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0. Summary

Historically, salmon stocks from the Columbia River and Snake River formed one of the most valuable fisheries on the west coast of North America. Annual returns of salmon and steelhead to the Columbia River basin were believed to be as high as 16 million fish during the late 1800s. However, salmon and steelhead returns sharply declined during the 1980s and 1990s to reach nearly 1 million fish. Although several factors may be responsible for the decline of Columbia River salmon and steelhead, there is increasing evidence that these drastic declines were primarily attributable to persistently unfavorable ocean conditions. Hence, an understanding of the effects of ocean conditions on salmon production is required to forecast the return of salmon to the Columbia River basin and to assess the efficacy of mitigation measures such as flow regulation on salmon resources in this system.

The Canadian Program on High Seas Salmon has been collecting juvenile salmon and oceanographic data off the west coast of British Columbia and Southeast Alaska since 1998 to assess the effects of ocean conditions on the distribution, migration, growth, and survival of Pacific salmon. Here, we present a summary of the work conducted as part of the *Canada-USA Salmon Shelf Survival Study* during the 2008 fiscal year and compare these results with those obtained from previous years. The working hypothesis of this research is that fast growth enhances the marine survival of salmon, either because fast growing fish quickly reach a size that is sufficient to successfully avoid predators, or because they accumulate enough energy reserves to better survive their first winter at sea, a period generally considered critical in the life cycle of salmon.

Sea surface temperature decreased from FY05 to FY08, whereas, the summer biomass of phytoplankton increased steadily off the west coast of Vancouver Island from FY05 to FY08. As in FY07, zooplankton biomass was generally above average off the west coast of Vancouver Island in FY08. Interestingly, phytoplankton and zooplankton biomass were higher in FY08 than was expected from the observed nutrient concentration that year. This suggests nutrients were more effectively by phytoplankton in FY08. In addition, the abundance of lipid-rich northern copepods increased from FY05 to FY08, whereas lipid-poor southern copepods showed the opposite pattern, suggesting that growth conditions were more favorable to juvenile salmon in FY08 than in previous years. However, growth indices for juvenile coho salmon were near the 1998-2008 average, both off the west coast of Vancouver Island and Southeast Alaska, indicating that additional factors beside prey quality affect juvenile salmon growth in the marine environment.

Catches of juvenile Chinook, sockeye and chum salmon off the west coast of Vancouver Island in June-July 2008 were the highest on record during summer since 1998, suggesting that early marine survival for the 2008 smolt year was high. Interestingly, the proportion of hatchery fish was high (80-100%) among the juvenile Columbia River Chinook salmon caught off the British Columbia coast during summer, suggest that relatively few wild Chinook salmon are produced in the Columbia River Chinook. In addition, we also recovered two coded-wire tagged juvenile Redfish Lake sockeye salmon in June 2008 off the west coast of British Columbia. As relatively few Redfish Lake sockeye smolts are tagged each year, this also suggests that early marine survival was high for these fish, and may result in a high return in 2009 if they mature at age three, or in 2010 if they mature at age four.

To date, our research shows that different populations of Columbia River salmon move to different locations along the coastal zone where they establish their ocean feeding grounds and overwinter. We further show that ocean conditions experienced by juvenile Columbia River salmon vary among regions of the coast, with higher plankton productivity and temperatures off the west coast of Vancouver Island than in Southeast Alaska. Hence, different stocks of juvenile salmon originating from the Columbia River and Snake River are exposed to different ocean conditions and may respond differently to climate changes. In particular, our work shows that the growth and fat content of Chinook and coho salmon vary along different parts of the

coast and among years. These growth differences appear to be associated with differences in prey *quality* rather than by a direct effect of temperature on salmon growth or prey *quantity*, indicating that changes in ocean conditions and circulation affect salmon production indirectly through changes in prey community composition and quality. Taken together, our analyses indicate that the relative survival of different stocks of salmon in the ocean will depend on where they migrate in the ocean, and that changes at the base of the food chain must be taken into consideration to understand the effects of ocean conditions on salmon growth, and hence, on salmon survival.

Our research also provides new insight into the migration behavior Snake River sockeye salmon. In particular, we show that Redfish Lake and Columbia River sockeye smolts undertake a rapid northward migration that brings them quickly well beyond the Columbia River Plume to the west coast of British Columbia then to Alaska and the Aleutian Islands, with migration speed averaging 30-45 km/d. These migration speeds are among the fastest of any sockeye salmon populations originating from other systems. However, the factors limiting their marine survival are still currently unknown.

Our analyses also demonstrate that the marine survival and production of Columbia River Chinook and coho salmon are strongly influenced by the growth conditions and food web quality off the west coast of Vancouver Island. As a result, we present a series of relationships may serve as leading indicators of adult salmon returns to the Columbia River 1-2 years before they migrate back to the river to spawn. In particular, these models predict that the returns of adult summer and fall Chinook to the Bonneville Dam will be average to above average in 2009 and 2010 (average based on the 2000-2008 return years). Although fishery managers should be cautious before they start using these relationship to manage Columbia River salmon due to the low number of data points presently available, these results indicate that the research conducted on the ocean environment in British Columbia has the potential to influence harvest strategies and conservation measures for Columbia River salmon. However, the development of these predictive models will require a long-term funding commitment, as the stability and reliability of these models needs to be assessed over a longer time frame.

1. Background

Salmon stocks from the Columbia River and Snake River form one of the most valuable fisheries on the west coast of North America. Annual returns of salmon and steelhead to the Columbia River basin were believed to be as high as 16 million fish during the late 1800s (NRC 1996). However, salmon and steelhead returns sharply declined during the 1980s and 1990s to reach nearly 1 million fish. As a result of this drastic decline, several Columbia River and Snake River stocks have been listed under the Endangered Species Act (ESA) (NRC 1996; Ruckelshaus et al. 2002). This prompted the implementation of several measures to protect and recover these ESA-listed stocks. These include hatchery enhancement, harvest reduction, hydropower regulation, and habitat restoration (Raymond 1988). However, it is necessary to understand the causes of these declines to assess the effectiveness of these measures (Bottom et al. 2006).

Although a number of factors may be responsible for the decline of Columbia River salmon and steelhead, several lines of evidence suggest that these drastic declines were partly attributable persistently unfavorable ocean conditions (NRC 1996; Bottom et al. 2006). First, large scale declines in the marine survival of salmon have occurred from California to south-central British Columbia coastal waters during the 1980s and 1990s, bringing some stocks to the verge of extinction in less than a decade even in nearly 'pristine' watersheds (Hare et al. 1999; Welch et al. 2000; McKinnell et al. 2001). The simultaneous decline of salmon originating from geographically-distant watersheds suggests that a common cause is affecting these stocks in the marine environment. Second, the marine survival of hatchery-released salmon has also decreased drastically during that period (Beamish et al. 2000; Logerwell et al. 2003). This provides evidence that, in some areas, the reduction in adult returns was due to changes in ocean conditions rather than to the production of salmon smolts (Beamish et al. 2000). Third, freshwater survival estimates through the hydropower system of the Columbia River were higher during the 1990s compared to the 1970s (Williams et al. 2001). Yet, returns of salmon to the Columbia River and Snake River were much lower during the 1990s than in the 1970s (Williams et al. 2001). Fourth, the return of salmon to the Columbia River rebounded from historical lows during the 1990s to historical high levels in 2001-2004 following a major shift in ocean conditions that occurred in the late 1990s (Peterson and Schwing 2003; Williams et al. 2005). Finally, the in-river survival of salmon smolts is similar in large rivers with and without dams (Welch et al. 2008). Hence, an understanding of the effects of ocean conditions on salmon production is required to forecast the return of salmon to the Columbia River Basin and to assess the success of mitigation measures on salmon resources (Brodeur et al. 2000).

While we cannot manipulate the ocean environment to improve the production of salmon (but see Boyd et al. 2004), it may be possible to establish linkages between marine survival and ocean conditions, and predict the size of Columbia River salmon runs. Without an understanding of the effects of ocean conditions on salmon production, it is also not possible to adequately assess the success of mitigation measures such as habitat restoration and flow regulation on the health of Columbia River salmon runs. Ocean conditions may mask, enhance, or even override actions taken in the freshwater habitat to improve salmon returns. For instance, an increase in salmon return after restoring a tributary of the Columbia River during favorable ocean conditions could be due to improved freshwater survival, improve marine conditions, or a combination of both. Hence, in order to evaluate the effectiveness of any mitigation measures, it is mandatory to evaluate the response of salmon to both the freshwater and marine environments.

The ocean conditions that influence Pacific salmon growth and survival vary on decadal scales, and appear to be mediated by changes in atmospheric circulation and climate (Hare and Mantua 2000; McGowan et al. 2003). In particular, the ocean conditions were generally less favorable for salmon growth in the California Current System during the 1980s and 1990s, and may be largely responsible for the decline of salmon stocks ranging from California to southern

British Columbia, including Columbia River salmon, during this period (Beamish et al. 2000; Welch et al. 2000). The 1990s was the warmest period on record with coastal temperatures that were typically 0.5-1.0°C warmer than during the 1970s (DFO 2006). These warmer waters may have increased the metabolic costs of salmon, which may have reduced the energy available for growth (Hinch et al. 1995). Plankton biomass also decreased in the California Current System during the 1980s (and to a greater extent during the 1990s), possibly due to weaker upwelling conditions combined with stronger and deeper vertical density stratification (McGowan et al. 1998, 2003; Mackas et al. 2001; Scheuerell and Williams 2005). Furthermore, lipid-poor southern copepods were abundant from Oregon to British Columbia during this period, while the abundance of lipid-rich northern copepods was unusually low in these regions (Peterson and Schwing 2003; Mackas et al. 2004; Hoof and Peterson 2006). In addition, the development of *Neocalanus plumchrus*, one of the most abundant mesozooplankton in the subarctic Pacific, was about 60 days earlier in warm than in cold years (Mackas et al. 1998), indicating that entry of salmon smolts into the ocean may not have coincided with peak plankton production during the 1990s.

