, there will be increasing impact on Geoduck populations which will inevitably lead to further reductions in the recommended harvest options. Currently, harvest options are not calculated for beds that have been impacted by sea otters. The continued expansion of predatory sea otters into Geoduck territory is of great concern and may significantly impact the ability to harvest certain beds.

I.5 ADDITIONAL STRESSORS

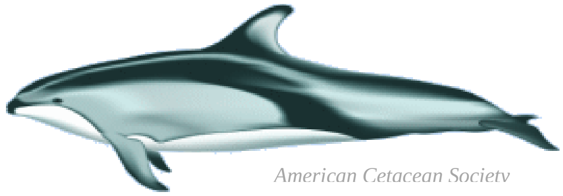
Natural events causing anoxic conditions such as massive squid spawning or drifting masses of vegetation can negatively affect Geoduck (Fyfe 1984; Anderson 1971).

I.6 GAPS AND UNCERTAINTY

Concern has been raised over the potential impacts of Geoduck aquaculture on wild populations. Specifically, whether reproduction and larval transport of cultured stock will negatively impact wild populations.

Higher oceanic temperatures may facilitate the spread of shellfish disease outbreaks. It is still unclear if local pathogens and parasites will have a large impact on Geoduck populations with further climate change but remains a concern among scientists and therefore should continually be monitored. Interactions between disease and ocean acidification are unknown.

The synergistic impacts of increasing carbon dioxide levels, rising temperatures, changing light density, and nutrient concentrations have yet to be determined for marine species but could be vital towards understanding future shellfish population trends.


American Cetacean Society

J. MARINE MAMMALS

Andrew Trites and Barbara Koot

KEY POINTS

- Changes in the distribution, diversity, abundance, concentration, timing and movements of prey species will affect the ability of all species of marine mammals to acquire sufficient prey to meet their daily energy requirements, and may reduce body condition, pregnancy rates and survival.
- Higher propagation of sound in CO_2 enriched water may increase anthropogenic noise levels and negatively affect foraging, reproduction and group cohesion of porpoise, dolphins and whales by interfering with communication.
- Higher rainfall will increase the flow of contaminants, novel pathogens and nutrients into the ocean—while increased temperatures and poorer water quality may increase the frequency and intensity of toxic algal blooms. Marine mammals that inhabit the nearshore (particularly near urbanized areas) such as seals, sea lions, and sea otters are likely to be more susceptible than other marine mammals to such stressors.
- Increased ocean temperatures may enable warmer water species such as California sea lions and striped dolphins to expand their ranges northward and compete with Steller sea lions and Pacific white-sided dolphins for food.
- Rising sea levels and increases in the frequency and intensity of storms will have a direct impact on the resting and breeding sites used by seals and sea lions. This may reduce the availability of sites they use, and could increase the frequency with which pups are swept into the ocean and drowned.
- Species such as harbour porpoise, Dall's porpoise and white-sided dolphins that are less tolerant of warmer waters compared to larger species of cetaceans may move northward and have their distributions contracted within BC.

J.1 BIOLOGICAL CHARACTERISTICS

Pacific LAB has at least 27 species of marine mammals (Table J1) —1 species of sea otter (northern sea otter), 5 species of pinnipeds (Steller sea lions, California sea lions, Pacific harbour seals, northern fur seals, and northern elephant seals), 7 species of dolphins (killer whales, Pacific white-sided dolphin, northern right whale dolphin, Risso's dolphin, false killer whale, short-finned pilot whale, and striped dolphin), 2 species of porpoise (harbour porpoise and Dall's porpoise), 5 species of toothed whales (sperm whale and Cuvier's, Baird's, Stejneger's and Hubb's beaked whales), and 7 species of baleen whales (grey whale, humpback whale, fin whale, blue whale, sei whale, minke whale and North Pacific right whale).

Table J.1. Species of marine mammals that occur in British Columbia, their designation by COSEWIC, their status under SARA, and their presence in British Columbia.

Species	COSEWIC Designation	SARA Status	Presence in BC
Sea Otters			
Northern Sea Otter (*Enhydra lutris*)	Special Concern (April 2007)	Special Concern	Coastal. year round, breeding
Fur Seals & Sea Lions			
Northern Fur Seal (*Callorhinus ursinus*)	Threatened (Nov 2010)	Under Consideration	Offshore, migratory, overwintering
Steller Sea Lion (*Eumetopias jubatus*)	Special Concern (Nov 2003)	Special Concern (Management plan in place)	Coastal. year round, breeding
California Sea Lion (*Zalophus californianus*)	Not at Risk (April 1987)	No Status	Coastal. non-breeding
True Seals			
Pacific Harbour Seal (*Phoca vitulina richardsi*)			Ubiquitous, coastal. year round, breeding
Northern Elephant Seal (*Mirounga angustirostris*)	Not at Risk (April 1986)	No Status	Occasional. offshore, migratory, rarely haul out
Toothed Whales (Dolphins)			
Killer Whales (*Orcinus orca*)	Various designations	Same as COSEWIC	Coastal and offshore, year round, breeding
Northern Resident:	Threatened (Nov 2008)		
Southern Resident:	Endangered (Nov 2008)		
Transient:	Threatened (Nov 2008)		
Offshore:	Threatened (Nov 2008)		
Pacific White-Sided Dolphin (*Lagenorhynchus obliquidens*)	Not at Risk (April 1990)	No Status	Common, inshore and offshore, year round
Northern Right Whale Dolphin (*Lissodelphis borealis*)	Not at Risk (April 1990)	No Status	Offshore. BC is likely the northern limit of the range
Risso’s Dolphin (*Grampus griseus*)	Not at Risk (April 1990)	No Status	Offshore, some individuals present in all seasons
False Killer Whale *(Pseudorca crassidens)*	Not at Risk (April 1990)	No Status	Rare. BC is likely the northern limit of the range
Short-Finned Pilot Whale *(Globicephala macrorhynchus)*	Not at Risk (April 1993)	No Status	Rare
Striped Dolphin *(Stenella coeruleoalba)*	Not at Risk (April 1990)	No Status	Rare. BC is likely the northern limit of the range

Table J.1 continued.

Species	COSEWIC Designation	SARA Status	Presence in BC
Toothed Whales (Porpoises)			
Harbour Porpoise *(Phocoena phocoena)*	Special Concern (Nov 2003)	Special Concern	Relatively common, coastal. year round
Dall's Porpoise *(Phocoenoides dalli)*	Not as Risk (April 1989)	No Status	Common, inshore and offshore, year round
Other Toothed Whales			
Cuvier's beaked whale *(Ziphius cavirostris)*	Not at Risk (April 1990)	No Status	Deep offshore waters
Baird's beaked whale *(Berardius bairdii)*	Not at Risk (April 1992)	No Status	Deep offshore waters
Stejneger's beaked whale *(Mesoplodon stejneri)*	Not at Risk (April 1989)	No Status	Deep offshore waters
Hubb's beaked whale *(Mesoplodon carlhubbsi)*	Not at Risk (April 1989)	No Status	Deep offshore waters
Sperm Whale *(Physeter macrocephalus)*	Not at Risk (April 1996)	No Status	Offshore
Baleen Whales (Balaenopteridae)			
Grey Whale *(Eschrichtius robustus)*	Special Concern (May 2004)	Special Concern (Management Plan in place)	Coastal. resident and migratory populations
Humpback Whale *(Megaptera novaeangliae)*	Special Concern (May 2011)	Threatened	Most frequently sighted baleen whale in BC, coastal. summer feeding ground;
Fin Whale *(Balaenoptera physalus)*	Threatened (May 2005)	Threatened (Recovery Strategy in place)	Offshore, some individuals present in all seasons
Blue Whale *(Balaenoptera musculus)*	Endangered (May 2012)	Endangered (Recovery Strategy in place)	Uncommon, offshore
Sei Whale *(Balaenoptera borealis)*	Endangered (May 2003)	Endangered (Recovery Strategy in place)	Offshore; extremely rare
Minke Whale *(Balaenoptera acutorostrata scammonii)*	Not at Risk (April 2006)	No Status	Coastal. some individuals present in all seasons
Baleen Whales (Balaenidae)			
North Pacific Right Whale *(Eubalaena japonica)*	Endangered (Nov 2004)	Endangered (Recovery Strategy in place)	Extremely rare (Seen twice since 1951, both in 2013)

J.1.1 Sea otters

J.1.1.1. Life cycle, age and growth

Sexual maturity is reached between the ages of 3 and 5 for female sea otters. Males start to reproduce between the ages of 5 and 6 when they are socially mature, even though they can be sexually mature earlier (COSEWIC 2007). Sea otters are polygynous, and spatially segregate by sex. Females give birth to single pups at one-year intervals, and pups are dependent on the mother for 6-8 months. Pupping occurs year-round, with some populations, including those in Pacific LAB, having distinct peaks in the spring. Females live 15-20 years and males live 10-15 years (COSEWIC 2007).

J.1.1.2 Distribution, habitat and environmental preferences

Sea otters occur in coastal areas of the North Pacific Ocean. Sea otters were extirpated from much of their global range in the 18th and 19th centuries due to commercial exploitation for the fur trade. Prior to exploitation, they ranged from northern Japan to central Baja California, Mexico. Sea otters were extirpated from BC in 1929 (COSEWIC 2007). Sea otters from Alaska were re-introduced to BC between 1965 and 1972 and they now occur along most of the west coast of Vancouver Island, and along a small section of the BC central coast. Historically, most of Pacific LAB was occupied by sea otters; today, about 25-33% of BC's historic sea otter range is occupied (COSEWIC 2007).

Sea otters are non-migratory, display high site fidelity and have small overlapping home ranges of a few to tens of kilometers of coastline (COSEWIC 2007). Expansion of population ranges occurs by males moving from the periphery of a range to new unoccupied areas. Females then move into the habitat vacated by the males (COSEWIC 2007).

In Pacific LAB, sea otters are most often found in rocky, exposed, shallow, coastal seas from the intertidal to a depth of about 50 m. The extent of their habitat is defined by water depths that are within range of their diving abilities, as they forage on the sea floor. Most foraging dives are less than 40 m deep, but dives can be as deep as 100 m (COSEWIC 2007). Sea otters occur within 1-2 km from shore, but can be found offshore where the water is less than 40 m deep. During inclement weather, particularly in the winter, sea otters appear to move to more sheltered areas inshore (COSEWIC 2007).

Kelp beds are used as rafting sites and for foraging. Kelp beds are important but not essential habitat components. Soft-bottom communities that contain clams are important foraging habitats (COSEWIC 2007).

Because sea otters have very little body fat, they rely on metabolic heat (generated by their very high metabolic rate) and an insulating layer of air trapped in their dense fur to stay warm. Due to their high metabolism, sea otters consume prey amounts equivalent to more than 20% of their body weight each day (COSEWIC 2007).

J.1.1.3 Predators and prey

Sea otter predators include killer whales (however, there is no evidence to suggest that killer whale predation is significant in Pacific LAB), bald eagles (which prey primarily on pups) and sharks, at least in California (COSEWIC 2007).

In BC, sea otter prey consists of a variety of marine invertebrates including bi-valves (such as butter clams, horse clams, Geoducks), snails, urchins, chitons, crabs and sea stars. Sea otter diet varies among individuals and regions, and with population status. In newly occupied habitat, sea otters target large easily accessible prey such as sea urchins. As preferred prey abundance is reduced, the diet diversifies (COSEWIC 2007; Tinker *et al.* 2008).

J.1.1.4. Abundance

The fur trade reduced the range-wide population of sea otters to less than 2,000 animals by 1911. This reduced the population to approximately 1-2% of its pre-exploitation size, causing a genetic bottle-neck (COSEWIC 2007). A second bottleneck occurred after their extirpation in 1929 due to the re-introduction of a small number of animals between 1969 and 1972. However this event has not been shown to have had a negative effect on genetic diversity (COSEWIC 2007).

In 2001, 2,673 otters were counted during a survey along Vancouver Island, and 507 were counted on the central BC coast. Population growth rate is 15.6% per year on Vancouver Island and 12.4% per year on the BC central coast. The Pacific LAB population represents about 3-4% of the global population of sea otters (COSEWIC 2007).

J.1.2 Steller sea lions

J.1.2.1 Life cycle, age and growth

Steller sea lions are polygynous breeders that form dense breeding aggregations. Males begin producing sperm at 3-7 years of age, but generally only those holding territories mate (usually at 9-13 years old). Males can hold a territory for an average of 40 days without feeding. Females become sexually mature at 3-6 years of age. Most mature females conceive each year, but the rate of reproductive failure and abortion appears to be high. Females give birth to a single pup, and have a long lactation period of generally just under one year, but can be up to three years. Pups are born between late May and early July and weigh 16-23 kg at birth. Pup mortality appears to be high and is influenced by factors such as storms. The juvenile mortality rate is uncertain, but appears to be fairly high (an estimated 48% of females and 26% of males survived to 3 years of age). Females generally live 22 years, and males 14 years (COSEWIC 2003b).

J.1.2.2 Distribution, habitat and environmental preferences

Steller sea lions range throughout the cool-temperate and sub-arctic coastal waters of the North Pacific Ocean. Although Steller sea lions are considered non-migratory, their populations are trans-boundary. An eastern population (California to southeast Alaska) and a western population (Gulf of Alaska, Bering Sea, Aleutian Islands, and Russia) are recognized based on genetic differentiation of mitochondrial DNA and other phylogeographic analysis (population trends, distribution, movements, and morphology). In British Columbia, Steller sea lions belong to the eastern population (COSEWIC 2003b).

Steller sea lions utilize terrestrial habitats throughout the year. From May to August animals aggregate at breeding sites (rookeries) sites to give birth, nurse pups and mate. There are three main breeding sites in Pacific LAB (Olesiuk 2011): 1) off the northeastern tip of Vancouver Island (rookeries on Maggot, Sartine and Triangle Islands); 2) off the southern tip of the Queen Charlotte Islands (rookeries on the Kerouard Islands); and 3) off the northern mainland coast (rookeries on North Danger Rocks). In addition to the rookeries, there are about 21 haulout sites that are used year-round (by immature animals, non-pregnant adults and females nursing pups from previous summers), as well as numerous winter haulout sites (COSEWIC 2003b).

Rookeries and year-round haulouts are located on remote, exposed, barren, rocky outcroppings that are protected from terrestrial predators. They are located in areas of high oceanic productivity, which are optimum feeding areas. Most winter haulouts are located in protected areas such as the Strait of Georgia, Strait of Juan de Fuca and Queen Charlotte Strait (COSEWIC 2003b).

Sea lion use of the aquatic environment is poorly known. At sea, Steller sea lions are found primarily within 60 km of shore in the summer, but they can range over 200 km from shore in winter. Steller sea lions generally appear to feed over the continental shelf and along the shelf break. Sea lions often congregate in the lower Fraser River during the spring eulachon run (Bigg 1985), and in estuaries during autumn when pre-spawning salmon are present (COSEWIC 2003b).

J.1.2.3 Predators and prey

Transient killer whales are the primary predator of Steller sea lions (COSEWIC 2003b).

The Steller sea lion diet has been documented to include over 50 species of fish and invertebrates. The diet appears to vary regionally, according to local and seasonal prey availability. In BC, the preferred prey of the Steller sea lion is small to medium sized schooling fish, including Pacific Herring, Pacific Hake, Sandlance, Pacific Salmon, Eulachon, Pacific sardine and dogfish. Bottom fish such as rockfish, flounder, skate can be important, and squid and octopus are less often consumed (COSEWIC 2003b).

Food requirements vary with the type and quality of prey (COSEWIC 2003b). Sea lions that consume higher proportions of low fat fishes such as gadids require significantly more prey than those that consume fattier fish such as Pacific Herring (COSEWIC 2003b).

J.1.2.4 Abundance

In contrast to the western population which is declining, the eastern population of Steller sea lions has been growing in recent years. Population numbers in Pacific LAB have increased by an average of 3.2% annually since Steller sea lions were protected in 1970 (COSEWIC 2003b).

J.1.3 Harbour seals

J.1.3.1 Life cycle, age and growth

Harbour seals are polygamous breeders, which do not congregate to breed. The birth season varies by latitude, with pups born from mid-May to early-July in northern BC, and from early-July to mid-August in southern Pacific LAB. Females give birth to a single pup and have a short lactation period of 3-6 weeks. Pups weigh about 10 kg at birth and double their mass during the lactation period. Both sexes mature at about 3-5 years of age and the average life expectancy is 10 years for females and 8 years for males (COSEWIC 2003a).

J.1.3.2 Distribution, habitat and environmental preferences

Harbour seals are non-migratory. Harbour seals inhabit coastal temperate and subarctic coastal waters throughout much of the northern hemisphere. Five geographically distinct subspecies are recognized. The eastern Pacific subspecies (*P.v. richardsi*) occurs in Pacific LAB, and its range extends along the Pacific Rim from Baja California northward to Bristol Bay and westward through the Aleutian Islands in Alaska (Olesiuk 2010).

Harbour seals use terrestrial habitats for haulouts, and typically spend a few hours each day hauled out on reefs, sandbars or log booms. Nearly 1,400 haulout sites have been identified in Pacific LAB. They generally forage locally within 10-20 km of haulout sites but can range as far as 100 km offshore. Harbour seals show a high degree of site fidelity and long-term marking studies in Europe indicate females return to natal areas to reproduce (Olesiuk 2010). Harbour seals also enter navigable rivers and lakes, and range as far as 250 km up the Skeena River and 500 km up the Fraser River (Olesiuk 2010).

J.1.3.3 Predators and prey

Transient killer whales are the primary predator of harbour seals (Olesiuk 2010), and harbour seals make up a significant component of transient killer whale prey (COSEWIC 2008).

Harbour seal diet in the Strait of Georgia is primarily hake and herring, which combined account for about 75% of the total diet. Pacific Herring predominated the diet during winter when migratory stocks move inshore in preparation for spawning, and Pacific Hake predominated the diet during summer after herring moved offshore and hake become more aggregated. Pacific Salmon made up only 4% of the overall diet, and were taken mainly in estuaries and rivers when adults were returning to spawn (Olesiuk 2010).

J.1.3.4 Abundance

In Pacific LAB, seal populations grew exponentially at a rate of about 11.5% per year during the 1970s and 1980s. The rate of increase began to slow in the mid-1990s, and abundance now appears to have stabilized at about 105,000 animals. The Pacific LAB population represents about 29% of the total of 360,000 harbour seals estimated to inhabit the northeastern Pacific Ocean (Olesiuk 2010).

J.1.4 Killer whales

J.1.4.1 Life cycle, age and growth

Male killer whales become sexually mature at about 13 years, and females at 14 years. The estimated lifespan is 80 years for females and 40-50 for males (COSEWIC 2008). Females give birth to a single calf about every 5 years (ranges from 2 to 11 years) following a gestation period of about 16-17 months. Resident killer whales have a matrilineal social system and calves remain with their mothers throughout their lives. Females produce their last calf at about 40 years of age, and then undergo a period of reproductive senescence that is rare in animals, and is thought to increase the survival of offspring (COSEWIC 2008).

J.1.4.2 Distribution, habitat and environmental preferences

Killer whales occur in all of the world’s oceans and are most common in areas associated with high ocean productivity in mid to high latitudes. Killer whales do not migrate to separate feeding and breeding grounds, but rather their distributions appear to be determined mainly by the distribution and accessibility of their prey (COSEWIC 2008). They are found from polar waters to the tropics, and have been recorded in water ranging from shallow (several meters) to open ocean depths (DFO 2011c). On the west coast of Canada, several distinct populations are recognized. These killer whales are not migratory, but rather they shift their distributions to follow prey. The west coast transient population occurs throughout the coastal waters of British Columbia; the southern resident population is generally found around southern Vancouver Island in summer and fall, although the animals may range widely at other times of year (as far south as California); and the northern resident population occurs from central Vancouver Island north to southeastern Alaska in summer and fall. The ranges of the southern and northern resident populations at other times of the year are not well known. Offshore killer whales are seen less frequently but are known to travel widely in coastal waters (COSEWIC 2008).

Killer whale movement does not seem limited by environmental features other than ice in high latitudes. Killer whales use nearshore and offshore habitats and can tolerate a range of temperature, salinity and turbidity levels. Killer whales require sufficient quantity and quality of prey and an acoustic environment that does not interfere with foraging and communication (COSEWIC 2008).

J.1.4.3 Predators and prey

Killer whales have no natural predators (COSEWIC 2008).

Killer whales are upper trophic-level predators. Globally, killer whales are known to feed on a wide range of prey species, yet within the eastern North Pacific different populations are highly specialized to feed on specific species.