The warm and poor ocean conditions that prevailed on the west coast of North America during the 1980s and 1990s changed dramatically in 1999 (Peterson and Schwing 2003). Sea surface temperatures were much cooler, and were apparently similar to ocean conditions holding in the early 1970s. The biomass of northern and southern copepods increased and decreased, respectively (Peterson and Schwing 2003; Mackas et al. 2004; Zamon and Welch 2005). Furthermore, the timing of plankton production returned to pre-1990s values from 1999 to 2003 (DFO 2006). Thus, this sudden and dramatic shift appeared to have improved the ocean conditions for salmon growth (Whitney and Welch 2002), and have subsequently led to significantly better survival conditions for Columbia River Chinook and coho salmon (Peterson and Schwing 2003; Scheuerell and Williams 2005; Williams et al. 2005). Notably, the 2001-2004 returns of adult steelhead, spring-summer and fall chinook, and coho to the Columbia River have reached either historical or near-historical highs, supporting the view that ocean and climate conditions strongly influence the abundance of Columbia River salmon.

The rapid shift to favorable ocean conditions that drastically improved the return of Chinook, coho, and steelhead to the Columbia River in recent years may not last for an extended period of time, as coastal temperatures have been warming by 2-3°C along the coast since the fall of 2002 (Mackas et al. 2007). This suggests that the poor ocean conditions that prevailed in the 1980s and 1990s may return to impact future returns of Columbia River salmon. For example, higher sea surface temperatures experienced by juvenile salmon in 2003 may be responsible for the low return of spring Chinook salmon to the Columbia River in 2005. Hence, there is an immediate need to continue documenting and examining current ocean conditions to better understand and predict the fate of Columbia River salmon.

Pacific salmon have a complex life cycle that involves a freshwater phase for spawning and rearing, as well as an ocean phase where they spend the greater part of their lives and gain the bulk of their mass and energy that is necessary for successfully completing their spawning migration. On the west coast of North America, juvenile Pacific salmon generally exhibit a northward migration and utilize the narrow continental shelf as a migration highway that brings them to the Aleutians, and eventually into the Gulf of Alaska, though some stocks appear to establish residence on the continental shelf or even undertake a southward migration (Hartt and Dell 1986; Pearcy and Fisher 1988; Fisher and Pearcy 1995; Welch et al. 2002). However, stock-specific migration patterns have only been described for a few stocks, possibly due to the logistical difficulty of inferring juvenile salmon migration using traditional approaches. Hence, future attempts to relate ocean research on salmon to Columbia River issues will require a more complete understanding of where specific Columbia River stocks of salmon go in the ocean, and what their growth, biological condition, and resulting survival are like.

2. Research Objectives

In this report, we present the results obtained during the 2008 fiscal year and highlight some of the major results obtained to date. The primary objective of this research is to assess the effects of ocean conditions on salmon production in the Columbia River basin. The working hypothesis of this research is that the marine survival of salmon is primarily determined by the productivity of the ocean environment encountered by salmon during their first year at sea. In particular, salmon experiencing faster growth are expected to have lower mortality rates (Holtby et al. 1988; Pearcy 1992; Beamish et al. 2004a; Moss et al. 2005). Similarly, salmon that accumulate higher energy and lipid reserves prior to the onset of winter are also expected to exhibit lower overwinter mortality than those in poor conditions (Beamish and Manhken 2001). Salmon growth and energy accumulation are expected to vary in relation to ocean productivity, which in turns varies among years in relation to climate conditions (McGowan et al. 1998; Whitney and Welch 2002; Chavez et al. 2003). Finally, ocean productivity is expected to vary among different regions of the ocean (Hare et al. 1999; Welch et al. 2000; Ware and Thomson 2005). Hence, salmon production may also vary among stocks depending on their migration behavior. A secondary goal of this research is therefore to establish which specific stocks of salmon remain resident in areas of poor growth, and therefore to develop some fundamental understanding of why marine survival differs among stocks of salmon (Levin 2003).

The objectives of this research are achieved by:

- (1) *collecting juvenile salmon and oceanographic data from the west coast North America (from Vancouver Island to Southeast Alaska) during spring/summer, fall, and winter;*
- (2) *assessing the growth and feeding conditions of juvenile salmon collected from these areas;*
- (3) *assessing the ocean productivity of these areas;*
- (4) *identifying the extent of region/regions of poor growth and survival;*
- (5) *identifying the physical and biological changes in the ocean that lead to reduced ocean survival through changes in growth;*
- (6) *establishing the relative impacts of temperature, food availability, and other ocean conditions on salmon growth through the application of bioenergetics models;*
- (7) *identifying stocks that utilize regions of poor growth and establish their migration strategies relative to stocks with migration behaviors that move them rapidly out of regions of reduced growth potential;*
- (8) *developing simple models to forecast adult returns to the Columbia River.*

Information generated from this study will quantify and allow the detection of impacts of differing ocean productivity on salmon growth and survival. Documenting the extent of changes in growth, along with changes in physical features of the ocean will help to further our understanding of the impact of climatic events in the ocean on important fish resources. More specifically, the samples collected will provide an assessment of whether different stock groups (including ESA-listed stocks) predominate in regions of poor growth and survival, and models that can be used to forecast how adult returns to the Columbia River will vary as a result of changing ocean conditions.

3. Methods

3.1 Data collection

3.1.1 General survey information

Ocean surveys for juvenile salmon were conducted using the *FV Viking Storm* in October-November 2007, February-March 2008 and June-July 2008 (Fig. 1), to assess the distribution, migration, growth, condition, and survival of salmon. These surveys conducted scientific operations off the west coast of Vancouver Island, in Queen Charlotte Sound, in Hecate Strait, in Dixon Entrance, and on the shelf region off the coast of Southeast Alaska. Scientific operations were also conducted in inside waters of the west coast of Vancouver Island, Strait of Georgia, British Columbia, and Southeast Alaska. A total of 401 fishing stations, 396 oceanographic stations, and 401 zooplankton stations were completed in FY08 (Table 1).

3.1.2 Fishing gear and fishing operations

The *FV Viking Storm* towed a rope trawl, originally manufactured by Cantrawl Nets Ltd., Richmond, BC, and later modified to a model 240 trawl by the fishing crew. The trawl has a heavy-duty front end of hexagonal web made from 3/8 in. (9.5 mm) and 5/16 in. (7.9 mm) Tenex rope, and a tapered body made of 64 in. (163 cm), 32 in. (81.3 cm), 16 in. (40.6 cm), 8 in. (20.3 cm) and 4 in. (10.2 cm) polypropylene sections, an intermediate section of 3 in. (7.6 cm) polypropylene, and a codend of 1.5 in. (3.8 cm) knotted nylon lined with 0.25 in. mesh (64 mm). The trawl has three 40 m bridles of 5/8 in. (1.6 cm) wire rope per side that are attached with a single hook-up to 5 m Jet doors. Typically, 100-150 m of 1.25 in. (3.2 cm) warp was paid out to tow the trawl at the surface.

The *FV Viking Storm* was able to tow the trawl at the surface at 5 knots ($2.6 \text{ m}\cdot\text{s}^{-1}$) in good sea conditions. This typically achieved a mouth opening of ca. 28 m wide by 16 m deep as measured acoustically by a Scanmar trawl eye mounted on the head rope. In rough weather, the trawl was towed at head rope depths down to 15 m.

Up to 30 juvenile Chinook, coho, and sockeye salmon were selected from each net tow. Priority was given to fish with preferred scales. The remaining fish were selected to approximately represent the size range of each species in the catch. All the juvenile Chinook and coho salmon, and only juvenile sockeye with their adipose fin missing, were scanned for coded-wire tags (CWT) and passive integrated transponder (PIT) tags. Fork length ($\pm 1 \text{ mm}$) and mass ($\pm 1 \text{ g}$) were determined onboard the research vessel. Otoliths and scales were removed for age determination. A skin sample was also taken from the operculum using a hole-punch and preserved in 70% ethanol for stock identification. Whole fish were then frozen individually at -20°C in pre-identified plastic bags for subsequent analyses.

Juvenile coho and sockeye salmon (i.e. ocean age 0) could be readily identified from their size, as juvenile and adult coho and sockeye salmon have non-overlapping size distributions (Trudel et al. 2007a). The lack of scales on most of the captured Chinook salmon, together with the complexity of their life-cycle (i.e., subyearling vs. yearling), prevented the determination of their ocean age and life-history type. For this species, we used coded-wire tag recoveries of known-age fish to separate yearling and subyearling Chinook salmon based on observed fork length (Table 2). These size limits were used for Chinook salmon caught off the west coast of Vancouver Island. For juvenile Chinook salmon caught in Southeast Alaska, we assumed that all these fish were spring Chinook, as over 98% of juvenile Chinook salmon caught in this area are spring Chinook (Orsi and Jaenicke 1996).

3.1.3. Oceanographic sampling

At oceanographic stations, the scientific crew (1) conducted CTD (conductivity-temperature-depth) casts, and (2) collected surface seawater samples with a Niskin bottle for salinity, chlorophyll a, and nutrient analysis (nitrate, phosphate, and silicate). CTD casts were conducted to within 5 m of the bottom or to a maximum depth of 250 m with a Seabird SBE

911+ probe. Several calibration samples from selected CTD casts were collected over the course of the survey with Niskin bottles at depths where the salinities were stable (i.e. at depths greater than 500 m). Duplicate nutrient samples were collected in acid-washed glass test tubes, and duplicate chlorophyll *a* samples were collected on GF/F glass fiber filter disks, folded in half and placed in polypropylene scintillation vials. All these samples were stored frozen at -20°C and analyzed at the Institute of Ocean Sciences (Sidney, British Columbia). Chlorophyll *a* samples were stored in dark crates to prevent photosynthetic degradation prior to analysis.

3.1.4 Zooplankton sampling

Vertical bongo tows were conducted with two 58 cm diameter Nitex nets (253 μm mesh) to within approximately 10 m of the bottom or a maximum depth of 150 m. One of the nets was equipped with a TSK flowmeter. Zooplankton collected from the net with the flowmeter were preserved in 10% formalin and sent to the zooplankton laboratory at the Institute of Ocean Sciences, Fisheries and Oceans Canada (Sidney, British Columbia) for species classification and enumeration. Zooplankton taken from the net without the flowmeter was sorted into four size fractions by successively sieving through 8.0, 1.7, 1.0, and 0.25 mm screens. Each size fraction was weighed wet, dried at 60°C for 48 hours, re-weighed, and stored in plastic bags for stable isotope, bomb calorimetry, and proximate analyses.

Oceanographic and zooplankton data for the October 2007, March 2008, and June 2008 have been partially completed. Hence, only partial results are presented in this report.

3.2 Laboratory analyses

3.2.1 DNA extraction

Tissue samples were collected from juvenile salmon caught in the trawl surveys and DNA was extracted from the samples as described by Withler et al. (2000). Juvenile Chinook, coho, and sockeye salmon were surveyed for 14 microsatellite loci (MSL) and for a major histocompatibility complex (MHC) locus. Further details on the loci surveyed as well as the laboratory equipment used are outlined by Beacham et al. (2004a).

3.2.2 Diet and chemical analyses

Fish frozen at sea were thawed and dissected in the laboratory. Stomach contents were removed, weighed, and pooled by species and tow for prey identification. The carcass was then dried at 60°C to constant weight to determine water content. Dried samples were ground in a food processor prior to chemical analyses.

Prey items were identified under a dissecting microscope to the lowest taxonomic resolution. The prey species were pooled into eight major categories: Fish, Decapods, Euphausiids, Hyperiids, Pteropods, Copepods, Insects, and "Other". The "Other" category included polychaetes, cephalopods, cirripede larvae, mysids, isopods, and echinoderms. The percent contribution of each prey item to the diet of juvenile salmon was expressed on a volume basis, and was averaged across tows within regions, years, and seasons.

To assess the variability in diet and trophic position of juvenile salmon among regions, seasons, and years, we measured stable isotopes of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) by mass spectroscopy in whole juvenile salmon and two size fractions of zooplankton (0.25-1.0 mm and 1.0-1.7 mm). $\delta^{13}\text{C}$ is an indicator of food source, while $\delta^{15}\text{N}$ is an indicator of trophic position (Vander Zanden and Rasmussen 2001; Post 2002a, b). The trophic position (*TP*) of juvenile salmon was then estimated by the following equation:

$$(1) \quad TP = \frac{\delta^{15}N_s - \delta^{15}N_z}{3.4} + 2$$

where $\delta^{15}N_s$ (‰) and $\delta^{15}N_z$ (‰) is the nitrogen signature in salmon and zooplankton, respectively, 2 is the trophic position of zooplankton, and 3.4 is the increase in $\delta^{15}N$ between two successive trophic levels (Vander Zanden and Rasmussen 2001; Post 2002a, b). The trophic position of juvenile salmon is expected to range between three and four depending on the proportion of fish in their diet. Juvenile salmon that feed exclusively on invertebrates should be close to trophic level three and will increase to four as the proportion of fish in their diet increases to 100%.

The application of Eq. (1) for estimating the trophic position of juvenile salmon requires that $\delta^{15}N_s$ is measured in the muscle. In contrast, all the $\delta^{15}N_s$ were performed on a subsample of whole dried and homogenized salmon. As $\delta^{15}N$ is higher by 0.68‰ in the muscle than in the whole fish in juvenile salmon (Trudel et al. 2007c), we simply added 0.68‰ to the $\delta^{15}N$ measured in whole fish to obtain $\delta^{15}N_s$.

The energetic status of juvenile salmon was determined on a subsample of the dried samples by bomb calorimetry (Philipson 1964) and was expressed as kilojoules per gram wet weight ($\text{kJ}\cdot\text{g}^{-1}_{\text{wet}}$). Replicate analyses were performed on 10% of the samples and were generally within 0.5% (range: 0-2.9%). The energy content of the remaining fish was determined using a series of empirical models derived by Trudel et al. (2005) between energy contents and water contents, and between lipid concentration and water contents specific to juvenile Chinook and coho salmon (Table 3).

In addition to energy content, we used the ratio of carbon to nitrogen (C:N) as an indicator of lipid contents in zooplankton and fish (McConnaughey and McRoy 1978). Lipids are composed of carbon (C), hydrogen (H), and oxygen (O), while proteins, in addition to C, H, and O, also contain nitrogen (N) and sulfur (S). Hence, a high C:N ratio indicates higher lipid content (Kiljunen et al. 2006; Sweeting et al. 2006; Post et al. 2007).

3.3 Data analyses

3.3.1 Stock identification

Analysis of mixed-stock samples of juveniles was conducted with a Bayesian procedure (BAYES) as outlined by Pella and Masuda (2001). A modified version of the program was developed as a C-based program (cBAYES) and used in the analysis. A 240-population baseline comprised of approximately 50,000 individuals ranging from Bristol Bay to California was used in the estimation of stock composition of individual samples, as well as in the determination of the origin of individual Chinook, coho and sockeye salmon (Beacham et al. 2001, 2003a, 2006). In the analysis, eight 200,000-iteration Monte Carlo Markov chains of estimated stock compositions were produced, with initial starting values for each chain set at 0.90 for a particular population which was different for each chain. Estimated stock compositions were considered to have converged when the shrink factor was less than 1.2 for the eight chains (Pella and Masuda 2001). The last 5,000 iterations from each of the eight chains were then combined, and the mean and standard deviations of estimated stock compositions determined. The model assigned the mixture composition to individual populations which were then summed into regional groupings for three seasons: spring/summer (May–August), fall (September–December), and end-of-winter (February–March). Identification of individual fish to region of origin was determined as the one with the highest probability of assignment. Individual fish were left without an assigned region of origin if the highest probability of assignment was less than 50%.

3.3.2 Ocean migration

The ocean migration of juvenile Chinook, coho, and sockeye salmon originating from the Columbia River system was inferred from CWT recoveries obtained during the surveys conducted by the Canadian Program on High Seas Salmon off the west coast of British

Columbia and Southeast Alaska between 1995 and 2008. Additional CWT data were provided by the Auke Bay Laboratory (Juneau, Alaska) for Icy Point and Icy Strait, by DFO for the west coast of Vancouver Island and the Strait of Juan de Fuca, and by Oregon State University (Corvallis, Oregon) for Washington and Oregon. The distribution of Columbia River spring Chinook, fall Chinook, and coho salmon were compared during spring (Mar-May), summer (Jun-Aug), and fall (Sep-Nov).

Although CWTs usually provide unequivocal assessment of the origin of individual salmon, few stocks are tagged relative to the total number of spawning populations that exist. Furthermore, this approach requires a large sample size to determine the migration timing and routes, as the recovery of tagged fish is generally quite low (Hartt and Dell 1986). Alternatively, the development of molecular techniques has enable fisheries scientists to accurately assess the origin of ocean-caught fish on an individual basis (Nielsen et al. 2001; Wirth and Bernatchez 2001; Beacham et al. 2002, 2004b). Hence, DNA analysis was also used to infer the migration of juvenile Chinook, coho, and sockeye salmon originating from the Columbia River (Beacham et al. 2001, 2005, 2006).

3.3.3 Size and growth

Regional and yearly differences in fall size, fall storage energy, and summer growth were assessed in juvenile spring Chinook salmon, fall Chinook salmon, and coho salmon collected by DFO. The energy available for storage (further referred to as storage energy) in juvenile Chinook salmon and coho salmon was estimated by subtracting $4 \text{ kJ} \cdot \text{g}^{-1}_{\text{wet}}$ from all the direct and indirect measurements of energy density obtained in this study (Trudel et al. 2007b). This threshold was selected for storage energy, as laboratory and field studies showed that mortality occurred in salmonids when energy content drops below $4 \text{ kJ} \cdot \text{g}^{-1}_{\text{wet}}$ (Simpkins et al. 2003; Crossin et al. 2004). Summer growth rates (SG, $\text{mm} \cdot \text{d}^{-1}$) were estimated using fish caught during the fall period as (Trudel et al. 2007b):

$$(2) \quad SG = \frac{FL_C - FL_{OE}}{DY_C - DY_{OE}}$$

where FL_C and FL_{OE} are respectively the size at capture and ocean entry (mm), and DY_C and DY_{OE} are respectively the day of the year at capture and ocean entry (d). Published and unpublished data were used to determine the timing and size at ocean entry to estimate the growth rate of juvenile Chinook salmon and coho salmon (Table 4).

3.3.4 Overwinter mortality

Overwinter survival of juvenile salmon during their first year at sea has been recognized as an important factor limiting the recruitment of salmon and has been linked to lipid and energy dynamics (Beamish et al. 2004a). As a result of low prey productivity, salmon often face food shortages during winter and must rely on the lipids accumulated during summer to fuel their metabolic functions. Hence, overwinter survival of salmon is expected to be influenced by the quantity of lipids stored prior to and utilized during winter. Since small salmon have higher metabolic rates and lower lipid reserves than large salmon, small salmon are expected to deplete their lipids faster and to sustain higher mortality during winter than large salmon (Post and Evans 1989; Beamish and Mahnken 2001). The extent of size-selective mortality and lipid depletion may also differ among regions and years, and thus affect the recruitment variability of salmon. An understanding of the factors contributing to salmon mortality during a critical period in the life cycle of salmon may thus enhance our ability to forecast the marine survival and return of Columbia River Chinook and coho salmon.