Resident killer whales feed exclusively on fish and cephalopods. Both northern and southern resident killer whales forage selectively for specific salmon species. Their predominant prey is Chinook Salmon from May through September, despite the low abundance of this species relative to other salmonids such as Pink Salmon (*O. gorbuscha*), and Sockeye Salmon (*O. nerka*). During October, Chum Salmon (*O. keta*) are abundant and dominate the diet of residents, although Chinook Salmon are taken as well. From November through April, the diet is not well known (COSEWIC 2008).

Transient killer whales feed exclusively on marine mammals. Harbour seals are the most frequently recorded prey, followed by harbour porpoises, Dall’s porpoises and Steller sea lions. They also consume California sea lions, Pacific white-sided dolphins, grey whale calves, common minke whales and, less commonly, river otters (*Lontra canadensis*), northern elephant seals and seabirds (COSEWIC 2008).

The diet of offshore killer whales is not well understood because they are not often encountered. They travel in large acoustically active groups, so their behavior is consistent with a predator that does not feed on marine mammals. They have been reported to feed on fish and their PCB contaminant levels resemble those found in transients, suggesting that they prey on heavily contaminated, long-lived, high trophic-level predators such as elasmobranchs (COSEWIC 2008).

J.1.4.4 Abundance

In 2006 there were 87 individuals in the southern resident killer whale population, and 244 whales in the northern resident population. Both populations showed a decline during the late 1990s, concurrent with declines in their principal prey, Chinook salmon (COSEWIC 2008).

In 2006, there were an estimated 243 whales in the west coast transient population. From the mid-1970s to mid-1990s the west coast transient population grew rapidly (average 6%/yr) coinciding with dramatic increases in the abundance of harbour seals and Steller sea lions in Pacific LAB coastal waters. This rapid growth (which exceeds the estimated rmax of 3-4% for toothed whales) suggests that the early increase was due, at least in part, to movement of adults into nearshore areas. Growth in the population since 1990 (average 2%/yr) has been due to recruitment (COSEWIC 2008).

At least 288 offshore killer whales occur in Pacific LAB (COSEWIC 2008).

J.1.5 Harbour porpoise

J.1.5.1 Life cycle, age and growth

Harbour porpoise females give birth to a single calf every 1-2 years in spring or summer following a gestation period of about 10-11 months. Calves are weaned within 4-5 months, but may remain with their mother for up to 18 months. Sexual maturity is reached at 3 to 4 years and the estimated lifespan is 10 to 30 years (DFO 2009b).

J.1.5.2 Distribution, habitat and environmental preferences

The harbour porpoise has a northern hemisphere, circumpolar distribution and inhabits cold-temperate, sub-arctic waters. They are seldom found in water warmer than 16°C. In the eastern Pacific Ocean, they occur from the Bering Strait, Alaska, to central California, and occur in Pacific LAB year round. Harbour porpoise tend to be found in relatively shallow coastal waters, generally less than 200 m depth. As a small marine mammal with limited energy reserves, it needs to feed frequently. Harbour porpoise are known to spend time in areas which have physiographic features that concentrate prey (DFO 2009b).

J.1.5.3 Predators and prey

Little is known about the diets of harbour porpoise in Pacific LAB, but in general they are shallow water predators and feed upon a variety of epipelagic and mesopelagic cephalopods and fish, such as squid, Pacific Herring, Sandlance and Pacific Hake. Juveniles prey upon large zooplankton (i.e. euphausiids) while transitioning from a milk to solid diet (DFO 2009b).

J.1.5.4 Abundance

Little information is available on the abundance and population trends of the harbour porpoise in Pacific LAB, and the information that is available is restricted to the southern inshore portion of Pacific LAB. Surveys conducted in 1996 recorded about 3000 individuals. There are reports that the harbour porpoise population of southern British Columbia and northwestern Washington has declined since the 1940's, but this is uncertain (DFO 2009b).

J.1.6 Dall's porpoise

J.1.6.1 Life cycle, age and growth

Life history information for the Dall's porpoise in the eastern North Pacific is very sparse. Females give birth after a gestation period of about 11 months. No defined breeding season may exist, with mating and birthing occurring year round (Money and Trites 1998).

J.1.6.2 Distribution, habitat and environmental preferences

Dall's porpoise are common across the entire North Pacific Ocean. In the eastern North Pacific they occur from Alaska to Baja, California. Dall’s porpoise occur in coastal and deep oceanic waters of Pacific LAB (Money and Trites 1998).

J.1.6.3 Predators and prey

Generally, Dall's porpoises feed on small squid, crustaceans, and both pelagic and deep-water benthic fish species (Pauly *et al.* 1998). No information is available on the diet of Dall's porpoise in Pacific LAB. Since these animals are commonly caught in salmon drift gillnet and high seas squid gillnet fisheries their diet is likely to consist of squid and prey pursued by Pacific Salmon (Money and Trites 1998).

J.1.6.4 Abundance

Dall’s porpoise may number about 5,000 individuals (Williams and Thomas 2007), but population trends are unknown.

J.1.7 Pacific white-sided dolphins

J.1.7.1 Life cycle, age and growth

Pacific white-sided dolphin females give birth to a single calf every 4-5 years in summer following a gestation period of about 12 months. Calves are nursed for at least 6 months. Sexual maturity is reached at 7 to 8 years and the estimated lifespan is 37 years for females (Heise 1996).

J.1.7.2 Distribution, habitat and environmental preferences

The Pacific white-sided dolphin is restricted to the temperate waters of the North Pacific Ocean. They range from as far north as the Aleutians, throughout the Gulf of Alaska, south to Baja California. Canadian waters lie at the central portion of their range (Stacey and Baird 1990; Rechsteiner 2012). Pacific white-sided dolphins occur both inshore and offshore, with some dolphins undertaking seasonal movements between the two habitats (Stacey and Baird 1990; Rechsteiner 2012). They have elevated metabolisms and require fatty prey to meet their high daily energy needs.

J.1.7.3 Predators and prey

Transient (mammal eating) killer whales are known to prey on Pacific-white-sided dolphins, but the rate of predation is unknown.

Pacific white-sided dolphins in Pacific LAB are opportunistic predators and are known to feed on at least 13 different prey species. Pacific Salmon are an important diet component (30 to 60%) from June through November (Heise 1996; Rechsteiner 2012). The majority of Pacific Salmon consumed were small (< 25 cm) though larger fish (> 50 cm) were taken occasionally. Pacific Herring is the most important year-round prey, occurring in 59% of samples (Heise 1996). Cod *spp*., shrimp *spp*., and Capelin were also consumed (6%, 3%, and 1% of the diet, respectively).

J.1.7.4 Abundance

Pacific white-sided dolphins are likely the most abundant cetacean in the inshore and nearshore waters of Pacific LAB. There has been a dramatic increase in sightings in coastal waters since the mid-1980's. This is thought to be due to immigration rather than an increase in population numbers (Heise 1996; Rechsteiner 2012). They may number about 26,000 in Pacific LAB coastal waters (Williams and Thomas 2007).

J.1.8 NORTHERN RIGHT WHALE DOLPHIN

J.1.8.1 Life cycle, age and growth

Northern right whale dolphin females give birth to a single calf at a minimum of every 2 years in summer. Sexual maturity is reached at 10 years (Money and Trites 1998).

J.1.8.2 Distribution, habitat and environmental preferences

The northern right whale dolphin occurs in temperate waters throughout the North Pacific Ocean ranging from Alaska to Baja, California in the eastern Pacific. In Pacific LAB, this species is most often recorded from the southern parts of the province (Money and Trites 1998).

J.1.8.3 Predators and prey

Northern right whale dolphins feed on a variety of fish and cephalopods (Money and Trites 1998; Pauly *et al.* 1998). Their diet in Pacific LAB waters has not been determined.

J.1.8.4 Abundance

No estimates of abundance or population trends are available northern right whale dolphins.

J.1.9 Risso's dolphin

J.1.9.1 Life cycle, age and growth

Risso's dolphin females give birth following a gestation period of about 13-14 months. Calving season, calving interval and age at sexual maturity are not known (Money and Trites 1998).

J.1.9.1 Distribution, habitat and environmental preferences

Risso's dolphins have a worldwide distribution and occur in tropical and warm temperate seas. They are found in the eastern North Pacific Ocean from the Gulf of Alaska to south of Baja, California. They have been recorded year-round in the waters off Pacific LAB (Money and Trites 1998).

J.1.9.1 Predators and prey

The diet of the Risso's dolphin consists almost exclusively of squid. Fish may also be incidentally consumed (Money and Trites 1998; Pauly *et al.* 1998).

J.1.9.4 Abundance

No estimates of abundance or population trends are available for Risso's dolphins.

J.1.10 Sperm whale

J.1.10.1 Life cycle, age and growth

Sperm whale females give birth to a single calf about every 7 years in summer following a gestation period of about 14-15 months. Calves may be nursed for up to 4 years. In females, sexual maturity is reached at an average of 18 years (Money and Trites 1998).

J.1.10.2 Distribution, habitat and environmental preferences

With the exception of the killer whale, the sperm whale is the most widely distributed of marine mammal species, occurring in all of the world’s oceans from the equator, to the north and south polar pack-ice (Mizroch and Rice 2013). Sperm whales are found throughout the eastern North Pacific, but are generally distributed below 40°N in the winter. Males move north to feed in the summer, while females and young remain in tropical and temperate waters throughout the year. Sperm whales are usually found far offshore, except in cases where the shelf break or submarine canyons occur close to land. Sperm whales are found to be more abundant in areas of high productivity which support higher densities prey. Sperm whale movements are nomadic in response to temporal and geographic changes in prey distribution and abundance (Mizroch and Rice 2013). The distribution of their prey is likely to vary based upon changes in oceanographic features such as currents and temperature (Mizroch and Rice 2013).

J.1.10.3 Predators and prey

Sperm whales feed primarily on medium to large-sized squids, but may also feed on large sharks, skates, fishes and octopuses (Mizroch and Rice 2013). It has been suggested that large male sperm whales prey more frequently on cold- and deep-water forms of cephalopods and fish because they are able to dive to greater depths than females. They can therefore forage more effectively in colder, deeper, more productive waters. Females make more shallow dives and tend to prey on a wider selection of cephalopods, including smaller, warm-water species (Mizroch and Rice 2013).

J.1.10.4 Abundance

No estimates of abundance or population trends are available for sperm whales.

J.1.11 Cuvier’s, Baird’s, Stejneger’s, and Hubb’s beaked whales

J.1.11.1 Life cycle, age and growth

Very little is known about the life history of beaked whales (family Ziphiidae). The Baird’s beaked whale reaches sexual maturity at 7 to 15 years of age, and the gestational period is estimated to be 17 lunar months (MacLeod and D'Amico 2006). A lactation interval of 1 or more years, and birth interval of 2 or more years is suggested, and may vary by species. The oldest recorded male Baird’s beaked whale was 84 years, while the oldest female was 54. The maximum age for other beaked whale species that have been examined is between 27 and 39 years (MacLeod and D'Amico 2006).

J.1.11.2 Distribution, habitat and environmental preferences

Beaked whales were commonly sighted by commercial whaling vessels in the mid-1900's, but sightings have been rare along the Pacific LAB coast since that time. Little is known about these species in Canada or elsewhere in the world (Money and Trites 1998). Beaked whales typically occur in deep offshore waters, where they hunt for deep-water prey. Beaked whales are often found in relation to topographic features such as slopes, canyons, escarpments and islands where water currents and high productivity can lead to concentrations of prey (MacLeod and D'Amico 2006).

J.1.11.3 Predators and prey

The beaked whales in the family Ziphiidae feed primarily on cephalopods, and more rarely on pelagic fishes and crustaceans (Pauly et al. 1998; MacLeod et al. 2003).

J.1.11.4 Abundance

No estimates of abundance or population trends are available for beaked whales.

J.1.12 Blue, Fin, & Sei whales

J.1.12.1 Life cycle, age and growth

Blue, fin and sei whales are large baleen whales. Females give birth to a single calf every 2-3 years in winter following a 10-12 month long gestation period. Calves are born at 6-7 m in length and are weaned at 6-7 months of age, likely during the summer when on feeding grounds. The whales are thought to reach sexual maturity between 5-15 years for both sexes, and live 70-80 years (COSEWIC 2002, 2003c, 2005).

J.1.12.2 Distribution, habitat and environmental preferences

Worldwide, blue, fin and sei whales have cosmopolitan distributions. In the eastern North Pacific, they range between the Arctic and Mexico. The sei whale appears to be somewhat more restricted to temperate waters than the other baleen whales (COSEWIC 2003c). Baleen whales generally undertake extensive seasonal migrations from low-latitude wintering (breeding and calving) areas to high-latitude, summer feeding grounds, although this may not be the case for all fin whales (Mizroch et al. 2009). No specific low latitude breeding grounds have yet been identified for eastern North Pacific blue, fin, or sei whales (Gregr et al. 2006; DFO 2011d).

The blue, fin and sei whales are largely pelagic, and are found in deep offshore waters and near the shelf break (Gregr and Trites 2001). Prey distribution determines much of the baleen whales' distributions at high latitudes. Multiple studies have demonstrated that baleen whales are often closely associated with oceanographic features that support or concentrate high densities of prey. Such features include eddies, fronts, sea surface temperature gradients, shelf-break upwelling areas and areas of high topographic relief (Gregr et al. 2006).

J.1.12.3 Predators and prey

Historically, commercial whaling caused large declines in the abundance of baleen whales in Pacific LAB and elsewhere. Between 1908 and 1967, the British Columbian stations alone killed at least 24,862 whales that included fin (n = 7,605), sperm (n = 6,158), humpback (n = 5,638), sei (n = 4,002), and blue (n = 1,398) whales (Gregr et al. 2000). The abundance of most baleen whales in Pacific LAB remains low compared to the pre-whaling era. Commercial whaling is not currently a threat to blue, fin and sei whales in Pacific LAB. Transient (mammal-eating) killer whales *(Orcinus orca)* and sharks are the only known predators of baleen whales. However, the rate of predation is unknown, and may be more prevalent off California and Mexico than elsewhere (Gregr et al. 2006).

Baleen whales are low trophic level foragers that filter plankton and small fish from the water with their baleen. Large quantities (i.e. several tonnes per day, per individual blue whale), and dense concentrations of prey are needed to sustain these large animals (Gregr et al. 2006).

The blue whale feeds almost exclusively on zooplankton. The primary component is euphausiids (*Euphausia pacifica*, *Thysanoessa spinifera, T. inermis, T. longpipes, T. raschii*, and *Nematoscelis megalops*). Calanoid copepods (*Calanus* spp.) and pelagic red crab (*Pleuroncodes planipes*) also occur in the diet (Gregr et al. 2006).

Fin whales forage on a variety of species. In the northern hemisphere they generally eat small invertebrates, schooling fishes and squids. Consequently, it has been suggested that fin whale diet is as much a function of availability as preference. In Pacific LAB and the North Pacific, the diet is dominated by euphausiids (70%) followed by copepods (25%) with some fish and squid (Gregr et al. 2006).

In the North Pacific, sei whales feed primarily on calanoid copepods (83%). However, the diet also contains euphausiids (13%), amphipods, and schooling fish and squid. There is evidence that sei whale diet varies with the available prey base which varies with ocean basin, season, year, and proximity to the coast. Based on this information, sei whales seem to have a generalist diet. However, whether this ability to generalize diet is a characteristic of all individuals, or if different individuals tend to specialize on different prey types, is unknown (COSEWIC 2003c; Gregr et al. 2006).

J.1.12.4 Abundance

It is presumed that the blue whales using Pacific LAB waters belong to a putative eastern North Pacific population ranging from Mexico to the Gulf of Alaska. Global estimates of blue whale numbers range from 5,000 to 12,000, and the eastern North Pacific population is estimated at 2000 individuals. Prior to commercial whaling blue whales ranged throughout the North Pacific, but sightings remain rare in Pacific LAB waters today (Gregr et al. 2006).

Population structure of fin whales in the North Pacific is not well known, although it is suggested that there may be an eastern and a western population. Pre-whaling abundance in the North Pacific has been estimated at 40,000 – 45,000. Whaling reduced the numbers to an estimated 13,000 – 19,000 by 1973, of which 8,500 – 11,000 were assumed to be from the eastern North Pacific. Recently, fin whales have been sighted only infrequently in Pacific LAB, and it is inferred that the population is below 50% of its pre-whaling level (Gregr et al. 2006).

Historically the most abundant of the baleen whales in the North Pacific, sei whales were severely depleted by whaling. The best estimates of abundance (which were made in the 1970s) for the entire North Pacific are 7,260-12,620 from one source, and 1,393-2,248 from another (COSEWIC 2003c). More recently, an abundance estimate of 56 animals (CV = 0.61) was calculated for the Eastern North Pacific population, to a distance of 560 km from shore (Gregr et al. 2006). Sei whales have not been reported in BC waters since the end of whaling (Gregr et al. 2006).

J.1.13 HUMPBACK WHALES

J.1.13.1 Life cycle, age and growth

Humpback whale females give birth to a single calf every 1-5 years in winter following a gestation period of 11-12 months. Most calves are weaned within a year, but some remain with their mothers for two years. Both sexes reach sexual maturity at 5 to 9 years and the estimated lifespan is 80 to 100 years (COSEWIC 2011b).

J.1.13.2 Distribution, habitat and environmental preferences

The humpback whale is a highly migratory baleen whale with a cosmopolitan distribution. Humpback whales undertake seasonal migrations from high latitude feeding grounds (including Pacific LAB), to low latitude breeding grounds. North Pacific breeding grounds are located in Hawaii, Mexico, Central America, and in the west from the Northern Philippines to southern Japan (COSEWIC 2011b).

Humpback whales occur in inshore coastal areas and across the continental shelf in productive high latitude feeding habitat, and travel offshore during migrations (COSEWIC 2011b).

J.1.13.3 Predators and prey

Humpback whales in the North Pacific feed on a highly variable diet that consists of crustacean zooplankton (particularly euphausiids and copepods) and small schooling fishes such as Pacific Herring (*Clupea pallasi*), Capelin, Sandlance, Pacific sardine (*Sardinops sagax*), juvenile salmonids (*Oncorhynchus* spp.), Pacific Cod (*Gadus macrocephalus*), Atka Mackerel (*Pleurogrammus monopterygius*), and Northern Anchovy (*Engraulis mordax*), in addition to pteropods and some cephalopods. Euphausiids seem to be the most common prey by far (COSEWIC 2011b).

J.1.13.4 Abundance

The best estimate of abundance for humpback whales in the entire North Pacific in 2006 was 18,302 excluding calves. Presently, the humpback whale is the most frequently encountered baleen whale in Pacific LAB, with a population of about 2,100 whales estimated in 2006 and a growth rate of 4% per year. Although the humpback whale population in Pacific Canada is increasing, numbers remain below pre-commercial whaling levels (COSEWIC 2011b).

J.1.14 GREY WHALES

J.1.14.1 Life cycle, age and growth

Grey whale females give birth to a single calf on average every 2 years, following a 13-14 month gestation period. Calves are born at 4.6 m in length and are weaned after 6 months. Both sexes reach sexual maturity at about 8 years of age (COSEWIC 2004).

J.1.14.2 Distribution, habitat and environmental preferences

The eastern Pacific grey whale is a coastal. migratory species that ranges as far north as the Beaufort and Chukchi Sea during the summer feeding season, and winters primarily in shallow subtropical lagoons along the west coast of Baja California, Mexico where it mates and calves (COSEWIC 2004; DFO 2010f). Grey whales require breeding lagoons which are characterized by shallow muddy bottoms, have eelgrass and mangroves, and winter temperatures of 15-20 °C.

Grey whales are almost exclusively benthic feeders, and on the feeding grounds are generally found in shallow (< 60m) soft bottom habitats (DFO 2010f). In the Arctic, whales will enter leads in the sea ice to feed. Feeding in Pacific LAB occurs in shallow, nearshore habitat in sheltered bays and inlets with waters depths < 3m (when feeding on ghost shrimp), in sandy bays < 35 m deep on exposed coasts (for amphipods) and over rocky substrate and kelp beds (for mysid shrimp and crab larvae) (DFO 2010f).

J.1.14.3 Predators and prey

Grey whales calves are an important food source for transient (mammal eating) killer whales.

For grey whales, amphipods (mainly *Ampelisca* sp. *Atylus* sp.) are an important prey in Pacific LAB and grey whales feed preferentially in areas where large individuals are common. They also feed extensively on ghost shrimp (*Calianassa californiensis*), planktonic mysid shrimp, crab larvae and eggs and larvae of herring. Grey whales are generalist feeders and are the only species of baleen whale known to regularly feed on benthic prey such as amphipods and ghost shrimp (COSEWIC 2004; DFO 2010f).

J.1.14.4 Abundance

The best estimate for the current size of the eastern Pacific population of grey whales is approximately 20,000 individuals. This is approaching the estimated current carrying capacity for this population; between 20,000 to 30,000 animals (DFO 2010f).

J.1.15 MINKE WHALES

J.1.15.1 Life cycle, age and growth

Minke whale females give birth to a single calf annually following a gestation period of about 10 months. Calves are weaned within 4-5 months. Sexual maturity is reached at 6 to 7 years. Average lifespan is unknown but the maximum is thought to be about 47 years (COSEWIC 2006).

J.1.15.2 Distribution, habitat and environmental preferences

Minke whales are a migratory species with cosmopolitan distribution. In the North Pacific, minke whales range from the Bering and Chukchi Seas to near the equator. Low latitude winter breeding areas are poorly known (COSEWIC 2006).

Minke whales are generally a coastal species (although they can be seen offshore) and appear to prefer shallow water (< 200m). It seems that they prefer to feed in areas over sloping bottom topography. In Pacific LAB, they are most often found in areas with high currents (COSEWIC 2006).

J.1.15.3 Predators and prey

Transient (mammal-eating) killer whales prey on minke whales but the rate of predation is unknown (COSEWIC 2006).

Mink whales have a generalist diet, feeding on a wide range of prey items. In the North Pacific, euphausiids, Japanese Anchovy, Pacific Saury, and Walleye Pollock are thought to be important food items (COSEWIC 2006). Minke whales off the San Juan Islands (just south of Pacific LAB) feed on juvenile Pacific Herring and likely also Pacific Sand Lance. The North Atlantic minke whale diet has been documented to include sand lance, euphausiids, copepods, Atlantic Salmon, Capelin, Haddock, Whiting, Wolffish, Pollock, Atlantic Cod, Atlantic Herring and species of mackerel, sprat, dogfish and squid (COSEWIC 2006).

J.1.15.4 Abundance

There are no abundance estimates of minke whales for the entire North Pacific. In the eastern North Pacific, minke whales are not considered abundant except perhaps in Alaskan waters, and they appear to be least abundant in Pacific LAB waters, where there may be only a few hundred present (COSEWIC 2006; Williams and Thomas 2007).

J.1.16 NORTH PACIFIC RIGHT WHALES

J.1.16.1 Life cycle, age and growth

The life history parameters of North Pacific right whales are unknown due to the extreme rarity of this species.

J.1.16.2 Distribution, habitat and environmental preferences

The post-exploitation distribution of North Pacific right whale is poorly known. Right whales are sighted in the summer in the southern Bering Sea and Gulf of Alaska. Sightings have been reported as far south as Baja California and Hawaii, but the locations of calving and wintering grounds are unknown (Gregr et al. 2006; DFO 2011d). Migratory patterns are unknown, but historically, right whales were found across a wide range of latitudes during summer and winter, suggesting a staggered or diffuse migration.

Very little is known about North Pacific right whale habitat and environmental preferences, but studies from other right whale populations suggest that much of the right whale’s distribution is determined by its dependence on large, dense aggregations of zooplankton prey. Feeding takes place in spring, summer and fall at higher latitudes, in cool and highly productive waters (DFO 2011d).

J.1.16.3 Predators and prey

Like the blue whale, the North Pacific right whale is a specialist forager - They are low trophic-level filter feeders that feed entirely on zooplankton, primarily copepods. Bio-energetic modeling suggests that right whales require between 407,000 and 1,140,000 calories per day– the equivalent of 0.25-2.6 billion late stage copepods (DFO 2011d).

J.1.16.4Abundance

Pre-exploitation abundance of North Pacific right whales was estimated to be in the range of 26,500-37,000 animals. Right whale populations were decimated by whaling, and today it is believed that considerably fewer than 100 individuals remain in the eastern North Pacific population. There have been only two sightings of right whales in Pacific LAB since 1951, and both were in 2013—one off the north end of Haida Gwaii, and the second at the mouth of the Strait of Juan de Fuca (DFO 2011d; Wikipedia 2014).

J.2 CLIMATE CHANGE AND MARINE MAMMALS

Marine mammals are one of the most visible groups of species in Pacific LAB's coastal waters. Some species such as sea otters, harbour seals and harbour porpoise breed and live here year round, while others such as California sea lions and humpback whales come to feed during the non-breeding season, and others such as northern fur seals and most grey whales swim past on their annual migrations north and south (Ford 2014). The physiologies and life cycles of all of these species have evolved to optimize survival and reproduction—and are seasonally timed to take advantage of optimal environmental conditions (water temperatures, storms, etc.) and the predictability of abundant prey species (i.e. spawning and feeding aggregations, qualities, locations, etc.).

The extent to which the mid-latitude marine mammals such as those inhabiting Pacific LAB will adapt to the effects of climate change is largely unknown (Simmonds and Isaac 2007; Okey et al. 2014). However, it is generally believed that climate change will affect marine mammals less at the mid-latitudes than it will in the Arctic (Simmonds and Isaac 2007). In the Arctic, the life cycles of marine mammals and their prey are tightly linked to the presence of seasonal and multi-year ice, which provides a platform for some species of seals to rest and breed on, a barrier to predation by killer whales, and dampens the effects of storms (Bluhm and Gradinger 2008; Kovacs et al. 2011). Ice is also associated with much of the primary production that forms the base of much of the Arctic marine food web (Michel et al. 2012; Jeffries et al. 2013; Post et al. 2013). As air and water temperatures warm, and the ice thins and retracts, a noticeable northward shift has been detected in the distribution of molluscs, crabs, fish and marine mammals (Mueter and Litzow 2008; Kovacs et al. 2011; Hollowed et al. 2013; IPCC 2014). Such effects of climate change will result in both winners and losers among species of Arctic marine mammals (Laidre et al. 2008; Moore and Huntington 2008). Those deemed to become the biggest winners are expected to be those with flexible habitat requirements, while the biggest losers are likely to be those that have small numbers, restricted distributions, feeding specialization and seasonal dependence on breeding sites (Laidre et al. 2008). Such general principles likely also apply to determining which species will be the winners and losers in Pacific LAB as marine mammals respond to the effects of climate change.

Some of the 27 species of marine mammal that occur in Pacific LAB are common (e.g. killer whales and Pacific white-sided dolphins), while others are rarely seen and may be currently at the northern limits of their ranges (e.g. Risso's dolphin and striped dolphin). In addition, some species have recovered from the effects of culling and hunting (e.g. harbour seals and Steller sea lions), while others appear to be on a much slower path to recovery if at all (e.g. sei whales and right whales). Distributions also vary, with some species occurring primarily in coastal waters (e.g. grey whales and humpback whales), while others occur mainly offshore along the continental shelf break (e.g. beaked whales and blue whales). Only 7 of the 27 species give birth and breed in Pacific LAB (northern sea otters, Steller sea lions, Pacific harbour seals, killer whales, Pacific white-sided dolphin, harbour porpoise and Dall's porpoise). The remainder may bring their young to Pacific LAB to feed, or may simply be here to improve their body condition and ultimately their own reproductive success. Thus, only 7 of the 27 species are considered to be year-round residents of Pacific LAB waters (although there is less certainty about the 4 species of beaked whales).

Some of the impacts of climate change include warmer air and water temperatures, increases in sea levels and the severity of storms, northward shifts in the distributions of fish and invertebrates, and changes in salinity, and ocean acidification (Parmesan 2006; Griffis and Howard 2013; IPCC 2014). Such changes can directly and indirectly affect the physiologies, distributions, and phenologies of marine mammals (Hughes 2000). However, assessing how these changes are currently affecting the 27 species of marine mammals that occur in Pacific LAB, and predicting how they will affect them in the future requires knowledge about their life histories, physiologies, abundances, habitat requirements, and prey needs (see Biological characteristics). Only then can the sensitivity of each species to change be assessed, as well as its resilience and the possible ecosystem level interactions that might result. Similarly, it is only through such an assessment that the critical knowledge gaps and levels of uncertainty can be identified.

J.2.1 Current/known impacts of climate change on marine mammals

Changes in numbers and distributions are likely to be the first response to climate change. However, it is difficult to disentangle the recolonization of previously hunted species from climate change effects (e.g. sea otters and fin whales). Similarly, there is insufficient data to know whether some recently observed shifts in distributions (e.g. Pacific white-sided dolphins and humpback whales) are due to a natural- or human-caused change in the distribution of their prey.

Sea otters

Prior to exploitation, northern sea otters ranged from northern Japan to central Baja California, Mexico (COSEWIC 2007). They were re-introduced to Pacific LAB between 1965 and 1972 (having been extirpated from Pacific LAB in 1929), and now occur along most of the west coast of Vancouver Island, and along a small section of the Pacific LAB central coast. Sea otters are believed to have once occupied most of Pacific LAB, and currently occupy about 25-33% of their former range (COSEWIC 2007). The population has expanded since being re-introduced and numbered 2,673 along Vancouver Island, and 507 on the central Pacific LAB coast in 2001 (representing about 3-4% of the global sea otter population). The Pacific LAB population is continuing to expand its range with an estimated growth rate of 15.6% per year on Vancouver Island and 12.4% per year on the Pacific LAB central coast (COSEWIC 2007). There is no indication that any of these changes are related to climate change.

Pinnipeds

Steller sea lions range throughout the cool-temperate and sub-arctic coastal waters of the North Pacific Ocean from California to northern Japan. In British Columbia, they have been increasing at an exponential rate and number about 35,000 during the summer breeding season and about 50,000 during winter. They have established two new breeding sites in the past decade (bringing the total to 5 rookeries in Pacific LAB) (Olesiuk 2011). This growth of Steller sea lion numbers coincides with an increase in high-energy prey species in their diet (e.g. herring and sand lance), and is opposite the declines of sea lions in Russia and the Gulf of Alaska (where diets are dominated by low energy species of gadids and hexagramids) (COSEWIC 2003b). The change in diets that appears to drive the different population trajectories is believed to be caused by an oceanic regime shift and not climate change (Trites et al. 2007).

California sea lions returned to Vancouver Island in the 1970s after the devastating culls and hunts in Mexico and California had ended (Bigg 1973). However, it is almost entirely adult and subadult male California sea lions that arrive each fall to fatten, and depart each spring to breed. Female California sea lions are believed to be too small to tolerate the colder waters of British Columbia. Male California sea lions appear to be slowly moving northward to feed in more northerly parts of Pacific LAB, but the expansion (if real) most likely reflects the continued growth of the breeding colonies rather than warmer water temperatures or a shift in prey distributions.

Harbour seals inhabit coastal temperate and subarctic coastal waters throughout much of the northern hemisphere. In British Columbia, they rest and give birth at about 1,400 haulouts (Olesiuk 2010). Their numbers increased exponentially during the 1970s and 1980s (~11.5% per year), and slowed in the mid-1990s. The Pacific LAB population appears to be at carrying capacity (105,000 animals) due perhaps to predation by killer whales, and accounts for about 29% of the 360,000 harbour seals estimated to inhabit the North East Pacific Ocean (Olesiuk 2010). None of these changes in harbour seal numbers is likely to reflect a change in climate.

Odontocetes

Killer whales occur in all of the world's oceans and are most common in areas associated with high ocean productivity in mid to high latitudes. They do not migrate to separate feeding and breeding grounds, but appear to be seasonally influenced by the distribution and accessibility of their prey (COSEWIC 2008). The west coast transient population (~250 individuals) occurs throughout the coastal waters of British Columbia, while the southern resident population (~85 individuals) is generally found near southern Vancouver Island in summer and fall (although the animals may range widely at other times of year as far south as California) and the northern resident population (~250 individuals) occurs from central Vancouver Island north to southeastern Alaska in summer and fall. The ranges of the southern and northern resident populations at other times of the year are not well known. Offshore killer whales (~300 individuals) are seen less frequently, but are known to travel widely in coastal waters (COSEWIC 2008). In general, numbers of killer whales in the different populations appear to have been slowly increasing, but are small (and have likely always been relatively low). However, none of these observations are believed to be associated with climate change.

Harbour porpoise have a northern hemisphere, circumpolar distribution and inhabit cold-temperate, sub-arctic waters from Bering Strait, Alaska, to central California in the eastern Pacific Ocean. They occur in Pacific LAB year round and are seldom in water warmer than 16°C. Harbour porpoise tend to occur in relatively shallow waters close to shore (generally <150m), but relatively little is known about their abundance and population trends in Pacific LAB. However, a reduction in sightings suggests that their numbers may be declining due possibly to human disturbance in nearshore coastal areas (DFO 2009b).

Dall's porpoise are common across the entire North Pacific Ocean. In the North East Pacific they occur from Alaska to Baja, California. Dall's porpoise occur in coastal and deep oceanic waters of Pacific LAB (Money and Trites 1998), and may number about 5,000 individuals (Williams and Thomas 2007). Unfortunately no data are available to assess population trends for Dall's porpoise.

Pacific white-sided dolphins are likely the most abundant cetacean in the inshore and nearshore waters of British Columbia. They are largely considered an open-ocean species and may number about 26,000 in Pacific LAB coastal waters (Williams and Thomas 2007). Sporadic sightings of Pacific white-sided dolphins began increasing in the nearshore and inshore waters of the central coast of Pacific LAB in the 1980s. This same nearshore phenomenon was noted around southern Vancouver Island in the 1990s. By the early 2000s, there were frequent sightings of Pacific white-sided dolphins in the Strait of Georgia. The appearance of dolphins is thought to be due to immigration rather than an increase in population numbers (Heise 1996), but whether it reflects a decrease in prey in the open ocean, an increase in energy rich prey in-shore, or a response to climate change is not known. They are however, the one species of marine mammal that has shown a marked shift in distribution since the 1980s.

The northern right whale dolphin occurs in temperate waters throughout the North Pacific Ocean ranging from Alaska to Baja, California in the eastern Pacific. In Pacific LAB, this species is most often recorded from the southern parts of the province (Money and Trites 1998). No estimates of abundance or population trends are available northern right whale dolphins.

Risso's dolphins have a worldwide distribution and occur in tropical and warm temperate seas. They are found in the eastern North Pacific Ocean from the Gulf of Alaska to south of Baja, California. They have been recorded year-round in the waters off Pacific LAB (Money and Trites 1998). No estimates of abundance or population trends are available for Risso’s dolphins.

Sperm whales are the second most widely distributed marine mammal species, occurring in all of the world’s oceans from the equator, to the north and south polar pack-ice (Mizroch and Rice 2013). Sperm whales occur throughout the eastern North Pacific, but are generally distributed below 40°N in the winter. Males move north to feed in the summer, while females and young remain in tropical and temperate waters throughout the year. Sperm whales are usually found far offshore, except in cases where the shelf break or submarine canyons occur close to land, such as along the west coast of Haida Gwaii. No estimates of abundance or population trends are available for sperm whales.

Beaked whales (family Ziphiidae) were commonly seen from commercial whaling vessels in the mid-1900's, but sightings have been rare along the Pacific LAB coast since that time. Relatively little is known about these species in Canada (Money and Trites 1998). They have been seen over the deep water canyons off Haida Gwaii (Ford et al. 2010a).

Mysticetes

The blue, fin and sei whales are largely pelagic, and are found in deep offshore waters and near the shelf break (Gregr and Trites 2001). The humpback, grey and minke whales are coastal species but humpbacks travel offshore during migrations (COSEWIC 2011b). Baleen whales undertake extensive seasonal migrations from low-latitude wintering (breeding and calving) areas to high-latitude, summer feeding grounds, although this may not be the case for all fin whales (Mizroch et al. 2009). The baleen whales occurring in BC belong to populations that range as far south as Mexico, and as far north as the Bering Sea, and west to Hawaii (in the case of the humpback whale). No specific breeding grounds have yet been identified for eastern North Pacific blue, fin, sei or right whales (Gregr et al. 2006; DFO 2011d). Blue and fin whales appear to be slowly rebuilding and recolonizing Pacific LAB following the end of whaling. However, there is no indication that the more frequent sightings today are related to climate change. In contrast, no sei whales and only two North Pacific right whales have been reported in BC waters since the end of whaling (Gregr et al. 2006; Wikipedia 2014).

Humpback whales feed in BC during summer and breed in Mexico and Hawaii during winter (COSEWIC 2011a). One of the BC populations feeds from central Vancouver Island through Southeast Alaska (about 3,000-5,000 whales) and winters mostly in Hawaii, while the smaller population that feeds around southwestern Vancouver Island and Washington State (about 200-400 whales) winters off Mexico, as well as Hawaii. Most of these whales are in Pacific LAB only during summer—although a small number remain throughout the year. The number of humpback whales relying on prey in Pacific LAB during summer is about 2,500 individuals (COSEWIC 2011a). Their increases in numbers are not believed to reflect climate change.

Winter habitat of eastern Pacific grey whales is primarily the subtropical lagoons along the west coast of Baja California, Mexico. Most grey whales summer in the arctic in the Bering, Chukchi, and Beaufort Seas (in Alaska and Russia). Almost the entire population passes each year within a few kilometres of the Pacific LAB coast. However, a small portion of the population summers along the North American coast and does not complete the long 20,000 km (roundtrip) migration. Of these summer-residents, a couple hundred individuals stay and feed in British Columbia. Grey whales must store significant amounts of fat to survive the winter. A number of grey whales in poor body condition have stranded in recent years during their northward migration suggesting that they had not acquired sufficient energy the previous summer. This might reflect climate-induced reductions in the quality or quantity of prey available to them in the Arctic. About one-third of the population disappeared from 1989 to 2002. The best estimate for the current size of the eastern Pacific population of grey whales is approximately 20,000 individuals (DFO 2010f).

Minke whales are common and abundant in most of the world’s oceans, but appear to be naturally rare in Pacific LAB and elsewhere along the west coast of North America. They were never hunted, but are preyed on occasionally by killer whales. They tend to use shallow waters (<200 m) in the coastal and inshore areas, and are seen most frequently in the spring and summer. Most are assumed to migrate to lower latitude breeding areas in the fall and winter. There may be only a few hundred present in Pacific LAB (COSEWIC 2006; Williams and Thomas 2007).

Pre-exploitation abundance of North Pacific right whales was estimated to be 26,500-37,000 animals. Fewer than 100 individuals remain in the eastern North Pacific population. There have only been two sightings of right whales in Pacific LAB (both in 2013) since 1951 (DFO 2011d) (John Ford, pers. comm.)

J.2.2 Sensitivity of marine mammals to climate induced changes

Physiologically, it is difficult to imagine that a change in water temperature of a few degrees will have much impact on the seals and sea lions that currently reside in Pacific LAB given how far south and north they range. At best, the warmer water might enable some of the smaller and less well-insulated species (such as female California sea lions) to expand the northern limits of their current range. Pinnipeds have evolved effective means to conserve heat when cold and to dump heat when too warm, which allows them to rest on shore under a hot sun, or remain under the icy cold sea. Thus, the wide thermal limits of pinnipeds should accommodate projected increases in water temperatures. However, the same does not appear to be true for cetaceans.

In general, water temperatures are a good predictor of current distributions of cetaceans (Kaschner et al. 2006). Some species such as killer whales, grey whales and humpback whales have cosmopolitan distributions that encompass tropical to polar waters—while others such as harbour porpoise, Dall's porpoise and Pacific white-sided dolphins are restricted to temperate to sub-polar waters. Increasing water temperatures will likely shift and contract the distributions of these smaller temperate species of cetaceans assuming that they stay within their preferred temperatures (MacLeod 2009). However, warmer water temperatures are unlikely to negatively affect sperm whales and most baleen whales (MacLeod 2009). Unfortunately, the thermal neutral zones of the cetacean species that occur in BC are unknown.

Climate induced changes in salinity, pH and CO_2 are unlikely to directly affect marine mammals. However, indirectly, cetaceans may be negatively affected by increased noise levels. Chemical absorption of sound in CO_2 enriched water is projected to become half of what it is currently (Ilyina et al. 2010), potentially causing an increase in anthropogenic noise levels. This would negatively affect foraging, reproduction, and group cohesion of porpoise, dolphins and whales by interfering with communication. Although there is no evidence yet of any biota being affected by the CO_2 induced increase in sound propagation (Ilyina et al. 2010), there is concern that the propagation range of noise in the ocean will increase, particularly for 1 kHz sounds (IPCC 2014).

Increases in CO_2 and ocean acidification is expected to significantly impact the shellfish that sea otters depend on (bivalves such as Butter Clam, Horse Clam, Geoduck; snails, urchins, chitons, and crabs). However, the extent to which this will impact the abundance of invertebrates and consequently the abundance and distribution of sea otters is unclear.

Rises in sea levels will cover some of the haulouts and rookeries currently used by seals and sea lions in Pacific LAB, as has been projected to impact pinniped populations elsewhere (Baker et al. 2007; Funayama et al. 2013). Harbour seals use the lowest land areas and are more likely to be affected than Steller sea lions that typically climb high out of the water on steeply sloped shorelines and rocky islands. The extent to which new haulout sites will be available to harbour seals as the waters rise is unclear. However, some sites such as beaches that have cliff backdrops will likely have to be abandoned. The increases in sea levels combined with intensified winds, wave heights and storm surges may alter the topography of some of the shorelines currently used by seals and sea lions.