We assessed the extent of size-selective mortality in juvenile Chinook salmon and coho salmon during their first winter at sea by comparing the mean and variance of fall and winter sizes, and by comparing the size-frequency distribution of juvenile salmon caught during fall and winter using quantile-quantile plots (Post and Evans 1989). Mean size and the variance are expected to increase and decrease, respectively, over winter as a result of size-selective mortality against smaller fish. In addition, the slopes of the quantile-quantile plots are expected to be smaller than one when size-selective mortality against smaller fish occurs (Post and Evans 1989)

Energy depletion in juvenile Chinook salmon and coho salmon during the winter was tested by comparing the slope of the relationship between energy density and size for fish that were collected during fall and winter. As smaller fish were expected to utilize a larger fraction of their energy reserve over the winter period, the slope and intercept of the relationship between energy density and size were expected to be higher and lower, respectively, for fish collected during winter. Slopes of the relationship between energy density (ED ; $\text{kJ}\cdot\text{g}^{-1}_{\text{wet}}$) and weight (W ; g) were compared among seasons as follow:

$$(3) \quad ED = \gamma \cdot W + \beta \cdot D + \delta \cdot D \cdot W + \varepsilon$$

where γ , β , and δ are regression coefficients, D is a dummy variable that takes the value of zero for fish caught during fall and one for those caught during winter, and ε is a randomly distributed error. Positive values of δ indicate that energy is depleted faster in smaller fish, while negative values indicate that energy is depleted faster in larger fish.

3.3.5 Food consumption rates

Food consumption rates of juvenile Chinook and coho salmon were estimated using a mass balance model of stable cesium (^{133}Cs) following the procedures presented in Rowan and Rasmussen (1996) and Trudel et al. (2000). Briefly, food consumption rates (C , $\text{g}\cdot\text{g}^{-1}\cdot\text{d}^{-1}$) of fish can be estimated as:

$$(4) \quad C = \frac{[^{133}\text{Cs}]_t - [^{133}\text{Cs}]_0 \cdot e^{-(E+G)\cdot t}}{\alpha \cdot [^{133}\text{Cs}]_{\text{food}} \cdot [1 - e^{-(E+G)\cdot t}]} \cdot (E + G)$$

where $[^{133}\text{Cs}]_0$ is the initial ^{133}Cs concentration in fish ($\mu\text{g}\cdot\text{g}^{-1}$), $[^{133}\text{Cs}]_t$ is the ^{133}Cs concentration in fish ($\mu\text{g}\cdot\text{g}^{-1}$) at time t (d), $[^{133}\text{Cs}]_{\text{food}}$ is the ^{133}Cs concentration in their food, α is the assimilation of ^{133}Cs from food (dimensionless), E is the elimination rate of ^{133}Cs by fish ($\mu\text{g}\cdot\mu\text{g}^{-1}\cdot\text{d}^{-1}$), and G is their growth rates ($\text{g}\cdot\text{g}^{-1}\cdot\text{d}^{-1}$).

^{133}Cs concentration in salmon caught in the spring and fall and their food was determined by Inductively-Coupled Plasma Mass Spectroscopy (ICP-MS). Approximately 1 g of sample was weighed into a Teflon™ bomb and reacted with 5 mL of nitric acid. The samples were then heated for 2 hours on a hot plate. This solution was then made to a final volume of 25 mL with de-ionized water. All samples were analyzed on an Elan ICP-MS in conventional mode, at a dilution of x5. The liquid sample solution was converted into a fine aerosol by a nebulizer, and then carried by an Argon gas stream into the plasma region of the ICPMS where it was ionized prior to analysis in the mass spectrometer. Replicate analyses were performed on approximately 10% of the samples and were generally within 2% (range: 0-15%).

The parameters α and E were taken from Rowan and Rasmussen (1995, 1996), while G rate was estimated as (Ricker 1979):

$$(5) \quad G = \frac{\ln(W_t / W_o)}{t}$$

where W_o is the initial weight (g) and W_t is the weight (g) at time t (d). Ocean entry size and date were taken from Table 4, and converted to weight using a length-weight regression specific to Chinook salmon and coho salmon. W_t was set to the average weight of fish caught during fall (Trudel et al. 2002).

4. Results and Discussion

To understand the effects of ocean conditions on Columbia River salmon, it is first necessary to determine where these fish go in the ocean, and then to assess the ocean conditions they encountered during their marine life and their effects on salmon growth and survival. Thus, we first present data on the catch and distribution of juvenile salmon of the the British Columbia and Southeast Alaska Coast, and on the migration of juvenile Columbia River salmon. We then follow with a description of the ocean conditions that they encountered in these waters, and their biological response to these conditions. Finally, we present a framework to assess the potential impacts of ocean conditions on the returns of Columbia River salmon.

4.1. Juvenile Salmon Distribution

A total of 3,771 Pacific salmon were caught during the October-November 2007 survey, including 1,101 juvenile Chinook salmon, 229 juvenile coho salmon, and 46 juvenile sockeye salmon. Juvenile Chinook salmon were primarily caught in the inlets of the west coast of Vancouver Island, northern British Columbia, and in Sumner Strait (Southeast Alaska) (Fig. 2), whereas juvenile coho salmon were primarily caught on the continental shelf off the west coast of Vancouver Island, and in the inlets of the central coast of British Columbia and Southeast Alaska (Fig. 3). Juvenile sockeye salmon were primarily caught north of Vancouver Island at this time of the year. Except for the lack of juvenile coho salmon in Portland Inlet (northern British Columbia) during the fall of 2006, these results are generally consistent with those obtained in previous years (Fig. 2-4).

Survey design was altered in March 2008 to collect juvenile salmon and oceanographic data in the Strait of Georgia, a high priority region of the British Columbia coast for DFO. We caught a total of 271 salmon, including 177 juvenile Chinook salmon, 18 juvenile coho salmon, and 52 juvenile sockeye salmon during this survey. The fall and winter distribution of juvenile Chinook were fairly similar for the west coast of Vancouver Island (Fig. 2). Except for a single fish caught in Juan de Fuca Strait, no juvenile coho salmon were caught off the west coast of Vancouver Island in March 2008 (Fig. 3). Most of the juvenile sockeye (44 out of 52) were caught in a single tow off the west coast of Vancouver Island (Fig. 4). Except for coho salmon, these results are consistent with the February-March surveys conducted between 2001 and 2007 (Fig. 2-4). Low catches of juvenile sockeye salmon are expected at this time of the year, as most juvenile sockeye that migrated to sea the previous spring should be in the Gulf of Alaska in February-March (Groot and Margolis 1991). However, the extremely low catches of juvenile coho off the west coast of Vancouver Island were unexpected, suggesting either that overwinter mortality was substantial, or that these fish migrated out of the sampling area.

A total of 18,117 Pacific salmon were caught during the June-July 2008 survey, including 835 juvenile Chinook salmon, 607 juvenile coho salmon, and 7,100 juvenile sockeye salmon. Juvenile Chinook salmon, most of which likely originated from the Columbia River, were quite abundant off the west coast of Vancouver Island and in Hecate Strait (Fig. 2). In contrast to the previous year, very few juvenile Chinook salmon were caught off the west coast of the Queen Charlotte Island in June-July (Fig. 2). This indicates that Columbia River Chinook that undertake a northward migration have the option of migrating on either the east or west side of the Queen Charlotte Islands once they reach Queen Charlotte Sound at the north end of Vancouver Island, and that their migration behavior vary among years, possibly due to changing ocean conditions (Fig. 3-4). Juvenile coho and sockeye salmon were quite abundant throughout the survey area in June-July 2008, which is consistent with the results obtained in previous years (Fig. 2-4).

Interestingly, the catch-per-unit effort of juvenile Chinook, sockeye and chum salmon off the west coast of Vancouver Island were the highest on record since 1998, and was the third highest for juvenile coho salmon (Fig. 5). This suggests that early marine survival was consistently high for all the species of salmon in 2008. Thus, adult returns are expected to be high in 2009 for coho salmon, in 2010-2011 for Chinook and sockeye salmon, and in 2011 for

chum salmon. In contrast to 2008, catch-per-unit effort of juvenile salmon off the west coast of Vancouver Island were generally the lowest on record for most species in 2005 (Fig. 5), suggesting poor marine survival for the smolts that migrated to sea that year. This may explain the poor returns of several stocks of salmon in recent years.

Over 90%, 80%, 85% and 75% of the juvenile Columbia River Chinook salmon caught in June-July 2005, 2006, 2007 and 2008, respectively, were marked (adipose fin-clipped, CWT, or both) (Fig. 6). Considering that about 20-40% of the juvenile Chinook salmon released in the Columbia River Chinook are unmarked (www.rmpec.org), less than 15% of the juvenile Columbia River Chinook salmon that we caught during summer would be considered wild. In contrast, 20-60% of the juvenile coho salmon caught on the continental shelf were clipped or tagged with a CWT (or both) during these years (Fig. 6). Although proportion of wild Columbia River coho salmon in these samples is currently unknown, it is expected to be low (Teel et al. 2003; Van Doornik et al. 2007). The proportion of marked juvenile Chinook salmon dropped considerably during fall, and to a lesser extent in juvenile coho salmon (Fig. 6).

4.2. Migration of Columbia River and Snake River salmon

4.2.1. Chinook salmon and coho salmon

4.2.1.1 Coded-wire tags

Coded-wire tag (CWT) recoveries are useful to examine the migration behavior of juvenile salmon, as CWTs can usually provide unequivocal assessment of the origin of individual salmon. As not all the CWT Chinook and coho salmon bear a visible mark (i.e. adipose fin clipped) (Morris et al. 2005), DFO and the Northwest Fisheries Science Center systematically scan all the Chinooks and coho salmon caught in their surveys for CWT. Prior to our June/July 2008 survey, we recovered a total of 333 juvenile CWT Chinook and coho salmon off British Columbia and Southeast Alaska from FY05 to FY08. Of these, 148 originated from the Columbia River System. Most of the CWT Columbia River Chinook and coho were recovered off the west coast of Vancouver Island and during summer, and none were recovered during winter (Table 5). Spring and summer runs dominated the catches of juvenile Columbia River Chinook salmon (Table 6).