The intensity of storms is projected to increase as climate change continues (Scavia et al. 2002; Webster et al. 2005; IPCC 2014). Greater wave heights and increased storm surges will negatively affect the survival of Steller sea lion pups and possibly harbour seal pups as well. Both species require land to give birth. Pups are unable to swim at birth and will not do so for a number of days in the case of harbour seal pups, or for a number of months in the case of Steller sea lion pups. Storms frequently wash Steller sea lion pups off the exposed rocky outcroppings where they are born and are the largest cause of death. Higher mortalities should therefore be expected as storm intensities increase. Steller sea lions are further limited by having only 5 breeding locations in Pacific LAB (Olesiuk 2011).

Storms also appear to disrupt the prey fields in the upper water column as shown in the Bering Sea for northern fur seals (Sterling 2009). Satellite-tracked northern fur seals from different breeding colonies feed in predictable areas on small schooling fish that occur near the surface

(<20 m). However, the predictability of their foraging paths and feeding areas disappears following a storm, apparently because prey are no longer where they once were. Whether the mixed layer deeper along with their prey following a storm, or whether the schools of prey are dispersed, or whether something else has changed the availability of prey is unclear. What is apparent however is that storms can alter the availability of some prey species, which will in turn negatively affect the foraging success of marine mammals. Species with less diversity in dietary preferences may therefore be more sensitive to storm-induced changes in prey availability.

Rainfall is expected to increase in the coming years as climate changes (Ohring 2014), which will increase the flow of contaminants, novel pathogens and nutrients from land into the ocean. Species at the upper end of their thermal tolerance may be stressed by warmer temperatures and be more susceptible to disease (Lafferty et al. 2004; Burge et al. 2014). They may also inhabit urbanized areas and more readily consume prey that are contaminated or contain deadly parasites (Ross 2000; Mos et al. 2006; Cameron et al. 2008; Johnson et al. 2009; Alava et al. 2012; Mazzillo et al. 2013). In addition, increased temperatures and poorer water quality are expected to increase the frequency and intensity of toxic algal blooms that kill marine mammals (Scholin et al. 2000; Bejarano et al. 2008; Bargu et al. 2010). Marine mammals that inhabit the nearshore (particularly near urbanized areas) such as seals, sea lions, sea otters, and harbour porpoise are likely to be most susceptible to such stressors.

Nutritionally, all marine mammals have high metabolisms that require consuming relatively large amounts of prey to meet their daily energy needs compared to their terrestrial counterparts (Williams et al. 2001; Williams and Worthy 2002; Williams 2007; McNab 2012). Some species such as sea otters, Steller sea lions and Pacific white-sided dolphins have particularly high metabolisms that require eating fatty species of prey (e.g. Pacific Herring), while others such as harbour seals can do fine on lower quality prey such as cod *spp*. or Pacific Hake. Marine mammals tend to have species-specific diets that appear to reflect differences in their relative costs of living (Spitz et al. 2012). As such, some species of marine mammals would stand to benefit if climate change increased the abundances of their needed prey, while others would receive no benefit or would lose out if climate change reduced the availability of their prey species.

Killer whales appear to be the most highly specialized group of marine mammals in Pacific LAB, and have highly specialized diets (primarily Chinook Salmon for resident killer whales, harbour seals for transient killer whales, and possibly sharks for offshore killer whales) (Ford et al. 2010b). They appear to have less flexibility in what they eat and may therefore be most at risk (COSEWIC 2008). Other species that need high lipid prey species may also prove to be more sensitive to climate-induced changes in the prey field compared to those that are adapted to living off the low caloric species (i.e. the junk food hypothesis) (Rosen and Trites 2000; Osterblom et al. 2008; Whitfield 2008; Spitz et al. 2012).

Baleen whales are relatively low trophic level feeders. Some such as blue whales and right whales feed exclusively on zooplankton (copepods), while others such as humpback whales feed heavily on krill, copepods and small schooling fish (e.g. Pacific Herring, Capelin, and Pacific Sand Lance, juvenile Pacific Salmon, Pacific Sardine, and cod and mackerel *spp*.) (Gregr et al. 2006; DFO 2011d). Dietary diversity (Harley 2011) suggests that species such as humpback whales would likely be more flexible and less sensitive to changes in the prey base compared to the more specialized zooplankton feeders. The specialized feeders may further be at risk should the warmer waters increase the abundance of the lipid poor copepods (*Calanus finmarchicus*) and reduce the abundance of lipid rich species (*C. glacisiallis*) as documented in the warming waters of western Greenland (Slagstad et al. 2011).

Of the baleen whales, humpback whales have the most versatile feeding behaviours, which include lunge feeding, flick feeding, co-operative bubble netting, and lob-tailing (COSEWIC 2011b). These behaviors appear learned, and spread through populations via cultural transmission as illustrated in the Atlantic when a new feeding behavior spread among the humpback whales in response to switching from herring to sand lance prey (Weinrich et al. 1992). Such behavioral plasticity is conducive to being able to adapt to climate change induced changes in prey. Minke whales also seem to have considerable plasticity in foraging, and are able to consume a wide variety of species at lower densities and younger age classes than either the fin whale or humpback whale (COSEWIC 2006).

Marine mammals thrive towards the polar regions of the world and occur in significantly fewer numbers in tropical waters where the prey base is typically very diverse, but the caloric density of the prey is quite low. The extent to which climate change might shift the distribution of prey species northwards and in turn lower the relative energy density of prey species in Pacific LAB will likely be a key determining factor influencing the continued presence and abundance of marine mammals in the region.

Marine mammals will have to contend with a number of projected changes to the behavior and distribution of their prey. Fish generally swim faster in warmer waters (Cairns et al. 2008), which will require predators to expend more energy to capture them. Prey may also be at deeper depths and again require marine mammals to expend more energy to access them (McIntyre et al. 2011). Similarly, abundance of prey could decline if warming surface waters shift the food web structure (O'Connor et al. 2009) or reduces the upwelling of the nutrition rich waters that forms the base of the marine mammal food chain (Roemmich and McGowan 1995). Disruption of the physical processes that concentrate prey could further impede foraging and reduce survival rates and reproductive success (Learmonth et al. 2006), while lower densities of prey may support smaller numbers of marine mammals and diminish the social cohesion of groups such as Pacific white-sided dolphins and resident killer whales (Lusseau et al. 2004).

Shifts in areas of high productivity will be particularly costly to central place foragers—most notably the lactating seals and sea lions that must transit from fixed terrestrial breeding sites to acquire sufficient energy to produce the rich milk needed to nourish their pups waiting on shore (Hazen et al. 2012). All these possible climate induced changes to the food base stand to increase energy expenditures and decrease the energy intakes of marine mammals in Pacific LAB.

Large baleen whales arriving at their northern feeding grounds in the summer typically have depleted energy reserves (due to the cost of breeding, fasting and migrating) and need to find food within a certain time-frame (Robinson et al. 2009). They may be particularly sensitive to disruptions in the availability of their prey at this time of year, or may be unable to acquire sufficient energy over a summer of feeding to attain the level of fitness needed to successfully reproduce (Hazen et al. 2012). Climate change may alter the timing of coupled events such as the bloom of primary production that in turn affects secondary production and so on up the food chain. Increased storminess may also disperse prey and make it more diffuse and difficult for marine mammals to acquire—particularly for species that feed in the upper water column compared to those that feed on benthic species. As such, it is conceivable that the quality and quantity of prey may not be present when needed most by lactating females, recently weaned young, or animals that have returned to Pacific LAB after fasting for most of the winter.

In summary, prey distribution strongly influences the distribution, abundance and movements of marine mammals. Species of marine mammals with highly specialized diets such as killer whales and blue whales may be more sensitive to climate-induced changes in prey than those that are generalists. Marine mammals that require fattier prey species may also have less flexibility to contend with climate-induced changes in the prey base than those that feed on lower quality and typically slower moving prey. Increases in the frequency of extreme storms may also disrupt the availability of prey and have a greater effect on the specialist eaters. Such storms will also play havoc on the breeding beaches of seals and sea lions. However, it remains to be seen the extent to which these events will outwardly kill individuals or induce nutritional stress, health effects, and reproductive failures that ultimately have population level consequences.

J.2.3 Resilience of marine mammals to climate-induced change

The resilience of marine mammals in Pacific LAB to climate-induced change will depend on their numbers, locations of breeding areas, and degree of specialization.

Ultimately, seals and sea lions should establish new breeding and pupping areas to replace those that are no longer useable, assuming that offspring born at novel sites survive and return as adults to breed where they were born. Increases in air temperatures should also be tolerable to harbour seals and Steller sea lions. However, it is conceivable that increases in air and water temperatures could benefit species currently breeding further south in California and Mexico (California sea lions and northern elephant seals) and could result in them establishing successful breeding colonies in British Columbia.

Other species of marine mammals that are currently at the northern limit of their range in Pacific LAB such as Risso's dolphins or striped dolphins may also find conditions more amenable to them as water temperatures warm and prey species shift their distributions northward. However, any such increases in the presence of other species of marine mammals will likely come at an increased competitive cost to the species of seals, sea lions, porpoise and dolphins that currently reside in Pacific LAB. Species such as harbour porpoise, Dall's porpoise and white-sided dolphins that are less tolerant of warmer waters compared to larger species of cetaceans may also have their distributions contracted within Pacific LAB as they are forced to move northward to cooler waters.

The extent to which the rare species of marine mammals are likely to increase and compete with those that are currently common in Pacific LAB will depend on the extent to which fish and invertebrate species shift their distributions northward. Mathematical models suggest that the marine communities that are most at risk from climate change induced changes in distribution and diversity are at the extreme ends of the environmental temperature spectrum (the poles and the equatorial belt) rather than temperate waters like Pacific LAB (Cheung et al. 2009). Hence, it is conceivable that there may not be significant shifts in the distributions of marine mammal species in Pacific LAB. However, southern species have regularly been observed to invade Pacific LAB waters during El Niño events (Okey et al. 2014)—suggesting there is a high likelihood that marine mammals currently in BC will have to contend with new species in the future. Species such as California sea lions and striped dolphins could expand their ranges northward and reduce reproductive and survival rates of Steller sea lions and Pacific white-sided dolphins through competitive interactions for food.

Marine mammals display considerable site fidelity to traditional feeding and breeding areas, but over time can also learn and take advantage of new opportunities whether it be new haulout sites for pinnipeds or ephemeral sources of prey (as shown by the establishment of new Steller sea lion breeding sites, or depredation by killer whales and sperm whales on fish caught with longline fishing gear). Adults are undoubtedly the most resilient to climate-induced changes, and the young the least. Thus, extreme negative changes will be borne first by the young, and much later by the old, with enough time presumably to adapt and change in step with climate change.

J.3 ECOSYSTEM LEVEL INTERACTIONS

Increases or decreases in marine mammals could have ecosystem level effects on Pacific LAB's marine waters given the role they play as consumers and competitors. For example, sea lions are major competitors of large flat fish such as Pacific Halibut, and harbour porpoise occupy the same trophic level as adult Pacific Salmon (which both feed on zooplanktivorous fish) (Trites et al. 1999). Changing numbers of marine mammals could have cascading effects on other species in the ecosystem. For example it has been suggested that ecosystems with sea otters are 2 to 3 times more productive and support a greater abundance and diversity of fish than those without sea otters (Sea Otter Recovery Team 2007). Similarly, baleen whale populations are sustained by large quantities of zooplankton and presumably have cascading effects in systems where they are present or are missing (Gregr et al. 2006).

In addition to being consumers and competitors, marine mammals also perform a dynamic role by transferring nutrients and energy, or by regulating the abundance of other species (Bowen 1997; Trites 1997). Top down control such as predation by transient killer whales can slow or stop the growth of other top predators (such as appears to have occurred for harbour seals, and may be occurring for harbour porpoise and white-sided dolphins in the coastal waters). Some, such as sea otters, also play a structural role by influencing the physical complexity of the environment. It is thought that patterns of food consumption by baleen whales have had strong effects on community structure in the Bering Sea (DFO 2011d). Conceivably the depletion of large baleen whales by whaling resulted in increases in ecologically-equivalent finfish stocks. The potential for trophic displacement may be more likely for blue and right whales due to their specialized diet of zooplankton.

The functional and structural roles of marine mammals in marine ecosystems as consumers and competitors are more likely to be most evident in simple short-chained food webs, and least obvious in complex long chained ones (Trites 1997, 2003). However, convincingly demonstrating that climate-induced changes in marine mammal numbers and distributions will propagate through the ecosystem seems unlikely, despite the theoretical probability that such things could occur.

Table J2. Summary of potential impacts, vulnerabilities and opportunities from climate change for marine mammals.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Species at the upper end of their thermal tolerance may be stressed by warmer temperatures and be more susceptible to disease; Increased temperatures and poorer water quality are expected to increase the frequency and intensity of toxic algal blooms that kill marine mammals; Impact of changes in prey abundance or composition may be positive or negative.	Increasing water temperatures will likely shift and contract the distributions of smaller temperate species of cetaceans assuming that they stay within their preferred temperatures; Warmer temperatures are unlikely to negatively affect sperm whales and most baleen whales; Possible shifts in feeding behaviours to track changes in prey distribution.	Temperature driven changes in prey abundance and distribution may impact migrating whales that depend on prey at specific locations and times to complete life cycle events.
Sea surface salinity	No information	No information	No information
Freshwater discharge	Increased flow of contaminants, pathogens and nutrients from land known to impact marine mammal health, mainly negatively	No information	No information
Sea level change	No information	Reduced access to areas used as haulouts and rookeries currently used by seals and sea lions.	No information
Ocean acidification	Indirect impacts may increase anthropogenic noise affecting reproduction; May significantly impact shellfish that sea otters depend on;	No information	No information
Ocean Currents	No information	No information	No information
Stratification	No information	No information	No information
Upwelling winds	No information	No information	No information
Dissolved oxygen	No information	No information	No information

J.4 ADDITIONAL STRESSORS

Marine mammals currently contend with a number of anthropogenic alterations to their environment that affect or have the potential to affect reproduction and survival. These range from contaminants, to underwater noise, entanglement in debris, illegal shootings, and competition with fisheries.

Harvesting species of fish consumed by pinnipeds and cetaceans can affect their availability to marine mammals. This is especially true for resident killer whales that feed almost exclusively on Pacific Salmon. Similarly, commercial harvesting of Pacific Herring, Pacific sardine, or other forage fish has the potential to impact the food sources of fin, sei, grey, humpback and minke whales although is unlikely inflict nutritional stress because these whales are generalist feeders and could presumably switch to another type of prey. Fisheries could nevertheless force cetaceans to feed on alternative species elsewhere thereby altering distributions of cetaceans. It is also possible for fishery reductions to benefit other species of whales that feed on plankton (blue and right whales) by removing competing fish stocks (Gregr et al. 2006; DFO 2011d). However, trophic interactions are complex and tend to be difficult to reliably predict.

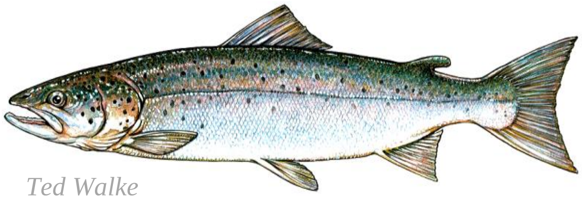
Sea otters may also have an added stress posed by commercial harvesting of their invertebrate prey (i.e. Geoduck, Dungeness Crab, sea urchins, sea cucumbers). Fishery induced reductions in densities of invertebrates combined with other projected effects of climate change on invertebrates may negatively affect the recovery of sea otters (COSEWIC 2007).

Contaminant levels in killer whales are considerably higher than those known to cause reproductive impairment, skeletal abnormalities, endocrine disruption, and immunotoxicity in other mammals such as pinnipeds (Ross et al. 2000; COSEWIC 2008). Insufficient prey availability results in the use of blubber reserves and causes mobilization of accumulated contaminants (Learmonth et al. 2006). Increased runoff of contaminants from terrestrial sources combined with greater concentrations in marine food webs and higher mobilization of accumulated contaminants may compromise killer whale populations in Pacific LAB.

J.5 GAPS AND UNCERTAINTY

Marine mammals are likely to respond most strongly to climate-induced changes to the distribution and abundance of the prey they depend on. Reliably predicting how marine mammals will respond to climate change thus requires reducing uncertainty in how fish and invertebrates will respond. Similarly, reliable projections of increases in sea levels and the frequency and severity of storms (e.g. wind speeds, wave heights, storm surges, etc.) caused by climate change will also improve predictions about how pinniped haulouts and rookeries might be affected, as well as how the availability of prey might respond.

Documenting the responses of marine mammals to climate change will require dedicated monitoring of population numbers, birth and death rates, distributions, diets, and measures of health and body condition. However, obtaining reliable estimates of population size, trends and structure and movement patterns are more difficult for some species such as the baleen whales that have extensive ranges and small populations (due to whaling) (Gregr et al. 2006). Another challenge is to separate short-term effects due to natural environmental shifts from climate-change induced responses. Thus, it may only be possible to confirm an effect of climate change on marine mammals on a decadal scale. Similarly, it may be difficult to investigate the effects of climate change on higher trophic levels because they likely involve relationships that are non-trivial, nonlinear and have time lags (Lusseau et al. 2004; Simmonds and Isaac 2007). And finally, the complex interactions between ocean processes and climate may vary greatly between areas, and further confound attempts to definitively identify the effects of climate change on marine mammals in British Columbia.



K. Atlantic Salmon

(***Salmo salar***)

Al Castledine, Joy Wade and Chris Pearce

KEY POINTS

- Farmed Atlantic Salmon is by far the most valuable seafood product from Pacific LAB.
- Performance of Atlantic Salmon may be affected by changes in ocean temperature, dissolved oxygen, salinity and acidity and, the advent of more frequent harmful algal blooms which may result in lost productivity or direct mortality.
- Higher ocean temperatures could result in more problems with native and invasive bio-fouling species and the need for more frequent cleaning which would increase production costs.

K.1 BIOLOGICAL CHARACTERISTICS

K.1.1 Life cycle, age and growth

Atlantic Salmon, native to the North Atlantic Ocean, are very similar to other salmonids having both freshwater and marine components in the life history. Eggs, fry (alevin) and parr stages require freshwater. The parr to smolt transformation is a radical change in anatomical and physiological characteristics enabling the fish to live in salt water. Juvenile and adult stages are spent in marine environment until adults return to spawn in freshwater. Atlantic Salmon, unlike the Pacific species, are iteroparous and do not necessarily die after spawning.

To simulate the natural life history pattern of Atlantic Salmon, all commercial operations involve an on-land freshwater hatchery phase followed by a marine ‘grow-out’ phase that occurs at licensed farm sites. There is one land-based grow-out facility currently operational on Vancouver Island. The culture methods described in Section 2.0 are intended to be for general reference. Individual companies culture animals in different ways.

K.1.2 Distribution, habitat and environmental preferences

Atlantic Salmon do not have a natural distribution in the Pacific Ocean.

Hatchery and marine grow-out phases of the cultured Atlantic Salmon life cycle rely on maintaining conditions that suit the species thermal preferences. Critical lower and upper temperature limits for the survival of Atlantic Salmon life stages (Elliott and Elliott 2010): eggs, 0°C to 16°C; alevin, 0-2°C to 23-25°C; parr/smolt (ultimate) -0.8°C to 30-33°C; parr/smolt (feeding), 0-7°C to 22-28°C. The lethal temperature in sea water is -0.75°C (Elliott and Elliott, 2010). For Atlantic Salmon in Norway, the temperature limits for optimum growth are 16.3-20.0°C and 12-18°C for growth efficiency (Elliott and Elliott 2010). Water temperatures in freshwater may increase in some systems, especially in the summer months when flow is reduced to require manipulation of water temperatures in culture operations.

K.1.3 Pathogen and culture issues

The advent of new diseases or parasites is unpredictable but some authorities fully expect that the industry will be challenged to manage them in future. The Canadian Food Inspection Agency lists Atlantic Salmon susceptible to the following reportable and immediately notifiable diseases: Infectious Pancreatic Necrosis (IPN), Ceratomyxosis (*Ceratomyxa shasta*), Infectious Haematopoietic Necrosis (IHN), Infectious Salmon Anaemia (ISA), whirling disease (*Myxobolus cerebralis*), Viral Haemorrhagic Septicaemia (VHS) and, Gyrodactylosis (*Gyrodactylus salaris*). This does not mean that these diseases have been found in Atlantic Salmon in British Columbia, only that as a species they are susceptible. There are other pathogens of concern to the health of Atlantic Salmon which are not reportable or immediately notifiable diseases. Sea lice is a term used to apply to several species of marine copepod which infect Atlantic Salmon as well as many other wild fish species. In British Columbia, sea lice are not considered a major fish health issue although fish are treated for them. Mitigation measures include single year class stocking, site fallowing; treatments with veterinarian prescribed in-feed therapeutants may also be required to decrease the number of lice/fish in accordance with management practices. Under climate change, increased freshwater inputs to marine growing sites could alter salmon-sea lice interactions and infection levels in some areas.

Individual companies, and sites, have their own fish health monitoring plans which include pathogen detection. Fish health plans are also a condition of licence. In addition, DFO also undertakes its own health and disease auditing of licenced facilities.

K.2 THE FISHERY

K.2.1 Culture methods

Broodstock are selected at various points in the grow-out cycle from marine farm sites and placed in a separate broodstock cage at the same site. Some companies may transfer broodstock to a dedicated broodstock rearing site; other companies may move them directly to the hatchery for spawning. Most companies have genetic selection programs which dictate which animals are destined to be broodstock and which crosses to make once the fish are transferred to the hatchery.

At the hatchery, fish are identified, the eggs and milt are manually expressed, disease samples taken, and eggs fertilized. Records are kept for traceability. Eggs are placed in labeled incubators where they will remain until hatch. Egg disinfections and mortality removals are recorded. Environmental parameters are also monitored and recorded.

Upon hatch, alevins are moved to tanks where they complete endogenous feeding, after which time they are provided a commercially produced starter feed. As fish grow, the feed size is increased to suit their developmental needs. Traditionally, fish remain in a hatchery for a year before smolts are transfer to the ocean. With the aid of photoperiod and temperature manipulation this time frame can be substantially decreased, sometimes up to 6 months. As such, some companies can stock marine cages twice a year, once in the spring with small smolts then another stocking 6 months later in the fall with larger smolts. Once fish are moved into marine cage sites they are grown for up to 24 months before harvest. This is however dependent on environmental conditions, market demands etc.

Both the fish and infrastructure at marine farm sites are heavily monitored. The fish are routinely monitored for pests and pathogens in addition to signs of stress and anything which would impact their survival and growth. Records are kept as to the amounts and types of feed, water quality, lengths and weights, health and disease records and fish escapes.

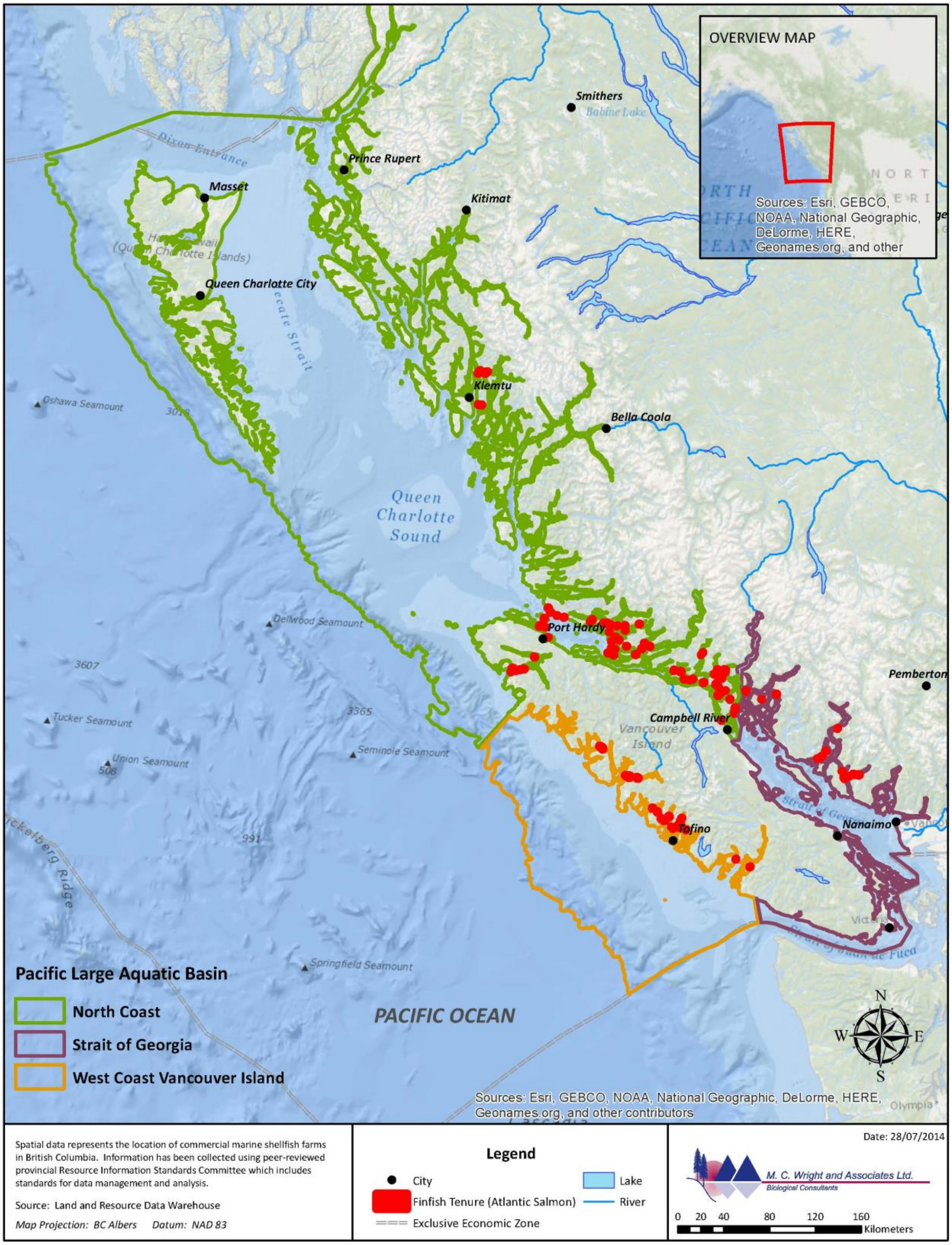
Harvesting practices can vary significantly. Fish can either be harvested on-site or brought to a processing plant for slaughter. Currently in Pacific LAB, most fish are harvested on-site. In general, the process involves pumping the fish from the cage onto a barge or boat where they are stunned, bled and placed on slush for transport to a plant for further processing.

K.2.2Management

Finfish aquaculture started to develop in earnest in the mid-1980's in British Columbia. After the BC Supreme Court ruled that finfish aquaculture in Pacific LAB is a fishery and a matter of exclusive federal jurisdiction in 2009, the federal government assumed regulation of the finfish and shellfish aquaculture industries in 2010.

Each site, marine grow-out or hatchery must have its own licence and renew it every year. The conditions of the licence will vary according to the operation. Site-specific licence conditions may also be applicable in some circumstances; these may be because of geography, species or facility type. Licence conditions are monitored by DFO and enforced under the *Fisheries Act*. In addition, Pacific aquaculture facilities must be in compliance with: the *Health of Animals Act*; *Food and Drugs Act*; *Pest Control Products Act*; *Canadian Environmental Assessment Act* and; *Species at Risk Act*. In addition to federal requirements for management, the provincial government also issues tenures under the *Land Act* for aquaculture operations which are not on private property.

Atlantic Salmon farms are distributed primarily on the South Coast of Pacific LAB (Fig. K1). The industry has areas of concentration on the west coast of Vancouver Island, Upper Strait of Georgia and Queen Charlotte Strait and the Broughton Archipelago. There were 132 sites licenced for marine finfish production located on approximately 4600 hectares of Crown Land in 2010. Not all of these sites will have harvested fish in 2010 due to the seawater production cycle being 16-24 months and production practices such as fallowing and year-class separation. In



Spatial data represents the location of commercial marine shellfish farms in British Columbia. Information has been collected using peer-reviewed provincial Resource Information Standards Committee which includes standards for data management and analysis.

Source: Land and Resource Data Warehouse

Map Projection: BC Albers Datum: NAD 83

Figure K.1. Location of Atlantic Salmon marine tenures in 2010 in Pacific LAB (2012).

2012, there were approximately 143 freshwater tenures in the province of which many service the production of cultured Atlantic Salmon.

For a detailed description of aquaculture regulation BC see the report written for The Cohen Commission entitled Policy and Practice Report: Aquaculture Regulation in Pacific LAB(2011) http://www.cohencommission.ca/en/pdf/PPR/PPR20-AquacultureRegulationInBC.pdf

For a complete list of licence conditions for a marine finfish aquaculture operation refer to http://www.pac.dfo-mpo.gc.ca/aquaculture/licence-permis/docs/licence-cond-permis-mar-eng.pdf

For a complete list of licence conditions for a freshwater aquaculture licence refer to: http://www.pac.dfo-mpo.gc.ca/aquaculture/licence-permis/docs/licence-cond-permis-fresh-douce-eng.pdf

K.2.3 Production and value

Over 95% of total production is salmonids, the bulk of which is Atlantic Salmon. It follows that Atlantic Salmon is the most valuable salmon species in Pacific LAB (BC 2012). Atlantic Salmon often contributes more than 50% of the landed seafood value in BC. Over 80% of Pacific LAB's Atlantic Salmon is exported to the US. Production has steadily increased from the 1980s forward (DFO 2014). From 2006-2011, production averaged 72 thousand metric tonnes with an average landed value of $421 million (Fig. K2).

Figure K2. Quantity and value of cultured Atlantic Salmon in Pacific LAB, 2006-2011 (DFO, 2014).

K.3 CLIMATE CHANGE AND CULTURED ATLANTIC SALMON

K.3.1 Sensitivity of cultured Atlantic Salmon to climate induced changes

Performance of Atlantic Salmon may be affected by changes in ocean temperature, dissolved oxygen, salinity and acidity and, the advent of more frequent harmful algal blooms (HABs) which may result in lost productivity or direct mortality. Recent research tying ocean acidification to increasing toxicity in a cosmopolitan species of harmful algae may increase the impacts of atmospheric carbon on aquaculture systems (Tatters et al. 2012).

Warming of sea surface temperatures may render some marine grow-out sites currently in use inhospitable for salmon farming. Warmer water also holds less dissolved oxygen (DO) than cooler water. Predictions are that increased ocean temperatures will result in greater stratification with lower oxygen levels in deeper layers. Incursions of deeper oxygen-poor water into growing areas may affect productivity. There is an existing phenomenon in Queen Charlotte Strait in which, on a seasonal basis, low DO waters penetrate salmon farm areas. Deep oxygen-poor waters flow into Queen Charlotte Strait from the continental shelf and margin. There are recent observations that DO levels in deep waters off the west coast of Pacific LAB have decreased over the past few decades and are likely to decrease further in coming years (Bill Crawford, DFO, Sidney, BC, pers. comm.). This could be problematic for salmon farmers in areas which suffer from incursions of deep, oxygen-poor water. This effect may also be compounded by changes in wind pattern increasing the incursion of poorly oxygenated water.

Increased stratification may lead to higher than average expected sea surface temperatures and in the water column occupied by farmed fish. This may be problematic in some areas subject to poor tidal exchange.

Fouling of equipment at marine farm sites is unavoidable. Bio-fouling increases the weight of nets creating stress on flotation infrastructure. More importantly, it can interfere with water flow through the nets resulting in lowered through-put of water. Higher ocean temperatures could result in more problems with bio-fouling and the need for more frequent cleaning which would increase production costs.

Blooms of *Heterosigma akashiwo,* a species of harmful algae, appear to be linked to river run-off (Taylor and Harrison 2002). Certain strains of *Heterosigma* may prosper at reduced salinity levels (Martinez et al. 2009). In the past, recurrent blooms of this species in some areas led (in part) to abandonment of sites that had significant losses. At the present time, algal monitoring is a daily routine at every operating Atlantic Salmon farm site. The presence of harmful algae could influence the feeding regime and may trigger the deployment of equipment such as perimeter net-skirts and compressed air bubble diffuser grids to bring up algae free water from depth and defend against the harmful effects of algal species of concern.

Fish feed is still composed of significant amounts of fish meal and oil from species harvested in reduction fisheries, primarily off the coast of South America. Considerable effort has and continues to be placed in replacing some of these fish oils and proteins with plant sources as well as fish processing wastes. However, because the industry is still reliant on fish sources, should these fisheries be affected by climate change and become less productive, the finfish industry may be affected through increased input costs.

Though not a focus of this report in general, it is generally assumed that climate change will engender more extreme weather events such as storms. This could render some farm sites unacceptable or create expense associated with more elaborate mooring systems.

K.3.2 Resilience of cultured Atlantic Salmon to climate induced change

Atlantic Salmon under culture conditions do not rely on live food sources directly from the environment, and unlike shellfish, they are not susceptible to contamination from biotoxins or coliforms. They are tolerant to a range of pH and salinity conditions but their production performance can be affected by having to continuously adapt to frequent changes in these water quality characteristics. Likewise, salmon farming is unlikely to be directly affected by changes in precipitation or freshwater runoff as the species has significant tolerance for different levels and changes in salinity (although stability is preferred).

There is no evidence of thermal adaptation at upper temperature limits for survival, feeding and growth of Atlantic Salmon in the wild. In some very cold rivers where mean annual temperatures are <6.5^{o}C, there is an adaptation to feed and grow at low temperatures near 0^{o}C (Elliott and Elliott 2010).

Salmon farming technology has proven to be quite robust in the face of storm events that have taken place over the past two decades in particular since new anchoring standards were set. There may be a need to relocate some farms but accessing new tenures has proven very difficult to date.

K.4 ECOSYSTEM LEVEL INTERACTIONS

There have been anecdotal reports of jellyfish "irritating" caged salmon in Pacific LAB but it is unclear whether mortality has occurred. Rising sea temperatures, reduced competition for food through over-fishing and increased acidity levels are suggested to be favourable to production of jellyfish (Harrould-Kolieb et al. 2010).

Increased distribution and abundance of invasive fouling organisms such as tunicate *spp.* could present further challenges maintaining clean nets on salmon farms.

K.5 KEY GAPS AND UNCERTAINTY

There has been no single long-term uninterrupted, systematic and comprehensive data collection program or effort to monitor plankton for harmful algae in British Columbia. Data are available for more recent years.

Table K1. Summary of potential impacts, vulnerabilities and opportunities from climate change for Atlantic farmed salmon.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Increased incidence of harmful algal blooms under warmer conditions	Warming of sea surface temperatures may render some marine grow-out sites currently in use inhospitable for salmon farming	N/A
Sea surface salinity	Growth can be affected by having to continuously adapt to frequent changes in salinity	N/A	N/A
Freshwater discharge	See above.	N/A	N/A
Sea level change	N/A	N/A	N/A
Ocean acidification	Increasing toxicity in harmful algae may increase the impacts of atmospheric carbon on aquaculture systems	N/A	
Ocean Currents	N/A	N/A	N/A
Stratification	Increased stratification may lead to higher than average expected sea surface temperatures and in the water column occupied by farmed fish impacting productivity.	N/A	N/A
Upwelling winds	N/A	N/A	N/A
Dissolved oxygen	Incursions of deeper oxygen-poor water into growing areas may affect productivity.	N/A	N/A

L. Pacific Oyster

(Crassostrea gigas)

Al Casltedine, Karen Hunter, Joy Wade, and Chris Pearce

KEY POINTS

- Decreases in ocean pH could affect shellfish larval production from hatcheries, directly affect the growth of shellfish or render them susceptible to stress-related disease.
- Thermal or salinity changes alone are not likely to negatively impact survival and productivity of Pacific Oyster to the extent that they would not be viable as a production species in Pacific LAB in future.
- Cumulative environmental changes may make this species more susceptible to pathogens.

L.1 BIOLOGICAL CHARACTERISTICS

L.1.1 Life history, age, growth

In Pacific LAB, the Pacific Oyster is a large non-native bivalve that is produced in both natural and cultured environments. It is favoured by industry as it grows quickly to reach the typical harvestable size of 8-10 cm.

In the wild or in culture operations, Pacific Oyster larvae are planktonic and develop quickly after fertilization. The planktonic feature is known as 'seed' to the industry (see Section 2.0). Time to settlement in any environment is dependent mainly on temperature (Quayle 1969). Once settled on a suitable substrate they metamorphose to the juvenile stage and remain sessile for the remainder of their lives.

In Pacific LAB, gonadal development commences as temperatures begin to rise in March (Gillespie et al. 2012). Temperatures of 16-34°C (optimal 20-25°C) and salinities of 10-42‰ (optimal 35‰) are required for spawning. Spawning occurs when water temperature is approximately 19.5^{o}C which can be in July or August depending on the location in BC (Quayle 1969). A Pacific Oyster can reach sexual maturity during the first year (Pauley et al. 1988). The species is highly fecund with 8-15 cm females producing between 50-100 million eggs per market size (76mm TL) female (Quayle 1969).

Pacific Oysters are protandrous hermaphrodites, meaning they can change sex, although this is erratic and seasonal (Fretter and Graham 1964; Katkansky and Sparks 1966). They normally mature first as males (Pauley et al. 1988). Quayle (1988) proposed that in areas of abundant food supply the sex ratio favours females. Females will revert to male when food is limiting.

Cultured Pacific Oyster spawn in the summer and at this time their meat is not at its peak. Farmed oysters can be harvested year round but they are generally harvested at a time of year when they are in peak condition. Smaller oysters which are not in spawning condition as well as triploids may be harvested year round.

L.1.2 Distribution, habitat and environmental preferences

The Pacific Oyster was first introduced to southern British Columbia from the east coast of Asia around 1912 and continued to be introduced until about 1961 (Quayle 1969, 1988; Bower 2010). Established populations are found high in the intertidal zone at depths between 5 and 40 m (Bourne 1978; Ruesink et al. 2005). Pacific Oyster can only disperse through pelagic larval stages. Preferred settlement substrates are oyster shell and rocks, and large aggregations can form if populations are not disturbed (Gillespie et al. 2012). They are distributed almost entirely in the mid-intertidal, possibly due to crab and starfish predation and the inability of young to survive at high tide levels.

Filtration rate (i.e. feeding rate), varies with temperature to a maximum at approximately 20°C. Pacific Oyster also has a significant tolerance for temperature and can survive at temperatures between -1.8 and 35^{o}C. There are however, disease issues associated with both high and low temperatures (FAO 2005-2013).

Quayle (1963) reported maximum filtration to be at salinities between 25-35‰, while increasingly sensitive to salinities below 20‰. Larvae require sustained temperatures of at least 18 C salinities of 19‰ for metamorphosis (Pauley et al. 1988; Mann et al. 1991; Shatkin et al. 1997).The optimal salinities for adults is between 20 and 25‰ but they can survive (but not breed) at salinities less than 10‰ and greater than 35‰ (Mann et al. 1991).

L.1.3 Predators and prey

As sessile, obligate filter feeders, oyster diets are limited to what is carried to them in the water column (Quayle 1969). Common food items are bacteria, protozoans, diatoms, invertebrate larvae and organic detritus. Numerous species are associated with oysters by virtue of possessing habitat preferences that match oyster grounds; see Quayle (1969) for a more complete treatment.

On the west coast of North America, crabs and sea stars are predators of oysters; the primary species involved are Dungeness Crab, red rock crab, graceful crab, sunstar, pink star, ochre star and mottled star (Quayle 1969, 1988; Chew 1983; Pauley et al. 1988). These predators are all limited by tolerance of desiccation or salinity, therefore Pacific Oysters have some refuge at higher tidal elevations. Pathogens are organisms known to cause serious disease (including gross signs of infection that affect market value, morbidity and mortalities). See Gillespie et al. (2012) for a list of existing and potential oyster pathogens.

L.2 THE FISHERY

L.2.1 Culture methods

There are many different variations of Pacific Oyster culture methods in Pacific LAB, but all are based in either deep water or beach culture. For either type of culture, seed must be secured. Seed can be obtained from several different methods: 1) collect from natural sets; 2) purchase eyed larvae and remote set on site; and 3) purchase seed that has already been set on cultch (e.g. oyster shells) ca 8-30 juveniles per shell as a small group or singles.

At 16-20 days post fertilization, juvenile oysters are “cemented” to a hard surface, known as a ‘set’. Growers can take advantage of this characteristic to set and place collectors in areas of high spawning activity. However, this can be a gamble as natural sets can be unpredictable and may not provide the numbers of individuals required to sustain a commercial production. Alternately, Pacific Oyster seed can be purchased from hatcheries before or after they are set. Oyster larvae can be set on large or small surfaces depending on the growers needs; broken bits of oyster shell serve as suitable substrates.