In June/July 2008, we recovered 210 juvenile CWT Chinook and coho salmon off British Columbia. Most of these fish (n=206) were caught off the west coast of Vancouver Island. Although these CWT's have not been processed in time for this report, we expect that nearly all of the CWT Chinook salmon to originate from the Columbia River, as 98% (88 out of 90) of the CWT Chinook salmon that we caught during summer in previous fiscal years were from the Columbia River. In contrast, approximately 55% for juvenile CWT coho salmon caught during the summer of FY08, or about 14 out of 25 fish, are expected to originate from the Columbia River. As the number of CWT released in the Columbia River has been decreasing during the last 2-3 years (Table 7), this substantial increase in CWT recovery strongly suggests that marine survival of Columbia River Chinook salmon improved drastically in FY08.

To date, our analyses of CWT recoveries revealed that Columbia River Chinook salmon exhibit a diversity of migration behavior (Trudel et al. 2009). As expected for "stream-type" Chinook salmon, Columbia River spring Chinook salmon generally undertake a rapid northward migration that quickly brings them well beyond the Columbia River Estuary and Plume to expose them to ocean conditions prevailing on the west coast of British Columbia, and subsequently to those in Alaska. However, like Columbia River coho salmon, the combined downriver and northward ocean migration speed of Columbia River spring Chinook salmon is highly variable, with both fast and slow migrants (Morris et al. 2007; Fisher et al. in prep.), and with the ocean migration speed varying among the different Columbia River stock groups (Fisher et al. in prep). Fall Chinook salmon also generally undertake a rapid downriver and northward migration, but very few are recovered north of Vancouver Island, and their ocean migration rates appear to be age related; the subyearling releases migrating considerably

slower than yearling releases (Fisher et al. in prep.). Although their ocean distribution extends over a broad geographic area of the continental shelf (1,600 km), Columbia River fall Chinook salmon remain in the Northern California Current System for an extended period of time well into their second year at sea, suggesting that they also establish residence on the shelf (Fisher and Pearcy 1995)

In addition to northern migrants, a fraction of the Columbia River spring and fall Chinook migrate south of the Columbia River as well. Fisher and Pearcy (1995) argued southern migrants had been advected south of the Columbia River by strong southward flows. In contrast, our analyses suggest that this southward migration is, at least in part, active. First, some juvenile Columbia River Chinook salmon are recovered more than 300 km south of the Columbia River, and in some cases, several months following ocean entry. Second, the release size of the juvenile Chinook salmon that are recovered south of the Columbia River is generally similar to those that are caught further north (M. Trudel, unpublished data), suggesting that the swimming capacity to overcome southward flows of the California Current is similar for both northern and southern migrants, though southern migrants are generally larger at capture. And finally, despite that most of the Columbia River Chinook salmon smolts enter the ocean in April-September when the southward flows of the California Current are strongest (Strub and James 2000; Huyer et al. 2005), the proportion of southern migrants varies among basins and life-history strategies within the Columbia River. The majority of the southern migrants are spring run fish from the Cowlitz River and fall run fish from the Snake River (Trudel et al. 2009; Fisher et al. in prep.). Interestingly, no Snake River spring Chinook salmon migrate south of the Columbia River, suggesting that migration behavior may differ among stocks within a large river system such as the Columbia River and Snake River (Fisher et al. in prep.).

The effects of climate and ocean conditions on highly migratory species like Pacific salmon are usually difficult to predict due to the diversity of environmental conditions that they encounter during their marine life. As the recruitment dynamics of Pacific salmon is expected to be set within the first year of their marine life (Pearcy 1992; Beamish and Mahnken 2001), the processes regulating Pacific salmon production should be examined at the spatial-scale where juvenile salmon occur. Our analyses indicate that the effects of ocean conditions on Chinook salmon are expected to be manifested at a local scale for coastal stocks (i.e. within 100-200 km of the natal river), compared to the scale of the Northern California Current (i.e. Oregon to the west coast of Vancouver Island) for Columbia River fall Chinook salmon. The appropriate spatial scale to consider for Columbia River spring Chinook salmon is presently difficult to determine, due to the diversity of migration behavior observed in these fish and ocean entry timing, with both fast and slow northward migrants, southern migrants, and late and early migrants (this study; Fisher et al. in prep.). As ocean conditions vary both among regions and months, different stocks of spring Chinook salmon originating from the Columbia River and Snake River system may be exposed to different ocean conditions and may thus respond differently to climate changes. A more specific description of the migration behavior of individual Columbia River and Snake River stocks is thus required to understand their responses to ocean conditions (Fisher et al. in prep.).

Few studies have attempted to assess the effects of climate and ocean conditions on Chinook salmon production (i.e. Beamish et al. 1995; Ruggerone and Goetz 2004; Scheuerell and Williams 2005; Wells et al. 2006, 2007, 2008). However, the results obtained in some of these studies are difficult to interpret, either because the authors relied on large scale climate indices, or because ocean and climate indices were not always measured in the areas where Chinook salmon occur or at a time when they migrated in these areas. For instance, Scheuerell and Williams (2005) used spring and fall upwelling indices measured at an offshore station (45°N and 125°W) to predict the marine survival of Snake River spring Chinook salmon. Yet, none of the juvenile Snake River spring Chinook salmon were observed south of the Columbia River (~46°12'N), and undertook a rapid northward migration, such that by October, none of

them appeared to be on the continental shelf. Similarly, Wells et al. (2008) correlated the marine growth of Puget Sound and Taku River Chinook salmon to ocean conditions measured on the continental shelf off the west coast of Vancouver Island and Southeast Alaska, respectively. While these conditions may be appropriate for these stocks during their second or third year of life at sea, they may not reflect the environmental conditions experienced by juvenile Puget Sound and Taku River Chinook salmon, as these stocks appear to migrate onto the shelf primarily during their second year at sea. Thus, the results obtained in these studies must be interpreted cautiously, at least with respect to the survival and growth of juvenile Chinook salmon.

4.2.1.2 DNA

To date, a total of 5,488 juvenile Chinook salmon have been analyzed for microsatellite DNA. Columbia River Chinook salmon represented nearly 100% of the juvenile Chinook caught in British Columbia and Alaska shelf waters during summer (Fig. 7), but comprised less than 5-10% of the samples caught during fall and end-of-winter. Spring Chinook from the Upper Columbia River and Snake River represented 21% and 50%, respectively, of the Columbia River Chinook caught in these regions during summer. This indicates that a component of the Columbia River and Snake River spring Chinook salmon undertakes a rapid northward migration that brings them well beyond the Columbia River Plume. These results are consistent with those obtained from CWT recoveries (Fig. 7).

In the fall and winter samples, juvenile Chinook salmon collected in southern British Columbia and Southeast Alaska originated mostly from the west coast of Vancouver Island and the Stikine River, respectively (Fig. 7). Stock composition of juvenile Chinook salmon in both regions remained fairly constant over the winter, suggesting that by fall, local stocks had established stable residence and dominated population structure. However, there was also some influx of Fraser River and Puget Sound stocks to the west coast of Vancouver Island over the winter months (Fig. 7). Approximately half of the Columbia River juvenile Chinook salmon caught off the west coast of Vancouver Island during fall (61%) and winter (52%) were classified as Upper Columbia River fall Chinook salmon, indicating that the majority of the Columbia River spring Chinook salmon had migrated further north to the Gulf of Alaska and were replaced by Columbia River fall Chinook salmon.

4.1.2. Sockeye salmon

Redfish Lake sockeye salmon has been added to the Endangered Species List in 1991 after reaching critically low levels and year-class failures (NRC 1996). Several factors likely contributed to the drastic decline of Redfish Lake sockeye salmon, including an extended period of poor marine survival. Yet, little is known on their ocean distribution and migration.

Redfish Lake sockeye salmon smolts have been marked with CWT since 2002, which made it, in principle, possible to track their ocean migration. Though, given their low abundance relative to other stocks, the likelihood of capturing a Redfish Lake sockeye salmon smolts was considered to be negligible. Yet, we recovered two juvenile Redfish Lake sockeye salmon off the coast of British Columbia in June 2008, and one on July 1, 2007 (Table 8; Fig. 8). These fish traveled approximately 1,450 km in the Snake River and Columbia River and another 350-1,050 km in the ocean in less than 60 days. Hence, the combined river and ocean migration speed, assuming that these fish were swimming in a straight line, ranged from 40 km/d to 49 km/d, or 3.5-3.7 body length per seconds (Table 8). This is about twofold faster than their theoretical optimal cruising speed at 10°C (Trudel and Welch 2005). This suggests that either these fish traveled quite rapidly through the river system, taking advantage of the high spring flows or that they were barged below the Bonneville Dam. The former is unlikely, as Snake River Chinook smolts migrate at about 20km/d through the hydropower system (Schaller et al. 2007). Alternatively, optimal cruising speed models may be inaccurate for sockeye salmon in

the marine environment, as the energetic costs associated with the basal metabolic rates and swimming of sockeye salmon is unknown in saltwater (Trudel and Welch 2005).

In addition to juvenile Redfish Lake sockeye salmon, we recovered five adipose-fin clipped juvenile sockeye in June 2008 and one in July 2007. Two of these had been tagged by DFO with an agency code only CWT. These two juvenile sockeye salmon likely originated from Cultus Lake, a stock that has been listed as Endangered by the Committee On the Status of Endangered Wildlife In Canada (http://www.cosewic.gc.ca/eng/sct5/index_e.cfm). The origin of the remaining three fish is currently unknown. The presence of endangered stocks in our catches combined with the highest catch-per-unit effort of juvenile sockeye salmon since 1998 strongly suggests that marine survival was high for the smolts that migrated to sea in 2008.

To further understand the migratory behavior of Columbia River sockeye smolts, we performed DNA analyses on a subset of the juvenile sockeye salmon we collected during our June-July surveys (partially funded by the Canadian Space Agency). Additional samples collected off the Washington coast in May-June 2007 were provided by D. Teel (Northwest Fisheries Science Center). Juvenile Columbia River sockeye salmon were primarily distributed off the Washington coast, the west coast of Vancouver Island, though a few fish caught in Dixon Entrance (54°30'N) (Fig. 8). These fish were swimming at roughly 30-40 km/d. These results suggest that, like spring Chinook salmon, Columbia River sockeye salmon smolts are also quickly undertaking a northward migration along the west coast of North America.

4.3. Ocean conditions

After peaking in 2005, coastal sea surface temperatures (SST) dropped by nearly 2°C in the fall of 2006, and remained 1-2°C cooler in 2007-2008 than in 2005 (Fig. 9). As expected, SSTs also decreased from south to north and were generally higher in open waters of the continental shelf than in the inlets and inside waters (Fig. 9). In contrast to SST, nutrient concentration generally increased in FY07 and FY08 (Fig. 10). In addition, nutrient concentration was higher at northern latitudes and in the inlets and inside waters (Fig. 10). Thus, there was a strong negative correlation between nitrate concentration and SST within the straits and inlets ($r^2=0.43$) as well as on the open shelf ($r^2=0.49$). This may result from the higher wind mixing that occurs during winter or due to tidal mixing, which increases the concentration of nutrients in surface waters while decreasing SST (Whitney et al. 2005). In addition, mixed-layer depth was shallower off the west coast of Vancouver Island than in Southeast Alaska, with shallower mixed-layer depth occurring in the inlets and inside waters than on the continental shelf (Fig. 11), possibly as a result of freshwater run-offs near shore.

Phytoplankton biomass reached the lowest values on record in the fall of 2006, both off the west coast of Vancouver Island and Southeast Alaska, and generally remained near or below average in winter and summer 2007 off the west coast of Vancouver Island (Fig. 12). In contrast, phytoplankton biomass was above average for Southeast Alaska in 2007 (Fig. 12). Overall, the summer biomass of phytoplankton increased steadily off the west coast of Vancouver Island from FY05 to FY08 (Fig. 12). As in FY07, zooplankton biomass was generally above average off the west coast of Vancouver Island in FY08 (Fig. 13). Interestingly, phytoplankton and zooplankton biomass were higher in FY08 than was expected from the observed nutrient concentration that year (Fig. 14). This suggests nutrients were more effectively by phytoplankton in FY08 (Fig. 14).

Overall, our analyses indicated that phytoplankton biomass and zooplankton biomass were generally higher off the west coast of Vancouver than in central British Columbia and Southeast Alaska (Fig. 12-13). Plankton biomass also generally increased during spring-summer, then decreased during fall and winter (Fig. 12-13), possibly due to a reduction in day length and SST. There was a positive correlation between zooplankton biomass and phytoplankton biomass (Fig. 14), indicating that the productivity of coastal ecosystems in the northeast Pacific Ocean are regulated by bottom up processes (Ware and Thomson 2005).

Phytoplankton and zooplankton biomass were positively correlated to SST (Fig. 14), but negatively correlated to nitrate concentration (Fig. 14). These results suggest that phytoplankton production and nutrient dynamics are regulated by changes in SST. As SST increases, the stability of the water column also increases (Gargett 1997). This enhances phytoplankton production as phytoplankton remains in the euphotic zone for longer periods of time. Phytoplankton may then deplete surface nutrients as the stability of the water column prevents the advection of nutrients from deeper waters (Whitney et al. 2005).

In addition to changes in plankton biomass, the zooplankton community composition varied in relation to ocean conditions (Mackas et al. 2007). In particular, the biomass of warm water California Current copepods were above average off the west coast of Vancouver from 2003 to 2006, while the biomass of cold water boreal shelf copepods near or below average during the same period (Fig. 15). This may result from a shift in ocean circulation, with stronger northward currents bringing southern species in the Northern California Current System during summer. The zooplankton community shifted to cold water boreal shelf copepods in FY07 and FY08 (Fig 15). As southern copepods typically have lower lipid contents than northern copepods (Båmsted 1986), the caloric contents of zooplankton is expected to be lower in 2003-2006 relative to 1999-2002, and 2007-2008.

Direct measurements of zooplankton caloric contents are generally difficult to obtain due to the large quantity of material required for these analyses. A simpler and relatively inexpensive alternative is to measure the carbon to nitrogen (C:N) ratio in zooplankton, as lipid concentrations and caloric contents are strongly positively correlated to C:N in aquatic organisms (Matthews and Mazumder 2005; Kiljunen et al. 2006; Sweeting et al. 2006; Post et al. 2007). Overall, the C:N ratio of zooplankton was higher off Southeast Alaska than off the west coast of Vancouver Island (Fig. 15), indicating that prey quality was higher off Southeast Alaska. The C:N ratio of zooplankton also varied among years and seasons: it was generally lower during summer than during fall off the west coast of Vancouver Island, whereas the opposite pattern was observed off Southeast Alaska (Fig. 16). Interestingly, the diversity of copepods also varied among years (Fig 17). In general, copepod diversity was high off the west coast of Vancouver Island when southern copepods were abundant, and low when boreal copepods were abundant. Similar results were obtained by Hoof and Peterson (2006) off the Oregon Coast. There was a strong negative relationship between the southern copepod anomaly and the C:N ratio in small zooplankton, and a strong positive relationship between the boreal copepod anomaly and the C:N ratio in small zooplankton (Fig. 18). Therefore, prey quality is expected to be lower in years with high southern copepod abundance, low boreal copepod abundance, and high copepod diversity.

4.4. Trophic ecology of juvenile Chinook and coho salmon

4.4.1. Diet

The diet of juvenile Chinook and coho salmon varied among regions, years, and seasons (Fig. 19-20), possibly due to changes in prey availability over time and among habitats (Brodeur et al. 2007a,b). Overall the diet of these species were fairly similar: fish was the dominant prey item (50-55%), followed by euphausiids (~20-25%), decapods (7-9%), and amphipods (~6-8%). Brittle stars and polychaetes were also important prey consumed by juvenile coho salmon off Southeast Alaska during the fall of 2001 and 2002, respectively (Fig. 19), whereas squid were important to juvenile Chinook salmon off Southeast Alaska during the fall of 2004 (Fig. 20). This is consistent with other studies that have showed that juvenile Chinook and coho salmon were primarily piscivorous (Brodeur et al. 2007a,b).

Juvenile Chinook salmon were more piscivorous off Southeast Alaska than off the west coast of Vancouver Island (65% vs 45%), possibly due to the larger size of juvenile Chinook salmon off Southeast Alaska (Table 9a). Juvenile coho salmon were more piscivorous off Southeast Alaska than off the west coast of Vancouver Island (64% vs 48%) during summer

(Fig. 19). This pattern was reversed during fall (Fig. 19). The importance of piscivory generally decreased over winter for coho salmon off the west coast of Vancouver Island as they primarily fed on euphausiids at this time of the year (Fig. 19). Note that no dietary information is available for juvenile coho salmon in northern British Columbia and Southeast Alaska during winter, as too few juvenile coho salmon have been caught in this region at this time of the year (Fig. 3). Euphausiids and fish were the primary prey of juvenile Chinook salmon during winter (Fig. 20).

4.4.2. Stable isotopes

Stable isotopes of carbon and nitrogen have frequently been used to infer the feeding relationships of aquatic organism in marine and freshwater ecosystems (Vander Zanden and Rasmussen 1999; Post 2002a,b). Carbon isotopes generally reflects food source, whereas nitrogen isotopes are indicators of trophic positions, and hence, indicators of piscivory in juvenile salmon. One of the first steps to assess the trophic position of juvenile salmon in coastal waters using this approach is to determine the isotopic composition at the base of the food chain, such as in zooplankton (Vander Zanden and Rasmussen 1999; Post 2002a,b). Stable isotopes of carbon and nitrogen varied among years, regions, and size-classes (Fig. 21-22). Overall, zooplankton was more enriched in ^{13}C off the west coast of Vancouver Island than in northern British Columbia and Southeast Alaska, especially during fall (Fig. 21). Zooplankton were more enriched in ^{15}N off the west coast of Vancouver Island than in northern British Columbia and Southeast Alaska during summer, whereas the pattern was reversed during fall (Fig. 22). These results indicate the importance of considering the spatial and temporal variability in carbon and nitrogen isotopes to properly quantify the trophic position of juvenile salmon using stable isotopes.

$\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ were measured in 1035 juvenile Chinook salmon and 690 juvenile coho salmon caught off the west coast of Vancouver Island and Southeast Alaska in 1998-2007. Additional samples from 2008 are currently being processed for stable isotope analyses. The $\delta^{13}\text{C}$ of juvenile Chinook and coho salmon was lower (i.e. more negative) at northern latitudes (Fig. 23). Two hypotheses may explain this result. First, the variability in $\delta^{13}\text{C}$ of salmon may be due to differences in phytoplankton biomass. Veefkind (2003) showed that $\delta^{13}\text{C}$ of primary producers increased with phytoplankton biomass. As phytoplankton biomass was higher off the west coast of Vancouver Island compared to Southeast Alaska (Fig. 12), $\delta^{13}\text{C}$ was expected to be higher off the west coast of Vancouver Island. Second, the variability in $\delta^{13}\text{C}$ of salmon may be due to differences in lipid concentration (or C:N ratio) at the base of the food chain. Lipids are generally depleted in $\delta^{13}\text{C}$ relative to proteins and carbohydrates (Matthews and Mazumder 2005; Kiljunen et al. 2006; Sweeting et al. 2006; Post et al. 2007). Hence, $\delta^{13}\text{C}$ in zooplankton should decrease as lipid concentration increase. In this study, the C:N ratio in zooplankton was lower off the west coast of Vancouver Island and increased with increasing latitude, suggesting that the lower $\delta^{13}\text{C}$ observed in zooplankton and salmon in Southeast Alaska may also be due to higher lipid concentration at the base of the food chain. Overall, the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ of juvenile Chinook and coho salmon indicate that juvenile Chinook salmon were more piscivorous than coho salmon in Southeast Alaska, whereas the opposite pattern was observed off the west coast of Vancouver Island (Fig. 24). The analysis of stomach contents supports this interpretation (Fig. 19-20).