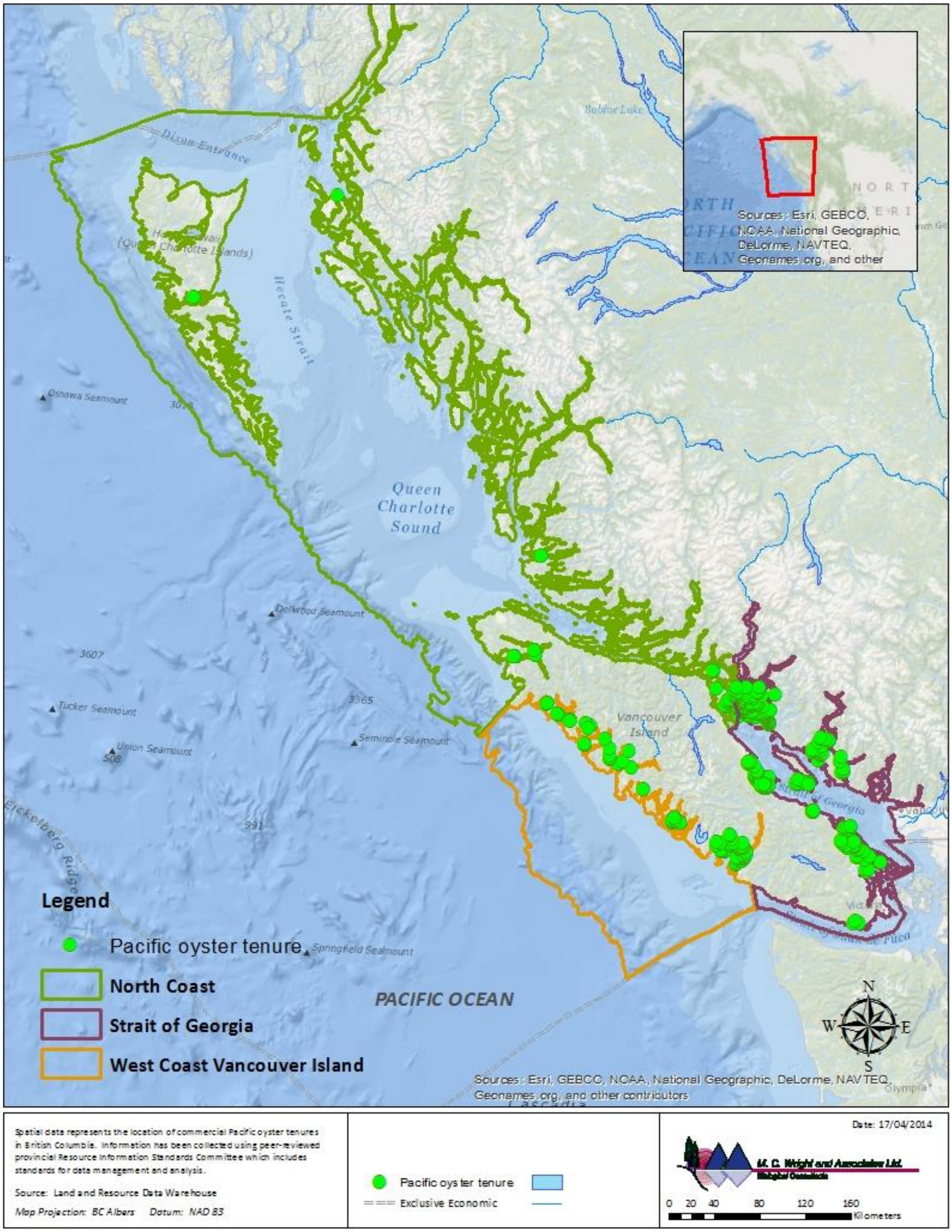
There are a few hatcheries in Pacific LAB which produce Pacific Oyster seed and the majority of hatchery product comes from the US. Broodstock are brought into the hatchery from marine farm sites and held under appropriate conditions to allow for gametogenesis and spawning in the spring. Gametes are most commonly removed from broodstock by opening up the animal. stripping the gonads and macerating them. Some hatcheries sell triploid offspring which are commonly created by crossing tetraploid and diploid animals or through chemical manipulation.

Regardless of the methods from which seed are procured, grow-out is either through beach culture or deep water culture. Beach culture involves directly seeding onto beaches or placing seed in vexar bags on beaches until harvest. There are various stages in beach culture, for example, moving stock to different parts of the beach or de-clustering. Oysters are also produced in deep water suspension in nets or cages suspended from rafts. There are two main products: single oysters destined for the restaurant trade (half shells) and shucking oysters to be sold fresh or frozen. Those grown in suspension as singles have thinner more fragile shells and are often hardened off prior to sale. The time from seed to market can take 18-30 months (FAO 2006-2013).

The land-base for the shellfish industry is about 4000 hectares composed of inter-tidal (beach) tenures, deepwater tenures used for suspended culture (lines, rafts), tenures that are a mix of inter-tidal and near-shore deepwater and tenures which are used for culture in deep water in or on the sea-bed. Different production locations and practices will have different susceptibilities to sea level rise and increases in severity and frequency of storm events. In addition, inter-tidal areas are used to harden or “finish off” some of the oysters produced in deep-water so they are in essence a product of both deep-water and inter-tidal culture.

L.2.2 Management

Farming of Pacific Oyster has been practiced in Pacific LAB since the early part of the last century. There are currently 432 tenures licensed to culture Pacific Oysters in Pacific LAB (Fig. L1). The shellfish aquaculture industry has major areas of concentration (e.g. Baynes Sound, in the Strait of Georgia). It is important to note that although an aquaculture site may be licensed for a species, there may be none growing on the site. For example, in 2009, only 61% of sites reported production. Producers may hold off harvesting anticipating better markets (or poorer), there may be temporary or long-term closures dues to biotoxin or coliform contamination. Some new sites may not yet be in production.



Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other

Sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, NAVTEQ, Geonames.org, and other contributors

Spatial data represents the location of commercial Pacific oyster tenures in British Columbia. Information has been collected using peer-reviewed provincial Resource Information Standards Committee which includes standards for data management and analysis.

Source: Land and Resource Data Warehouse

Map Projection: BC Albers Datum: NAD 83

Date: 17/04/2014

Figure L1. Location of Pacific Oyster tenures in Pacific LAB, 2012. All locations on the map are licensed to produce Pacific Oyster, but production does not occur at every location.

After the British Columbia Supreme Court ruled that finfish aquaculture on the Pacific LAB coast is a fishery and a matter of exclusive federal jurisdiction in 2009, the federal government assumed regulation of the finfish and shellfish aquaculture industries in Pacific LAB in 2010. The province of BC continues to license marine plant cultivation and issues tenures where operations take place on Crown land, issues business licenses under the Fisheries Act and maintains the mandate to protect the provincial public interest in sustainable aquaculture development.

The shellfish aquaculture industry operates under a rigorous and sophisticated regulatory management regime designed to safeguard public health from exposure to potential pathogens (biotoxins, coliforms etc.) and contaminants that may be present in shellfish.

L.2.3 Market

In 2010, the shellfish industry produced 10,000 tonnes of shellfish (primarily bivalves), consisting of 11 species (Table L1). This production was valued at $22 million farm-gate and $33 million wholesale. Most of the value was in Pacific Oysters, Manila clams and Pacific scallops.

Table L1. 2010 Pacific LAB shellfish aquaculture production value by sub-basin, fisheries statistical area and species. Data provided by B. Patten, Aquaculture, DFO.

	Strait of Georgia					WCVI				
Stat Area	*13*	*14*	*15*	*16*	*17*	*18&20*	*23*	*24*	*25*	Total
Eastern blue mussel	922	0	0	0	0	0	0	0	0	922
Gallo mussel	661	*	*	*	0	0	0	0	0	661
Giant rock scallop	0	0	0	0	0	0	*	0	0	0
Geoduck clam	*	*	*	*	66	0	0	0	0	66
Littleneck clam	1	14	*	0	3	*	*	0	*	18
Manila clam	*	2960	140	91	2892	*	91	0	*	6173
Pacific Oyster	1083	5691	877	62	245	*	365	382	117	8822
Pacific scallop	151	2655	48	*	0	0	*	0	0	2854
Sea cucumber	*	0	*	0	0	0	0	0	*	0
Western blue mussel	0	0	*	0	0	0	0	0	0	0
Varnish clam	6	230	0	*	0	0	*	0	0	236
Confidential items total	597	93	1035	209	0	189	31	0	39	2192
Total	3420	11641	2100	362	3205	189	486	382	156	21943

Excludes Area 2 production. “0” No value reported for that species in that area. “*” A value for that species reported in that area but value held confidential as less than three companies reported production. Confidential values are summed in the next to last column

In Pacific LAB, the Canadian Shellfish Sanitary program (CSSP) classifies the harvesting areas and controls the commercial and recreation harvesting and processing of shellfish. It is run by three organizations: Environment Canada, which monitors water quality in shellfish areas;

Canadian Food Inspection Agency (CFIA), which monitors marine toxins, registers and inspects shellfish processing plants and; DFO, which closes harvest areas and prohibits harvesting when bacteriological and toxin levels are unsafe (BCCDC no date). All commercially harvested bivalves must be processed and inspected by federally registered processing plants (BCCDC no date).

L.3 CLIMATE CHANGE AND CULTURED PACIFIC OYSTER

Pacific Oysters are sensitive to changes in their environment. Under culture conditions, and in the wild, they are completely dependent on their local environment to provide all that is required to live, grow and reproduce. Periodic changes to their environment such as high rainfall events affect growing water quality for wild shellfish, particularly those in in-tidal and near-shore areas. Although they are highly resilient to environmental changes, the cumulative impacts of these changes may make them more susceptible to predation, irritants and pathogens.

L.3.1 Sensitivity of cultured Pacific Oyster to climate-induced change

There are instances when harvest may be closed due to an increased risk of Paralytic Shellfish Poison (PSP), Diarrhoeic Shellfish Poison (DSP) and other neurotoxins from harmful algal blooms. Harmful algal blooms can affect shellfish growth and/or survival. Massive die-offs have been attributed to algal blooms resulting in high biological oxygen demand and low oxygen levels.

Shellfish are sensitive to changes in salinity. Increases in freshwater discharge from major river systems such as the Fraser River will affect surface salinity levels. It is not known if periodic moderate decreases in salinity will affect production on a regional or localized basis. Effects, if any, may be dependent on life stage. Direct changes to salinity and freshwater runoff are also known to be a contributing factor in the increased incidence of fecal coliforms in the water and subsequent animal tissue.

Animals raised under beach culture conditions are susceptible to several pathogens. One of which, *Vibrio parahaemolyticus*, is currently only a problem during the summer when air temperatures and surface water temperatures are high. With increases in water and air temperature as a result of climate change it is possible that incidences of this zoonotic pathogen may rise.

Depending on the site location and farming practices, sea level rise and increases in severity and frequency of storm events may have negative impacts on production and survival. Rise in sea level could diminish the productive inter-tidal growing area in some cases or increase it in others. Storms and surges could dramatically exacerbate any issues related to waste water management or septic systems.

Elevated water temperatures, changes in salinity, elevated sea level and shifts in flow patterns could all lend themselves to establishment of new invasive species or result in spread of those already in provincial waters. Invasive species could compete with farmed species for resources (space, nutrients), predate on farmed species, increase the incidence of disease or diminish productivity and increase operational costs.

Hatchery successes in the US have been highly variable over the past few years. Considerable work and effort has been placed in determining the causes for these massive hatchery failures. Many are attributing these losses to changes in environmental conditions such as ocean acidification especially on early development of oysters.

Ocean acidification could affect the quality of phytoplankton food sources as species mix changes due to differential effects of pH. Reduced calcification of oyster shells with increasing $p\mathrm{CO}_2$ could negatively affect oyster production (Gazeau et al. 2007, 2011) via impacts to larvae that experience minimal exposure to stressful pH (Hettinger et al. 2013). Other potentially important interactions with changes in ocean pH involve increased toxicity of harmful algae species that impact oysters directly (Tatters et al. 2012).

L.3.2 Resilience of cultured Pacific Oyster to climate-induced change

As a species, Pacific Oyster has the ability to survive over a wide range of environmental conditions such as temperature and salinity. In a production system however, it is ideal to culture under optimal environmental conditions to decrease cost of production and increase survival.

Increased sea surface temperatures tend to lead to stratification with less nutrient concentration in ocean surface layers. Areas such as the Strait of Georgia may escape such stratification due to increases in wind and strong tidal flows. Nutrient levels may be maintained or even enhanced with increases in runoff from the land.

There is little to suggest that survival and productivity of Pacific Oysters will be affected by thermal or salinity changes to the extent that they would not be viable as a production species in Pacific LAB in future. In fact, the species may benefit more than other cultured species from temperature increases. Tolerances will vary depending on life stage and impacts of ocean acidification however.

L.4 ECOSYSTEM LEVEL INTERACTIONS

Increased ocean temperatures may result in changing planktonic species composition and increased primary productivity providing nutrients and light are not limiting. Such productivity may enhance shellfish growth but could lead to greater issues concerning harmful algal blooms (HAB) causing direct losses of stock or issues concerning biotoxin management.

L.5. KEY GAPS AND UNCERTAINTY

The immediate and latent effects of environmental changes such as those attributed to ocean acidification on all stages of development.

It is not known what processes are causing hatchery failures.

There are still unexplained mortalities associated with grow-out, for example “summer mortalities”.

Table L2. Summary of potential impacts, vulnerabilities and opportunities from climate change for Pacific Oyster.

Physical parameter	Recruitment and Abundance	Distribution and migration	Timing of life events
Sea surface Temperature	Links to increased incidence of harmful algal blooms may impact growth and/or survival; Increases in *Vibrio* pathogens	Increases in *Vibrio* pathogens may limit farm sites and distribution of wild oysters	No information
Sea surface salinity	Decreases in salinity can affect production negatively.	No information	No information
Freshwater discharge	Increases in discharge that results in altered salinity conditions can affect production.	No information	No information
Sea level change	No information	Rise in sea level could diminish the productive inter-tidal growing area in some cases or increase it in others	No information
Ocean acidification	Reduced calcification of oyster shells with increasing $p\text{CO}_2$ could negatively affect oyster production	No information	No information
Ocean currents	No information	No information	No information
Stratification	No information	No information	No information
Upwelling winds	No information	No information	No information
Dissolved oxygen	No information	No information	No information

5.0 SUMMARY OF CLIMATE VULNERABILITIES OF SELECT MARINE BIOTA IN PACIFIC LAB

The vulnerability of marine biota to climate change relates to life history stage impacts and resulting species interactions to the magnitude and rate of change and cumulative stressors that reduce species and ecosystem resilience. Vulnerability of wild and cultured marine species in Pacific LAB to changing ocean conditions is based in part on their current distribution and exposure to multiple changing climate parameters. This report used a screening level approach to document impacts, vulnerabilities and opportunities (IVO) on key Pacific LAB marine species and aquaculture. Large gaps in the literature currently limit the ability to document IVO at a fine spatial scale across Pacific LAB.

Table 5.1 provides a high level summary of sensitivities and exposure factors that may contribute to vulnerability or opportunity for biota examined in this report. The summary shows that we have the greatest conceptual understanding of the impacts of changing sea surface temperature on biota. As water temperature continues to rise, we can expect species to exhibit vulnerabilities documented here and likely others that are not yet part of the scientific record. Changes in upwelling strength and duration were also important factors for many species in Pacific LAB given that this circulation features strongly affects regional productivity. Large gaps in knowledge of the impacts of ocean acidification on species and ecosystems hampered the effort to document vulnerabilities and opportunities associated with this important phenomenon. More prominently, the unidentified cumulative effects of climate change on species and ecosystem interactions are likely to exacerbate any documented or hypothesized IVO.

While some opportunities may exist for fisheries with respect to expanded distributions and greater abundance, more likely ‘opportunities’ will be captured within the Department’s activities as it responds to impacts of climate change on aspects of its core mandate (i.e. sustainable fisheries). Table 5.1 provides a brief list of opportunities and adaptations that might be considered to close knowledge gaps and temper vulnerability.

Table 5.1. Summary of climate change impacts, vulnerabilities and opportunities of select marine biota and cultured species.

Key sensitivity	Drivers	Opportunities/Adaptation	Supporting sections	Affected sub-basins
Juvenile and adult distribution at southern range may contract	SST; decreased oxygen concentration at depth	Effective groundfish monitoring system could be used to develop an early warning system; Link between climate forcing and recruitment and growth requires more research. There is consideration of climate variables in management of Pacific Halibut.	Pacific Halibut; Sablefish; Dungeness Crab; smaller cetacean species	WCVI; North Coast
Change in primary and secondary productivity affecting food availability for all life stages	SST; Change in upwelling strength; Increased stratification	Monitoring of plankton productivity of WCVI and Oregon contributes to ongoing understanding of lower trophic dynamics in southern outer regions of Pacific LAB. There is a need to expand monitoring efforts in North Coast and Strait of Georgia.	All species profiles including marine mammals	WCVI; North Coast; Strait of Georgia
Disrupted larval distribution affecting recruitment to the population	Altered/stronger currents; Change in upwelling strength	Very little is understood in Pacific LAB about larval fish and invertebrate distribution or how this key life stage is impacted by climate change and/or climate forcing. There seem to be large research opportunities in this area.	Pacific Halibut; Sablefish; Pacific Herring; Dungeness Crab; Spot Prawn; Geoduck	North Coast; WCVI
Adult migration range may extend northward with thermal habitat expansion	SST	Expansion of populations into Pacific LAB waters could increase fisheries production. Other species not considered in detail here could also contribute to new fisheries (e.g. squid, mackerel spp.)	Pacific Hake; Albacore Tuna; Pacific sardine; Pacific Oyster	WCVI; North Coast
Northward change in spawning distribution related to physiologic stress of nearshore habitats; Change in spawning time	SST; Upwelling	Seasonal monitoring and study of the herring spawn occurs along the coast. Opportunity to work with industry to develop spatial mapping and monitoring tools to assist stock assessment and climate-related research.	Pacific Herring	North Coast; WCVI
Decline in recruitment to the fishery related to mortality from physiologic stress and increased predation and competition	SST	Opportunity to explore multi-species management of principal predatory (Pacific Hake) and competitor (Pacific sardine) species that will likely become more numerous across the Pacific Herring distribution with warming.	Pacific Herring	Strait of Georgia; WCVI

Table 5.1. continued

Decline in egg, larval and juvenile survival from impacts on development (shell formation and moulting)	SST; pH	Opportunity to develop a strategic response (research and monitoring) to this broad reaching risk within Pacific LAB.	Dungeness Crab; Spot Prawn; Geoduck; Pacific Oyster; Lower trophic levels	North Coast; Strait of Georgia; WCVI
Loss of spawning and foraging habitat	Sea level rise	Mediation of non-climate oriented stressors (shoreline development, storm water contamination) could ease the burden in areas not impacted by SLR; Pacific Herring are not faithful to spawning locations but require marine plants and algae for spawning in nearshore areas. Opportunity to develop no-take spawning areas (i.e. no spawn on kelp fishing) and industry-led research to develop artificial spawning habitat.	Pacific Herring	North Coast; Strait of Georgia; WCVI
Loss of spawning and foraging habitat and/or farm lease area.	Salinity/fresh water discharge	Loss of key nearshore rearing habitats (estuaries); Shift to greater use of deepwater oyster aquaculture tenures.	Dungeness Crab; Albacore Tuna; Pacific Oyster	North Coast; Strait of Georgia; WCVI
Altered growth and recruitment/production	SST; pH	Barring any negative effects from decreasing pH, some shellfish species could increase yields within their current distribution. Thermal limits of some beach-culture species may be exceeded.	Geoduck; Pacific Oyster	Strait of Georgia; North Coast
Increased prevalence of diseases and nuisance species affecting culture operations	SST; pH	Monitoring at farm sites could expand to include potential future site locations or broader sampling programs; Continued HAB monitoring; More sophisticated monitoring and contaminant detection methodologies may be necessary; Shift to more controlled systems - hybrid land/sea or land-based.	Atlantic Salmon; Pacific Oyster; wild-aquaculture interactions	Strait of Georgia; WCVI
Animals may become stressed by warmer temperatures and be more susceptible to disease	SST	Shift to greater use of deepwater oyster aquaculture tenures; Conduct research on known diseases and ocean climate stressor (ocean acidification, temperature) interactions; Risk assessment of disease for species inhabiting affected marine areas.	Pacific Oyster; Atlantic salmon; pelagic species; marine mammals	WCVI; North Coast; Strait of Georgia

5.1 Summary of impacts and vulnerability of select marine species

5.1.1 Increases in sea surface temperature

In Pacific LAB, smaller, less energy-rich prey species are associated with warmer ocean conditions and weaker upwelling that originate in southern, warmer waters (Hoof and Peterson 2006). Changes in the timing and strength of upwelling in combination with warmer temperatures may contribute to biomass declines of larger zooplankton species that are important food for many marine species in Pacific LAB. Increased sea surface temperature may further affect the diversity and abundance of lower trophic levels through stratification of the water column that may resist upwelling and limit primary productivity. Changes to productivity at the lowest trophic levels will have cascading impacts in Pacific LAB ecosystems (Ware and Thompson 2005).

Further up the food chain, pelagic fish appear to be sensitive to sea surface temperature as their distributions and growth are tied to habitat and food availability and quality at the surface. For example, warmer sea surface temperatures affect the average latitude of spawning for Pacific Herring and Pacific sardine (McFarlane et al. 2005; Hay et al. 2009; Demer et al. 2012) and negatively impacts survival and growth of Pacific Herring (Schweigert et al. 2002) by decreasing productivity (Ware and Schweigert 2002; Rose et al. 2008) and increasing predator and competitor abundance (Ware 1991; Schweigert et al. 2010). A consequence of these interactions may be a reduction in Pacific Herring abundance, particularly in WCVI. Because Pacific sardine is at the northernmost extent of its range in BC, this species' climate change sensitivity bottleneck has been identified as the timing and quality of marine conditions conducive to spawning success and recruitment off WCVI (Song et al. 2012). Warmer surface waters, combined with a robust subpopulation will likely result in a larger proportion of the northern stock migrating into Pacific LAB waters. Similarly, spawning and rearing of Albacore Tuna may be expected to occur further north as a response to water temperature increases. Other regionally important pelagic species such as Humboldt Squid, Pacific Mackerel and jack mackerel (known as 'transient species) may also show similar responses to water temperature increases associated with climate forcing. Consequences of warmer waters off the Pacific LAB coast will likely introduce opportunity for some species, and thus some fisheries, to expand their activities from south to north.

Also in the pelagic environment, planktonic larvae of groundfish species are exposed to variable habitat conditions where they feed and drift prior to settlement. There is some agreement that survival at the larval stage determines population recruitment. Strong year classes of some groundfish species have been correlated with climate forcing events (i.e. temperature and upwelling-mediated seasonal timing) that produce high quantities of prey for larval and juvenile fish. However, there is great variability in recruitment among species and among populations of the same species in Pacific LAB leading to incomplete understanding of this effect. Exposure of fish larvae to increased sea surface temperature, altered currents, and changes in ocean stratification may result in new patterns of recruitment and localized changes in abundance.

Long-term changes to the availability of preferred thermal habitats will have consequences for adult fish, particularly impacting growth, movement and migration. For example, as adults, Pacific Hake are especially sensitive to sea surface temperature change. Warmer waters in BC during the annual hake foraging migration often results in a more northerly migration of the population. In the future, if abundances of the offshore population increase with an increase in water temperatures, more fish are predicted to move into Pacific LAB waters, with possible larger abundances occurring in WCVI and North Coast. Further, recruitment of halibut to the Canadian portion of the fishery is currently believed to be generated, for the most part, from juveniles emigrating from Alaskan rearing areas to the North Coast. Warming from south to north may alter growth patterns or reductions in juveniles migrating into Canadian waters.

Projected increase in sea surface temperature will likely have direct physiologic and indirect habitat changes are anticipated to affect many invertebrates through every life history phase. Many adult stages of invertebrate species in Pacific LAB exhibit far less mobility than most finfish and rely on nearshore habitats for the majority of their life history. Overall, recruitment may be more significantly affected as species with lower mobility are believed to be less adept at adjusting time and location for spawning and larval survival with changes in environment. Species interactions, feeding and movement behaviour that relate to stages of moulting may also be disrupted with unknown consequences.

Strong effects on survival, growth, and development of larval and post-larval invertebrates will take place through changes in food availability influenced by temperature and currents. Temperature-mediated effects on the quantity and quality of food and habitat for invertebrates will vary across species. For example, Geoduck growth rate is positively correlated to sea surface temperature that may increase food abundance for this species. Species that depend on other species for habitat (e.g. Dungeness Crab/oyster shells; Spot Prawn/kelp) may benefit from warmer temperatures if they accompany a longer growing season, but may also experience higher mortality caused by higher temperatures in shallow habitats.

5.1.2 Changes in strength of upwelling winds and timing of the upwelling season

Predictable timing of the spring transition dictates the success of several biological interactions including key plankton prey availability for larval fish and invertebrates. Changes in the timing or strength of the transition can negatively affect recruitment for both marine fish and invertebrates. Shifts in the timing of upwelling winds observed for the past decade along the Pacific LAB coast indicate a change is occurring to which marine biota will need to adapt. One result that can be deduced is that an early start to the upwelling will result in good ocean conditions, however, the initiation of the upwelling season and the strength of the upwelling are both unpredictable and cannot yet be explored with global climate models.

5.1.3 Changes in hydrology

Seasonal increases in volumes of freshwater projected to enter Pacific LAB marine waters, more markedly in Strait of Georgia and North Coast, will affect temperature, salinity and stratification especially in surface layers. Flow from the Fraser River greatly affects the salinity profile of the Strait of Georgia. Nearshore habitats in this sub-basin may experience the greatest fluctuations in salinity under regional hydrological change (Morrison et al. 2013). Changes of this nature to coastal water properties could impact the spatial pattern of plankton productivity that would affect nearshore marine invertebrate production on a regional or localized basis (wild or cultured). Settled animals require sufficiently saline waters to feed and grow; larvae at drift may experience alternative impacts from lower salinity. Some hypotheses link potential changes in groundfish abundance and distribution to changes in precipitation and its effects on coastal marine food webs. For example, changes in hydrography such as an earlier spring freshet may lead to trophic mis-matches in the marine environment when key prey items for larval fish are not abundant at the right time or place.

Higher rainfall will increase the flow of contaminants, novel pathogens and nutrients into the ocean—while increased temperatures and poorer water quality may increase the frequency and intensity of toxic algal blooms. Marine mammals that inhabit the nearshore (particularly near urbanized areas) such as seals, sea lions, and sea otters are likely to be more susceptible than other species to such stressors.

5.1.4 Sea level change

Variability in sea level change across Pacific LAB will result in a patchy ecological response. Directly sensitive marine organisms include nearshore inhabitants or migrants relying on shorelines for specific portions of their life history. Critical spawning habitat for forage fish and rearing habitat for invertebrates could be lost in areas subject to erosion, subsidence and submersion associated with sea level rise. Sea level rise has been raised as a concern for Pacific Herring spawning habitat given that the species prefers coastal marine algal species as spawning substrate. The abundance and availability of coastal plants and algae, along with nearshore invertebrate habitats, could be altered if important inter-tidal habitat becomes permanently sub-tidal.

5.1.5 Changes in strength of ocean currents

Projections of increased coastal wind strength in the summer, in addition to resulting impacts of increased sea surface temperature on stratification may affect coastal currents and upwelling strength or timing. For groundfish, the greatest sensitivity to perturbations and change in climate may be the larval stage, with possible consequences for year-class strength. Invertebrates are also sensitive to changes in ocean conditions that affect distribution of larvae. Planktonic larvae are at risk when prevailing oceanic currents advect and concentrate larvae in areas with inadequate conditions for growth or survival. For species such as Dungeness Crab, it is known that landward surface transport keeps larvae near the surface water close to shore for months and directs them toward estuaries and inland waters; changes in these transport forces may change larval distribution. In southern areas of Pacific LAB's continental shelf, stronger coastal winds and weaker upwelling could impact productivity in the WCVI sub-basin.

5.1.6 Decreases in ocean pH

It is highly likely that changes in ocean acidification will affect at least some life history stages of calcifying organisms by interrupting reproduction and growth. In addition, the quality of plankton food sources as species assemblages may change in response to differential effects of pH adding additional direct stress on mid-low trophic levels. Recent studies demonstrate that fish may experience difficulties with olfaction, osmoregulation and cardiorespiratory control that could lead to impacts on the physiology of reproduction, metamorphosis and survival (Munday et al. 2009; 2014). The extent of these impacts, nor the most vulnerable locations along the nearshore or continental shelf are currently known. A literature survey of impacts of ocean acidification on organisms in Pacific LAB is currently underway (Haigh et al. 2015).

5.1.7 Dissolved oxygen

The implications of low dissolved oxygen and hypoxic areas in the nearshore are of concern for culture operations, species with low mobility, or species adapted to low oxygen that may succumb to episodic events, such as Dungeness Crab or Spot Prawn, and larvae of both demersal fish and invertebrates. Dissolved oxygen is important for fish relying on deep water habitats. Permanent changes to oxygen conditions would likely alter distribution of species ranges from south to north, as well as offshore-onshore.

5.2 Summary of impacts and vulnerability of select cultured species

In general, the threats to finfish aquaculture appear less severe and direct than those for shellfish from both production and infrastructure perspectives. Cultured finfish do not rely directly on primary productivity and they are not as susceptible to contamination from biotoxins or coliforms as other cultured species. Consequences of increased ocean temperature could include: 1) more problems with bio-fouling, elevating costs; 2) negative interactions with new invasive species and diseases; and 3) potential alteration of hospitable locations for finfish aquaculture along the coast, subject to licensing.

Increased ocean temperatures may result in changing planktonic species composition and increased primary productivity providing nutrients are not limiting at the nearshore. Such productivity may enhance shellfish growth but could lead to greater issues concerning harmful algal blooms causing direct losses of stock or issues concerning biotoxin management (Moore et al. 2008), in particular contamination with *Vibrio spp.*. Increased water temperature may benefit production and increased distribution of some non-native cultured invertebrate species (e.g. Pacific Oyster).

Ocean acidification was not the main subject of this review but its potential impacts on commerce in cultured shellfish could outweigh all other climate-related influences. Concerning culture facilities, increases in ocean acidification could affect shellfish larval production from hatcheries, and directly affect the growth and disease susceptibility of shellfish including increased toxicity of common pathogens (Tatters et al. 2012). Cultured salmonids and Atlantic Salmon in particular, appear quite tolerant to a range of pH conditions but their production performance might be affected by having to continuously adapt to frequent changes in water chemistry.

For shellfish culture operations concentrated in the Strait of Georgia, rise in sea level could diminish the productive inter-tidal growing area in some cases or increase it in others. Because of the variety of species under culture as well as the oceanographic variability in production sites, different production locations and practices will have different susceptibilities to sea level rise.

5.3 Summary of impacts and vulnerability of marine mammals

Climate change will potentially have direct and indirect effects on the food, habitat, physiology, and health of the 27 species of marine mammals that occur in British Columbia. Species of marine mammals that are most likely to be negatively affected in BC by climate change are those with few breeding locations (i.e. Steller sea lions), those that are few in number (i.e. killer whales, blue whales), those with relatively specialized diets (i.e. killer whales, blue whales), those with less tolerance for warmer waters (i.e. harbour porpoise, Dall's porpoise and Pacific white-sided dolphins), and those that occur nearshore where runoff from land is greatest (seals, sea lions, sea otters and harbour porpoise). Species of marine mammals that are more abundant in BC, and have wider thermal tolerances and more generalist diets are more likely to adapt to the new normal that climate change has begun to impose.

Changes in the distribution, diversity, abundance, concentration, and movements of prey species will likely affect the ability of all species of BC marine mammals to acquire sufficient prey to meet their daily energy requirements. Changes in oceanographic processes may disrupt the concentration of prey patches, and could mismatch the timing of key life history events that support present food chains. Such indirect effects of climate change on prey could reduce the body condition, pregnancy rates, and survival of individuals—and the population dynamics of all marine mammals.

Specialist predator species such as many marine mammals have preference for a few key prey items, suggesting that any significant change to spatial or temporal overlaps of predator and prey linked to climate change may impact predator populations negatively. Increased ocean temperatures may enable warmer water species such as California sea lions and striped dolphins to expand their ranges northward and compete with Steller sea lions and Pacific white-sided dolphins for food. Such increased competition could reduce reproductive and survival rates of the marine mammals currently present. Species such as harbour porpoise, Dall's porpoise and white-sided dolphins that are less tolerant of warmer waters compared to larger species of cetaceans may move northward and have their distributions contracted within BC. Higher propagation of sound in CO_2 enriched water may increase anthropogenic noise levels and negatively affect communication among porpoise, dolphins and whales needed to successfully forage, reproduce, and maintain group cohesiveness.

Rising sea levels and increases in the frequency and intensity of storms (wind speeds and wave conditions) will have a direct impact on the resting (haulout) and breeding (rookery) sites used by seals and sea lions. This may reduce the availability of sites they use, and could increase the frequency with which pups are washed into the ocean and drowned.

6.0 KEY GAPS AND CONSIDERATIONS

Despite the breadth of information presented in this report, it does not achieve a full exploration or documentation of gaps in knowledge associated with climate change impacts, vulnerabilities or opportunities. A full list would require local scale scientific knowledge of current physical and ecological processes, and predicted interactions under projected climate conditions. Readers are referred to species profiles for a more extensive treatment by species examined here.

Information gathered here presented reveal that the ability to deliver DFO’s mandate in Pacific LAB is vulnerable to the effects of climate change. Given that the authors acknowledge that not all gaps in knowledge are captured by this report, the inventory of impacts, vulnerabilities and opportunities compiled should be considered greater that what is offered here. For example, the assessment did not allow consideration of cumulative interaction of climate drivers or the interaction of multiple drivers on ecosystems. It is highly recommended that future phases of program work and research give attention this substantial gap.

The current inventory of key gaps in knowledge consists of several different categories that relate to various tasks associated with the Department’s business explored in this document (i.e. no infrastructure). Key categories included ocean climate parameter monitoring and modelling from the biological perspective, marine species and aquaculture. The following list identifies research and management areas that will likely require more attention as the Department experiences and addresses the effects of climate change.

6.1. OCEAN CLIMATE MONITORING AND MODELLING FROM THE BIOLOGICAL PERSPECTIVE

Stable support for the collection of oceanographic and biological observational data is necessary to understand changes in the marine environment and improve model projections. Positive adaptive responses will be impacted if scientific data needs to address adaptive management are not maintained. Large natural climate variability in Pacific LAB extends the need for long data records to be able to detect oceanographic and biological trends. The following research needs and knowledge gaps are some of the key limitations to understanding and managing successfully for climate change in Pacific LAB:

- There is a need for reliable and continuous time-series of observations (biological and oceanographic). Sustained observations must be maintained of atmospheric and ocean physical variables along with coastwide surveys of plankton, krill and fish both in open ocean and coastal waters.
- Limited information on near shore environments translates into a lack of knowledge of climate-habitat interactions and resulting impacts on fish and invertebrates using these areas for important life stages.
- The lack of data and knowledge of some key regions, in particular in the North Coast and Gulf of Alaska sub-basins, limits opportunities to understand and mitigate impacts of climate change.
- There is a need for greater capacity to predict environmental changes and ecosystem responses at sub-basin scales, including the development of regional biogeochemical coupled-physical and downscaling models. Biogeochemical feedbacks between ocean acidification and climate change and the impact of these global scale changes to local and regional scales.
- There is a need for greater capacity in predicting shifts in the timing of environmental drivers and in determining their consequences to the phenology, adaptation and productivity of key freshwater and marine species.

- Understanding consequences of changing rainfall and temperature for nutrient discharge to the sea would improve with more use of catchment models and a better understanding of nutrient cycling.
- Improved projections of how ocean currents and primary productivity are likely to change at regional and local scales for a range of climate change scenarios. The projections are critical for understanding how population dynamics and connectivity patterns may change over the coming century.
- Open ocean subsurface waters of the subarctic Pacific have extremely low oxygen concentrations and calcium carbonate saturation states. Future trends in these properties and their transport onto the continental shelves are poorly understood. In coastal waters modulation of ocean acidification by freshwater inputs and interaction with the sediments are poorly understood.

6.2 MARINE SPECIES

Climate change projected for marine areas of Pacific LAB suggest changes to the abiotic environment that are likely to induce responses at all levels of biological organization (DFO 2013a). Knowledge gaps remain across all areas of DFO’s responsibilities regarding the sustainable management of fish and fisheries under climate change.

- There is limited understanding of the effects of changes in spatial distributions and abundance of key species on regional productivity.
- There is a gap in our understanding of how to incorporate cumulative effects into models (i.e. multiple life history stages; species interactions etc.) and assessment (i.e. risk, vulnerability) processes.
- There is a lack of baseline data on the distribution and structure of deep-sea biological communities in BC waters and how they vary in time.
- A better understanding of how increased temperature is expected to affect adult reproduction and the development, survival and behaviour of larvae.
- Unknown impacts on a wider range of species that are of fisheries or conservation importance.
- There is limited understanding of the consequences to the management decision making process caused by the effects of climate change on migration, alterations in production and changes in stock-recruitment relationships.
- There is very little relevant ecological or molecular information on invasive marine species in Pacific LAB.
- Management and monitoring systems in Pacific LAB are undeveloped for managing existing populations and newly discovered marine invasive species. Because invasions are expected to increase with climate change, gaps in knowledge and management for invasive species represents a currently under managed risk.

- Lack of information on itchyoplankton for most species of fish leads to large gaps in knowledge of the impacts of ocean climate changes on survival and recruitment of commercially and culturally important species.
- We do not know enough about whether fishing pressure affects the ability of fish populations to cope with climate change. For example the removal of the largest, oldest and potentially most fecund (reproductive) individuals may prevent species from rapidly benefitting during years with favourable temperatures.
- There is a need to identify non-commercially important species, communities and habitats particularly vulnerable to climate change impacts.
- Need to identify critical habitat of species at risk, and linkages between these and climate change drivers.
- Knowledge relating to impacts of ocean acidification on marine species and their ability to adapt to increased acidity is limited. The potential implications of ocean acidification for fin-fish are not well understood; this applies to both indirect consequences through the marine food web but also direct physiological effects.
- Investigations of how ocean acidification affects the development, survival and behaviour of broadcast spawning and pelagic fishes are sparse. Almost nothing is known about how increased sea surface temperature and CO_2 might interact to affect marine fishes.
- Experiments are needed to understand effects of hypoxia and ocean acidification on eggs and larvae of regionally important phytoplankton and zooplankton species.
- There is a research gap on the nature and extent of synchronicity (e.g. timing of reproduction) between bottom and water column living species (benthic-pelagic coupling), including higher trophic levels such as fish, seabirds and marine mammals in order to understand the ecosystem-level consequences of climate change.
- We need better assessments of climate change impacts on marine mammals at the population level in order to discriminate between regional population responses and those occurring on a wider geographical scale.

6.3 AQUACULTURE

Pacific LAB supports a highly productive and highly valuable finfish and shellfish aquaculture industry. Climate change impacts on production from hatcheries to harvest are largely unknown. Proliferation of disease and algal blooms are among the largest concerns under climate change. Knowledge gaps in these areas, as well as aquaculture product management are considerable.

- Little to no understanding of the response of different harmful algal bloom groups and genera to the influences of climate change.
- Lack of understanding of increases in harmful algal bloom events on finfish.
- Climate change may exacerbate challenges related to product safety management related to increased biotoxic events or other contaminants.

- We do not understand the prevalence, distribution and seasonal dynamics of pathogenic and non-pathogenic strains of non-cholera vibrios in coastal waters and shellfish.
- Limited on-site environmental monitoring may lead to management challenges and product losses including mass mortalities.
- The effects of ocean acidification on shellfish and finfish aquaculture are little studied and impacts on shell formation, growth and survival are extremely limited.

6.4 CLIMATE-READY FISHERIES

Based on this compendium, it appears that very few stock assessment models for the most lucrative fisheries in Pacific LAB are implicit in incorporating climate forcing in model forecasts. This gap potentially leaves Pacific LAB vulnerable to management surprises in the future in addition to existing management uncertainty (Lindenmayer et al. 2010). In a review of literature for climate change adaptation in fisheries there did not appear to be any source that indicated that fishery management decisions would become easier as a result of climate change (Grafton 2010). In fact, a discussion of a reduced ability to predict abundance of fishery resources is more common (Robards and Greenberg 2007; Grafton 2010). Therefore, it may be timely for a specific discussion on climate-ready fisheries to occur in Pacific LAB.

7.0 CONCLUSION

This work documents key impacts, vulnerabilities and opportunities of Pacific LAB marine species of major commercial and ecological importance. To date, projected changes in sea surface temperature, and altered upwelling and ocean chemistry conditions seem to be the most important climate-related drivers that could independently affect change for important living marine resources in Pacific LAB. Impacts such as altered productivity due to vulnerabilities in trophic interactions, altered distribution or availability of habitat, and a reduction in abundance linked to changes in recruitment and growth could all occur. All Pacific LAB sub-basins should expect to see changes in living marine resources in the future including the possibility of a reduced ability to predict abundance of fishery resources. Ocean climate changes will also interact with existing stressors such as fishing, invasive species and diseases. This is a cumulative problem whose combined effects (multiple stressors, possibly synergistic) have not been examined but may pose the greatest risk to Pacific LAB. Keep in mind recommendations from Rykaczewsiki and Dunne (2010) who noted that their analysis illustrates that anthropogenic climate change may be unlike past variability, i.e. empirical relationships based on historical observations may be inappropriate for projecting ecosystem responses to future climate change. In closing, the Department should prepare for an altered ocean climatology resulting in some reorganization of marine species assemblages and possible changes in productivity and/or ecosystem function across Pacific LAB.