4.5. Growth and food consumption rates

In general, juvenile Chinook salmon caught off the west coast of Vancouver Island in June-July measured 150-200 mm, compared to 190-230 mm for juvenile coho salmon (Table 10; Fig. 25). Overall, marked fish were about 10 mm larger than unmarked fish (Table 10; Fig. 25). No trends in size were apparent over time. Juvenile Chinook and coho salmon were generally larger and had higher energy densities in Southeast Alaska than off the west coast of

Vancouver Island (Table 9, 11; Fig. 26-29). Fall size decreased by 10-20 mm between 2006 and 2007 for all species and regions, except for Southeast Alaska Chinook salmon which reached similar sizes in both years (Fig 26-27). Similarly, fall energy density was also generally lower in 2007 than in 2006 (Table 11; Fig. 28-29). This suggests that juvenile Chinook and coho salmon were in poorer conditions in 2007 than in 2006.

Growth rates of juvenile Chinook salmon ranged from 0.5 to 1.3 mm/d, and were higher off Southeast Alaska than off the west coast of Vancouver Island (Fig. 30). Growth rates of juvenile coho salmon ranged from 0.8 to 1.6 mm/d, and grew faster off Southeast Alaska than off the west coast of Vancouver Island (Fig. 30). Except for the two warmest years (1998 and 2005), growth rates of juvenile Chinook salmon were strongly correlated to the growth rates of juvenile coho salmon (Fig. 31), suggesting that similar processes are regulating the growth of these species in both regions. This was expected, as both species typically feed on similar prey (Fig. 19-20). Like growth rates, energy contents were higher off Southeast Alaska in both species during fall (Table 11), suggesting that, despite higher plankton biomass off the west coast of Vancouver Island (Fig. 13), feeding conditions were overall more favorable in Southeast Alaska than off the west coast of Vancouver Island. This may be due to the higher lipid contents in zooplankton at northern latitudes (Fig. 16).

Growth rates were near the long-term average for juvenile coho salmon in FY08, and above average for juvenile Chinook salmon in Southeast Alaska (Fig. 30). In contrast, growth rates appeared to be on a downward trend in juvenile Chinook salmon off the west coast of Vancouver Island (Fig 30). This may simply reflect a bias in sampling effort rather than a real trend, as sampling effort has increased considerably in the inlets of the west coast of Vancouver Island, and in Quatsino Sound in particular, from 2001 to 2008. These sheltered waters are important nursery areas for small juvenile Chinook salmon during fall (M. Trudel, personal observations).

Food consumption rates of juvenile Chinook salmon were generally higher than those of coho salmon, ranging from 8.6 to 14.4% body weight per day, and averaging around 11% body weight per day (Fig. 32). Juvenile Chinook salmon appeared to consume more food off the west coast of Vancouver Island than off Southeast Alaska (Fig. 32). Food consumption rates of juvenile coho salmon ranged from 6.6 to 11.5 % body weight per day, and averaged around 9% body weight per day (Fig. 32). The highest values for juvenile coho salmon were observed during the 1999 La Niña, while the lowest value was observed during 2005 (Fig. 32). Food consumption rates were near the long-term average for juvenile coho salmon caught off the west coast of Vancouver Island in FY08, but near the historical high for Southeast Alaska (Fig. 32). No regional differences in the feeding rates of juvenile coho salmon were apparent (Fig. 32). Food consumption rates of juvenile Chinook salmon were positively correlated to those of juvenile coho salmon ($r^2=0.34$). This suggests that annual and regional variation in prey availability have similar effects on both species, possibly because they are feeding on similar prey (see section 4.4).

Growth rates were positively correlated to food consumption rates in juvenile Chinook and coho salmon (Fig. 33). Interestingly, the relationship between growth rates and consumption rates varied between regions in both species (Fig. 33). Overall, juvenile coho and Chinook salmon grew faster in Southeast Alaska than off the west coast of Vancouver Island for any given feeding rate (Fig. 33). Thus, additional factors are required to explain the annual and regional variation in juvenile coho and Chinook salmon growth rates between 1998 and 2006, such as a direct effect of temperature on energy expenditures (i.e. metabolic rates) of salmon or changes in prey quality with ocean conditions. The increase in zooplankton C:N with latitude suggests that juvenile coho and Chinook salmon may grow faster in Southeast Alaska than off the west coast of Vancouver Island because they are feeding on higher prey quality. Furthermore, interannual variation in the growth of juvenile coho salmon were strongly

correlated to indices of prey quality (Fig. 34), indicating that changes in growth are mediated by changes in zooplankton composition, which are likely driven by changes in ocean circulation.

Bioenergetics model simulations indicate that coho salmon would reach a size of approximately 200g and 400g while feeding on prey of low and high quality, respectively (Trudel et al. 2002). This corresponds quite well to the mean size of coho salmon collected off the west coast of Vancouver Island and southeast Alaska in 1998. In contrast, increasing SST by 3°C decreased the final weight by only 10 g, suggesting that the direct effects of SST on salmon growth are negligible. Instead, our analyses indicate that the effects of SST on salmon growth are mediated by changes in prey community structure and quality rather than by changes in food consumption and metabolic rates. These results also illustrate the importance of measuring bioenergetics parameters *in situ* for better understanding the effects of climate change on fish populations.

4.6. Overwinter mortality

Juvenile Chinook and coho salmon were generally larger in February-March than in October-November (Table 9; Fig. 35-36). On average, the size of juvenile Chinook and coho salmon increased by 10-100 mm over the winter, and generally increased faster for juvenile salmon that had reached smaller size in October-November for both species (Fig. 35). The variance of winter size was generally higher than the variance of fall size for juvenile Chinook salmon and coho salmon collected off the west coast of Vancouver Island, while the opposite pattern was generally observed for juvenile Chinook salmon caught in Southeast Alaska (Fig. 37). The slope of the quantile-quantile plot was generally steeper than a value of one in juvenile Chinook and coho salmon caught off the west coast of Vancouver Island, but less than one in juvenile Chinook salmon caught in Southeast Alaska (Fig. 38). This indicates that size-selective mortality was more apparent for juvenile salmon in Southeast Alaska. It also suggests that size-selective mortality is more influential of salmon population dynamics at northern latitudes than at southern latitudes, possibly due to cooler temperatures or to lower food availability in the north (Fig. 9, 13).

Perhaps one exception to the rule was juvenile coho salmon caught off the west coast of Vancouver Island during November 2005 (Fig. 35-37). These fish were the smallest on record in the fall since 1998 (Table 9b), and appeared to exhibit size-selective mortality. The low catches of juvenile coho salmon during the fall of 2005 off the west coast of Vancouver Island and off the Washington and Oregon Coasts (Peterson et al. 2006), suggest that ocean conditions were not favorable to juvenile coho salmon in these regions, and thus these coho populations may have experienced a high rate of mortality during their early life and first winter at sea.

As sampling was only carried around Vancouver Island in February-March 2008, we could not assess the significance of size-dependent overwinter mortality of juvenile Chinook salmon in Southeast Alaska in FY08. In addition, only one juvenile coho salmon was recovered off the west coast of Vancouver Island in February-March 2008. Hence, overwinter mortality could not be assessed in juvenile coho salmon in FY08. For FY08, juvenile Chinook salmon gained 80 mm off the west coast of Vancouver Island over winter (Table 9a). The variance of fall and winter size were similar for these fish. However, the slope of the quantile-quantile plot was below one for these fish suggesting that overwinter mortality was larger for smaller juvenile Chinook off the west coast of Vancouver Island between October-November 2007 and February-March 2008.

Energy density ranged from 3.1 to 8.4 kJ·g⁻¹ and increased with size in juvenile Chinook and coho salmon during fall, but only increased with size in juvenile Chinook salmon during winter. A large fraction (<14%) of the energy densities were below the threshold of 4 kJ·g⁻¹ that was suggested as the limit at which mortality would be induced in salmonids (Simpkins et al. 2003; Crossin et al. 2004). Thus, most of the fish that were captured in this study were well

above this threshold, indicating that they had sufficient energy reserves to sustain their physiological functions. Overall, 43% of the juvenile Chinook salmon caught in October-November 2007 were below this threshold, suggesting that these fish were in poor condition. The slope of the relationship between energy density and weight was generally steeper during fall than during winter in juvenile Chinook and coho salmon collected off the west coast of Vancouver Island and Southeast Alaska (Fig. 39). Thus, contrary to our expectations, energy depletion was higher in larger rather than in small salmon.

Taken together, these observations are inconsistent with the hypothesis that overwinter mortality is higher in juvenile salmon due to higher energy depletion in smaller fish. Our results suggest instead that, overall, larger fish are growing faster than smaller fish, and that they are using a larger proportion of their energy reserves for growth during winter. Alternatively, weight-specific metabolic rates may be higher in larger fish under field conditions (Trudel and Rasmussen 2006). This is contrary to laboratory experiments that generally indicate that weight-specific metabolic rates are higher in smaller fish (Bokma 2004; Trudel and Welch 2005). However, it is important to note that these relationships are derived for standard metabolic rates, which represent the minimum amount of oxygen that the fish must consume under resting conditions, and ignore the costs of swimming and foraging. These costs may represent a significant portion of the energy budget of fish, and have been shown to be higher in larger fish (Boisclair and Rasmussen 1996; Rowan and Rasmussen 1996; Trudel and Rasmussen 2001; Pazzia et al. 2002). Thus, we hypothesize that the weight-specific metabolic rates of fish increase with body size under field conditions.

The analyses performed in this section assume that we sampled a closed population, meaning that there was no immigration or emigration within the areas that were surveyed. Although stock composition was reasonably stable over winter (Fig. 7), there was an influx of juvenile Chinook salmon from the Strait of Georgia and Puget Sound to the west coast of Vancouver Island (Fig. 7). Thus, the assumption that stock composition was stable over time was not fully supported. Further tests of the importance of overwinter mortality in regulating the dynamics of salmon populations need to be conducted on specific stocks of salmon, rather than on a mixture of stocks like we did in this study.