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10.0 APPENDICIES

10.1 CLIMATE VARIATION IN THE NORTH PACIFIC OCEAN

Situated along a transition zone of the North Pacific Ocean, Canada's west coast is naturally subjected to swings in ocean conditions that relate to El Niño events and climate phenomena that produce decadal patterns of warm and cool periods (i.e. Pacific Decadal Oscillation; Mantua et al. 1997). Long term cyclic and physical variations in the north Pacific marine environment, as defined on a scale of annual or greater, are mediated by changes in the oceanic and atmospheric environment (Di Lorenzo et al. 2013). They include inter-decadal periods (approximately 20 years), intra-decadal periods (between 2-7 years) and inter-annual (year to year) periods (Weingartner, 2007). The inter and intra-decadal periods in the north Pacific are accompanied by specific physical patterns, sea surface temperature patterns are the easiest to measure and are most frequently used. The Pacific Decadal Oscillation is a prominent feature of the inter-decadal period; the El Niño Southern Oscillation is a prominent feature of the intra-decadal period.

10.1.1 Inter-Decadal

Pacific Decadal Oscillation (PDO)

The Pacific Decadal Oscillation (PDO) is based on the analysis of Mantua et al. (1997) and Zhang et al. (1997). It is the 1st mode of ocean surface temperature variability in the North Pacific Ocean, and it is has been good indicator of weather patterns that persist for a decade or more. Positive PDO values are associated with warmer than normal conditions in the NE Pacific. During a cool (negative) phase PDO—characterized by colder than average water temperatures in the Northeast Pacific ocean—more cold water is shifted into the California Current and southward flow is enhanced. During a warm (positive) phase, the converse is true and more water is shifted into the Alaska Current and southward flow in the California Current is decreased. PDO phase affects all trophic levels throughout the California and Alaska Current ecosystems (Hooff and Peterson, 2006; Keister et al. 2011; Mantua et al. 1997). The time series can be found at http://jisao.washington.edu/pdo/PDO.latest.

10.1.2 Intra-Decadal

El Niño Southern Oscillation (ENSO)

ENSO is a climate-ocean phenomenon which impacts physical transportation of water. An index has been created to measure ENSO called the Cold Tongue Index (CTI). ENSO is composed of two phases, the warm phase, El Niño (positive) and the cold phase La Niña (negative). Large positive CTI values are indicative of El Niño, large negative value of La Niña (Weingartner 2007). El Niño events are characterized by above normal sea surface temperatures (SST) across the eastern, north eastern and equatorial regions of the Pacific Ocean with below normal temperatures in central and north western Pacific regions (Weingartner 2007). La Niña events are the opposite however, strong anomalies do not develop along the west coast of the US (Weingartner 2007). The duration of each of these events may be between 8 and 15 months and time between events can vary from three to seven years. El Niño is characterized by a weak southward flow in the California Current (Hickey 1989). This results in a weak spring transition and higher than normal northward transport, decreased upwelling and increased temperatures. Spring transition drives coastal ocean currents and primary productivity.

It has recently been recognized that there are two “flavors” of ENSO – eastern Pacific (the more familiar one) and central Pacific, a.k.a. Modoki). The eastern pacific (EP) events are characterized by warming in the EP due to a weakening of the trade winds which in turn teleconnects with the Aleutian Low, yielding the PDO pattern in the North Pacific -- positive PDO values are associated with “EP” El Niño events. The CP Modoki events may be more linked with the NPGO (Di Lorenzo et al. 2013). Regardless, there is as yet no evidence that ENSO activity will increase in the future nor is their evidence that his “new” type of El Niño is anything more than a manifestation of natural climate variability (McPhayden et al. 2011; Ray and Giese 2012).

Both PDO and ENSO are characterized by changes in sea surface temperature (SST). However the differences are that PDO is based on a time scale of 10s of years, whereas ENSO is based on time scale of months; the most significant effects of PDO are seen in the north Pacific while the most significant effects of ENSO are seen in tropical waters; equatorial SST changes attributed to PDO are smaller and more broadly distributed than those of ENSO. ENSO and PDO when working in concert, can amplify or diminish atmospheric-oceanic responses (Weingartner 2007). The effects of ENSO are compounded by the contribution by the Kelvin Wave cycle, the PDO is not (Weingartner 2007).

In recent years, there has been increased variability in these dominant climate modes of the North Pacific that strongly impact sea surface temperature in Pacific LAB. The PDO index shows that it has tended to remain in one phase or the other for 20-30 year periods but since 1998, phase changes have come every five years; similarly, a new type of “El Niño is now recognized (Central Pacific-type) whose impact on the Pacific LAB is still being investigated. Other strong regional characteristics such as seasonal upwelling-favourable winds may modulate some effects of warming in certain regions and seasons.

10.1.3 Inter-Annual

North Pacific Index

This is a climate pattern that emerges as the 2nd dominant mode of sea surface height variability in the Northeast Pacific Ocean (Di Lorenzo et al. 2008). When the NPGO index is positive the westerly winds over the eastern North Pacific are often stronger than normal influencing the circulation processes. Positive NPGO is generally associated with cooler than normal conditions off the BC coast and a strong Aleutian low. The Aleutian low itself is a major low pressure area around the Aleutian Islands. It is a highly active atmospheric circulation area. “Normal” is considered to be a low pressure system in the winter in the Aleutian Islands, hence Aleutian low. During El Niño years, the pressure is lower than normal and is a strong Aleutian low (or +); this is also true during the warm phase of PDO (JISAO no date). If during an El Niño there is an intensifying Aleutian Low, there will be changes in the upper ocean temperatures, heat and moisture fluxes and mix-layer depths (Weingartner 2007).

10.2. TYPE, TIME SERIES, AND LIMITATIONS FOR LOWER TROPHIC LEVELS DATA

The southern part of the WCVI region has been sampled for zooplankton since 1979 by Dave Mackas during DFO research surveys, and results presented annually at the DFO 'State of the Ocean meeting'[1] for annual State of the Ocean summary reports. Mackas et al. (2004) also provides further information. Vertical net hauls from near bottom to the surface with black bongo nets were taken, (0.25m^2 mouth area and 230µm mesh). Sampling dates very between years, confounding the annual variability with seasonal variability, so typically annual data are compared with monthly climatologies and annual anomalies calculated. See http://www.meds-sdmm.dfo-mpo.gc.ca/csas-sccs/applications/publications/index-eng.asp

Continuous plankton recorders (CPRs) have been deployed on transects originating in the western Strait of Juan de Fuca and traversing the NE Pacific on a regular basis since 2000. These transects sample the WCVI region and the offshore, although the frequency of transects sampling the WCVI region increased after 2003 to provide seasonal data there.

A full description of the CPR instrument and sampling is given in Batten et al. (2003a) and Richardson et al. (2006) describe data analysis methods. The CPR is towed behind commercial ships at a fixed depth of about 7m and collects plankton on a moving band of filtering mesh with a mesh size of 270 µm. The mesh is subsequently divided into discrete samples, each representing 18km of tow and containing the plankton from about 3m^3 of seawater. These samples are analysed microscopically and abundances of taxonomic entities recorded. Large, hard-shelled phytoplankton are recorded as well as robust mesozooplankton. Gelatinous plankton are not well sampled by the CPR, and organisms smaller than the 270µm mesh are under-sampled.

Three indices of phytoplankton are available from CPR sampling. The Phytoplankton Colour Index (PCI), is determined by comparison with standard colour charts. This is a semi-quantitative representation of the total phytoplankton biomass and includes the organisms that are too fragile to survive the sampling process intact but which leave a stain on the mesh (Batten et al. 2003b). The index has four categories, which represent increasing concentrations of chlorophyll (Raitsos et al. 2013). Total diatoms and total dinoflagellates are indices calculated from summed counts of individual taxa. It should be emphasized that only larger, chain-forming diatoms are well represented, and only large, hard-shelled dinoflagellates. The phytoplankton counts from the CPR may not be truly representative of the phytoplankton community, with the relatively large mesh size and preservative unsuitable for athecate cells used in the CPR, however, it does present an internally-consistent data set.

Zooplankton are identified to varying degrees of taxonomic resolution depending on the robustness of the organism and how it survives the sampling mechanism and preservation; most copepods are identified to species, other groups to class or even just to phyla level. Gelatinous plankton are not well sampled by the CPR. Separate taxa may be summed to give abundances of broad taxonomic groups.

Figure 10.1 shows the location of the midpoints of CPR samples that were collected from the WCVI region between 2000 and June 2012 (analysis of late summer and fall 2012 data is not yet complete). Seasonal sampling began in 2004 in this region, but there was some sampling in June each year of 2000 to 2003. The data for 2008 should be treated with caution as a lack of funding in this year meant that sampling intensity was reduced and did not start until June.

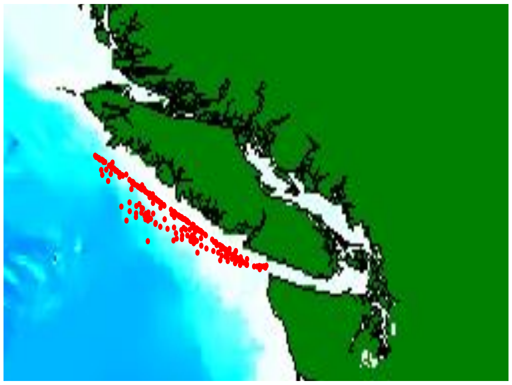

Fig. 10.1. Location of CPR samples collected in the WCVI region, June 2000 to June 2012.

Zooplankton data from the Strait of Georgia, collected during a variety of short time scale studies and with a variety of nets, have been recently reviewed and analyzed by Mackas et al. (2013) and relevant conclusions from that paper will be summarized here.

The North Coast sub-basin has been sampled by Mackas since 1990 as part of the West Coast research cruises which extended to the north of Vancouver Island and with sampling also in Hecate Strait from 1998. The methodology was the same as for the WCVI surveys described above.

Also available for this report is a long-term oceanographic sampling program based at Newport, Oregon (Fig. 10.2). This line was sampled extensively in the 1960s and early 1970s by oceanographers from Oregon State University for hydrography, zooplankton, krill and ichthyoplankton, however after the mid-1970s, routine monitoring ceased and only occasional sampling was done. The line was reopened in 1996 and has since been occupied regularly by W.T. Peterson (NOAA, Newport, OR). Sampling the complete line involves biweekly cruises to stations at 1, 3, 5, 10, 15, 20 and 25 nautical miles from shore. Routine measurements at each station include water column profiles of temperature and salinity and more recently fluorometry and oxygen. Sea water samples are collected and later analysed for chlorophyll (total and < 5 µm size fraction) and nutrients (nitrate, silicate, phosphate and ammonium). Zooplankton tows include a vertical haul from near the sea floor to the sea surface with a ½ m diameter net with 202 µm mesh, and a 60 cm diameter bongo net with 333 µm that is towed double obliquely from 20 m to the sea surface. The usual sampling routine involves leaving the dock in late afternoon, sampling the line outbound with everything but bongo nets. Bongo tows are then taken on the inbound leg, after dark, to sample the krill and ichthyoplankton. Figure 3 shows the location of the Newport Hydrographic (NH) Line, at 44°40’N. Germaine to this report is that hydrography, zooplankton abundance and species composition off Newport is very similar to measurements made off the west coast of Vancouver Island (see Mackas et al. 2004, 2006).

Figure 10.2. Location of the Newport Hydrographic Line. Stations located 1, 3, 5, 10, 15, 20 and 25 nautical miles from shore have been sampled biweekly since 1996.

10.3. SUMMARIZED CLIMATE TRENDS AND PROJECTIONS FOR PACIFIC LAB

See Christian and Foreman (2013).

Climate Driver	Trends in past conditions[1]	Climate projections over next 50 years
Atmospheric Processes and Precipitation		
Air Temperature	Annual mean air temperature has increased at a rate of ~0.1 °C / decade, with greater increases in winter, in the Strait of Georgia and WCVI[2] sub-basins. In the North Coast sub-basin the rate of increase is 0.1-0.15 °C /decade in winter and spring and negligible in summer.	An annual air temperature increase of 1-3°C is projected for coastal regions, with winter temperatures at the high end of this range and summer temperatures near the low end. Open ocean regions offshore expect an annual mean increase of ~3°C. Interior continental temperatures affecting freshwater ecosystems will warm 3-5°C.
Precipitation	In the Strait of Georgia and WCVI subregions annual precipitation has increased by 25-50% since 1930, with the largest increases in winter and spring. In the North Coast sub-basin the increase is slightly smaller and occurs predominantly in winter.	The warmer atmosphere leads to increased precipitation globally, but increasing summer drought over land. Over land, more precipitation will fall as rain rather than snow, leading to a slightly earlier peak spring runoff. Projections are for increased precipitation in winter and less in summer for most coastal regions. Precipitation over open ocean waters should see a slight increase.
Upwelling winds	Winds along the British Columbia (BC) outer coast are upwelling-favourable in summer and downwelling-favourable in winter. The recent trend in the WCVI region is for stronger downwelling winter winds and a shorter summer upwelling season, but with slightly stronger winds. For the North Coast sub-basin the trend is similar but without the intensified wind in summer. In the Strait of Georgia winds appear to have decreased slightly over the late 20th century.	Winds along the BC outer coast are upwelling-favourable in summer and downwelling-favourable in winter. Projections are for slightly stronger winds in both summer and winter (WCVI), or for downwelling winter winds and summer upwelling winds of similar strength but slightly reduced duration (North Coast). No robust projection information is available for GOA or Strait of Georgia.

Climate Driver	**Trends in past conditions**[1]	**Climate projections over next 50 years**
Streamflow	Time of peak Fraser River flow is moving forward by about 10 days/century while total annual flow remains about the same. Summer river temperatures are increasing by about 1.2°C/century.	Streamflow is expected to be ~10% lower in June-August and 10% higher at other times of the year in the Strait of Georgia. Seasonal pattern is similar in other coastal sub basins, but summer reduction is less.
Water and Sediments		
Water temperature	In the open waters of the GOA, the recent trend has been for warming at a rate up to 1°C/century at the surface, declining to zero at 500 m depth. In coastal regions, surface temperatures are increasing at 0.51 ± 0.72 °C/century at Kains Island and 1.39 ±0.52 °C/century at Entrance Island.	Sea surface temperature is expected to increase by 1.5-2°C, except in summer in WCVI where increased upwelling will reduce the overall warming by about half. Less warming is projected in lower layers.
Sea surface salinity (ppt)	In the open waters of the GOA, the recent trend has been for freshening (decrease salinity) at a rate up to 0.2 ppt/century at the surface, declining to zero at 100 m depth. In coastal regions, surface salinity trends are -0.47 ± 0.49 ppt /century at Kains Island and -0.76 ± 0.53 ppt /century.	Sea surface salinity (SSS) will decline by 0.25-0.3 ppt in GOA and by up to 1 in coastal subbasins, but there is considerable seasonal variation. In Strait of Georgia summer SSS may increase by up to 0.5 ppt due to reduced precipitation and runoff; in WCVI it will increase in winter due to increased downwelling-favourable winds and narrowing of the relatively fresh Vancouver Island Coastal Current. In PNCIMA it will likely decrease by ~1 ppt in summer/fall with no appreciable change in winter/spring.
Stratification	In the open waters of the GOA the recent trend has been towards greater stratification, with the density difference between surface and subsurface waters increasing at up to 0.5 kg/m^3/century.	Greater stratification in Strait of Juan de Fuca in spring and summer, and in the open waters of the Gulf of Alaska. Mixed layer depth may increase slightly off the west coast of Haida Gwaii in North Coast. Changes in lake stratification have been observed at temperate and high latitudes lakes and are anticipated to continue.

Climate Driver	**Trends in past conditions**[1]	**Climate projections over next 50 years**
Currents	In the open waters of the GOA there is no evidence of systematic changes in circulation.	Vancouver Island Coast Current is narrower, deeper, stronger most seasons. Surface currents may be stronger in Strait of Juan de Fuca in summer. Haida eddies may increase in strength and coherence, and possibly in number.
Sea and lake level variations	Sea level has risen by 3.1 cm at Victoria and 2.0 cm at Vancouver over the past 50 years. At Tofino sea level has declined by 8.4 cm over the same period, while at Prince Rupert it has risen 10 cm in 77 years. Local deviations of sea level rise from the global mean are likely to be small except where they are associated with isostatic motion of the land, which is likely the case in many areas of BC.	Local deviations of sea level rise from the global mean are highly uncertain and if they occurs are likely to be small (< 5 cm). Global mean increase is projected to be ~30 cm. This is a lower limit because it does not take account of accelerating loss of glacier mass; the upper limit could be substantially higher. Changes in lake water budgets (evaporation, evapotranspiration, glacial melt water, snowpack) are anticipated to produce changes in seasonal lake elevation.
Acidification	Recent trends from other locations suggest a downward trend in surface pH of about 0.0017/yr and in aragonite saturation of 0.007/yr. Deviations from the global mean are expected to be small at the surface but could be significant in the thermocline. Data records from Line P Program sampling are short due to early problems with alkalinity but current and ongoing trends are being monitored.	Surface ocean pH declines by 0.13, and aragonite saturation declines by 0.29 at the 1026.6 kg m^3 density surface. This isopycnal (i.e. water surface that is constantly at 1026.6 kg m^3 density) was chosen to be representative of the main thermocline of the Gulf of Alaska, and represents waters that potentially impact the BC continental shelf. The surface pH trend should be close to the global mean for open ocean waters, but local deviations from the global trend in coastal waters are not yet known.
Oxygen concentration	In the coastal subregions, oxygen concentration declined by ~0.5 μmol/kg/yr from 1960-2012. In the open waters of the Gulf of Alaska a similar rate of decline is observed in the 1026.3-1027.0 kg m^3 density range (about 100-400 m depth).	Oxygen concentration will decline by ~36 μmol/kg at the 1026.6 kg m^3 density surface in the open waters of the Gulf of Alaska. Deep water oxygen depletion in lakes is expected to become more frequent in certain areas.

Climate Driver	Trends in past conditions[1]	Climate projections over next 50 years
Nutrients	In the open waters of the Gulf of Alaska there is a weak trend of increasing thermocline nitrate concentration, of about 0.13 μmol/kg/yr at 150 m depth (1956-2011).	No significant change in surface nitrate concentration is projected in the Gulf of Alaska. In freshwater ecosystems, changes in delivery of limiting nutrients are anticipated.

10.3.1 Definitions as provided by Pacific LAB Trends and Projections Group

A trend is based on past observations, and the length of the observational records varies. A projection is estimated from climate model output based on assumptions about future anthropogenic greenhouse gas emissions. We make projections only for the 50 year timescale due to some unique features of North Pacific climate as described below.

Because in the North Pacific interannual to interdecadal climate variability is large relative to secular trends, climate model projections have no predictive skill on the 10-year time scale, and trends based on less than 20-30 years of data cannot be assumed to represent longer term trends.

So 10-year projections are best estimated as linear extrapolations of past trends, with the caveats that (a) only those based on relatively long time series are robust trends, and (b) even these are only *our best estimate of the long-term secular trend on which unpredictable shorter term variability is superimposed*, and not the total signal.

Trends and projections information is the basis for understanding current and future climate conditions. Past observations establish a trend, although lengths of time series of different parameters at different locations vary. Projections from climate model outputs use assumptions about future anthropogenic greenhouse gas emissions to estimate the anthropogenically-influenced climate trend. In the Pacific LAB, observed high variability of natural physical climate drivers is large in the marine environment relative to the projected increase associated with the long-term anthropogenic change on 10-50 year time scales. This variability has consequences for the ability to make meaningful climate projections at shorter time-scales, especially for the marine environment.

Ten-year projections are best estimated as linear extrapolations of past trends, with the caveats that (a) only those based on relatively long time series provide robust trends and (b) even these are only our best estimate of the long-term trend on which unpredictable short-term variability is superimposed, and not the total signal. The uncertainty associated with extrapolation of a trend depends on the length of the data record used to estimate the trend and the temporal extent of the extrapolation. On a 10-year time scale, it is possible to extrapolate present trends if the data record is sufficiently long (> 20-30 years), but as noted above, the natural variability in the Pacific LAB currently overwhelms the anthropogenic component.

Climate model outputs are the basis of the 50-year projections provided here, and uncertainty is derived from three sources: (1) the forcing scenario (the greenhouse gas emissions used to force the model), (2) model error, and (3) model internal variability. The latter is analogous to the natural variability discussed above. A good model reproduces the general characteristics of this variability (e.g. the frequency and magnitude of events), but can never reproduce the timing of them exactly. Therefore model projections are only useful when averaged over longer periods (20-30 years has been used routinely). Projections for several important variables are not resolved at the ACCASP sub-basin scale, so information on future climates at that scale remains sparse.