5. Management Implications

5.1. Forecasting salmon returns to the Columbia River

The analyses we have performed to date suggest that the west coast of Vancouver Island may act as a bottleneck for the survival of juvenile Columbia River salmon that undertake an extensive northward migration, due to the relatively poor growth conditions that prevail in this region. Hence, we may be able to understand and predict changes in the marine survival and adult returns to Columbia River salmon from the ocean conditions measured in the regions surveyed by the *Canada-USA Salmon Survival Shelf Study*. This may in turn help to assess the success of mitigation measures such as habitat restoration and flow regulation on the health of Columbia River salmon runs.

The working hypothesis of this research is that the marine survival of salmon is mediated by changes in the growth rate of juvenile salmon. Our analyses indicate that the marine survival of west coast of Vancouver Island and OPI coho is strongly correlated to the growth conditions off the west coast of Vancouver Island (Fig. 40). As juvenile coho salmon growth is affected by prey quality, the marine survival of coho salmon was also linked to indices of prey quality such as the abundance of large lipid rich copepods (i.e. boreal copepods) and the lipid contents of zooplankton (Fig. 34, 40). Similarly, adult return and the marine survival of Columbia River¹ summer and fall Chinook salmon were also strongly affected by the growth conditions and prey quality that prevailed off the west coast of Vancouver Island (Fig. 41-42). These relationships may serve as leading indicators of adult salmon returns to the Columbia River 1-2 years before they migrate back to the river to spawn. For instance, the growth conditions and prey quality indices observed in the summer of FY07 and FY08 suggest that the return of adult summer and fall Chinook salmon to the Bonneville Dam will be averaged to better than average² in 2009 and 2010 (Fig. 41-42). Although fishery managers should be cautious before they start using these relationship to manage Columbia River salmon due to the low number of data points presently available, these results indicate that the *research conducted on the ocean environment in British Columbia has the potential to influence harvest strategies and conservation measures for Columbia River salmon*. However, the development of these predictive models will require a long-term funding commitment (ISRP 2005-14), as the stability and reliability of these models needs to be assessed over a longer time frame by comparing observed and predicted values.

5.2. Assessing the effects of the hydropower system on Columbia River salmon

Perhaps the most contentious issue in the Columbia River Basin relates to the potential effects of hydropower systems on salmon production (Schaller et al. 2007). Confounding effects of ocean conditions and hydropower system operation may lead to unnecessary and costly mitigation actions for BPA.

In an attempt to assess the impacts of dams on the survival of Columbia River salmon, Schaller et al. (1999) compared the survival of Lower Columbia River (LOCR) spring Chinook salmon with the survival of Upper Columbia River (UPCR) and Snake River spring Chinook salmon. Their analyses suggested that LOCR spring Chinook salmon had higher survival than either UPCR or Snake River spring Chinook salmon. They attributed the lower survival of UPCR and Snake River spring Chinook salmon to the higher number of dams that they have to migrate through as smolts (7-9 dams) relative to LOCR spring Chinook salmon (1-3 dams). By focusing their analyses on a single life-history type, the authors assumed that the only difference between the upper and lower stocks was the number of dams that smolts encounter

¹ Adult return data were obtained from the Fish Passage Center (www.fpc.org). This analysis assumes that adult returns are good indicators of the marine survival of smolts. As most (>85%) of the Columbia River Chinook salmon we caught were of hatchery origin and smolt releases from hatcheries have been relatively constant in the Columbia River during the last decade (www.rmhc.org), adult returns may be a good surrogate for marine survival in the Columbia River.

²Relative to the 2000-2008 return years.

during their downstream migration. It was further assumed that ocean conditions would have similar effects on these stocks.

In contrast to these assumptions, our research indicates that different stocks of Columbia River and Snake River Chinook and coho salmon migrate to different regions of the oceans, and hence, may not be exposed to the same ocean conditions. Furthermore, an examination of the CWT juvenile Chinook salmon caught by the *Canada-USA Salmon Shelf Survival Study* and by NOAA Fisheries indicates that LOCR spring Chinook salmon exhibit a very different migration behavior than UPCR and Snake River spring Chinook salmon. In particular, LOCR spring Chinook salmon smolts migrate to sea 8-10 weeks earlier than upper stocks, possibly due to the shorter distance that they have to travel in the river system. In addition, the proportion of southward migrants also varies among regions, with respectively 24%, 5% and 0% of the LOCR, UPCR, and Snake River spring Chinook salmon migrating south of the Columbia River. The migration speed along the coast also differs among stocks, with LOCR comprising both fast and slow migrants, while UPCR and Snake River spring Chinook salmon tend to migrate at intermediate speeds. Hence, the disparity in survival observed by Schaller et al. (1999) between lower and upper stocks of spring Chinook salmon could also be explained by differences in migration behavior. *These results indicate the importance of selecting an appropriate experimental design and the need to include ocean effects in order to accurately assess the effects of dams on Columbia River salmon.*

6. Conclusions and perspective for future research and monitoring

The favorable ocean conditions that drastically improved the return of Chinook, coho, and steelhead to the Columbia River from historical low to historical high levels appear to have returned in 2007 and 2008. However, it is unclear how long these favorable ocean conditions will persist, as ocean temperature continue to rise globally (NOAA 2009). This suggests that the poor ocean conditions that prevailed in the 1980s and 1990s may recur and impact future returns of Columbia River salmon. Hence, there is an immediate need to continue documenting and analyzing current ocean conditions to better understand and predict the fate of Columbia River salmon.

Our research shows that different populations of Columbia River salmon move to different locations along the coastal zone where they establish their ocean feeding grounds and overwinter. We further show that ocean conditions experienced by juvenile Columbia River salmon vary among regions of the coast, with higher plankton productivity and temperatures off the west coast of Vancouver Island than in Southeast Alaska. Hence, different stocks of juvenile salmon originating from the Columbia River and Snake River will be exposed to different ocean conditions and respond differently to climate changes. In particular, our work shows that the growth and fat content of Chinook and coho salmon vary along different parts of the coast. These growth differences appear to be associated with differences in prey quality rather than by a direct effect of temperature on salmon growth, indicating that changes in ocean conditions and circulation affect salmon production indirectly through changes in prey community composition and quality. Taken together, our analyses indicate that the relative survival of different stocks of salmon in the ocean will depend on where they migrate in the ocean.

Future analyses will include (1) a more detailed analysis of the variability in ocean conditions, (2) estimation of the interannual variability in the trophic position of juvenile Chinook and coho salmon, (3) examination of the interannual variability in Columbia River salmon migration, (4) investigation of the relationships between salmon growth, energy accumulation and utilization with ocean conditions, and (5) further assessments of the impact of changes in ocean conditions on the marine survival of Columbia River Chinook and coho salmon. In particular, we will assess how plankton biomass, community composition, and diversity vary among years and regions, and in relation to changes in temperature and nutrients.

The short time-series (1998-2008) of ocean conditions, salmon growth and energetics, trophic position, and stock composition will provide a better understanding of the effects of ocean conditions on salmon survival. In addition, the monitoring component of the project may also be used to develop forecasting models for adult Columbia River salmon. For instance, we showed that the marine survival of OPI coho salmon and the return of adult summer and fall Chinook salmon return to the Columbia River were positively correlated to the growth conditions off the west coast of Vancouver Island. However, 10-20 years of continuous observations will be required to demonstrate the predictive capabilities of the relationships derived from the Salmon Shelf Survival Study. In particular, the stability of these relationships needs to be assessed across regimes (Beamish et al. 2004b). Given that regimes last 10-20 years (Beamish et al. 1999; Hare et al. 1999), and that the last regime shift is believed to have occurred around 1998 (PICES 2004), it will be necessary to continue the time series of the Salmon Shelf Survival Study surveys for at least another five years to cover more than one regime.

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8. References

- Båmstedt, U. 1986. Chemical composition and energy content, pp. 1-58. In: The biological chemistry of marine copepods. Corner EDS, O'Hara SCM (eds), Clarendon Press, Oxford.
- Baxter, B. E. 2003. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 2002. Can. Man. Rep. Fish. Aquat. Sci. 2646.
- Baxter, B.E., C.Y. Stephens, and B.L. Nass. 2001. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 1998. Can. Man. Rep. Fish. Aquat. Sci. 2566.
- Baxter, B.E., and C.Y Stephens. 2002a. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 1999. Can. Man. Rep. Fish. Aquat. Sci. 2597.
- Baxter, B.E., and C.Y Stephens. 2002b. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 2000. Can. Man. Rep. Fish. Aquat. Sci. 2598.
- Baxter, B.E., and C.Y Stephens. 2002c. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 2001. Can. Man. Rep. Fish. Aquat. Sci. 2601.
- Baxter, B.E., and C.Y Stephens. 2004. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 2003. Can. Man. Rep. Fish. Aquat. Sci. 2703.
- Baxter, B.E., and C.Y Stephens. 2005. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 2004. Can. Man. Rep. Fish. Aquat. Sci. 2730.
- Beacham, T.D. 1990. The Marine Survival of Salmon Program: program outline and investigators summaries for 1990/91. Fisheries and Oceans Canada Document, Pacific Biological Station, Nanaimo, British Columbia, Canada, 63 p.
- Beacham, T.D., B. McIntosh, and C. MacConnachie. 2002. Microsatellite identification of individual sockeye salmon in Barkley Sound, British Columbia. J. Fish Biol. 61: 1021-1032.
- Beacham, T.D., J.R. Candy, B. McIntosh, C. MacConnachie, A. Tabata, K. Kaukinen, L. Deng, K.M. Miller, R.E. Withler, and N. Varnavskaya. 2005. Estimation of stock composition and individual identification of sockeye salmon across the Pacific Rim using microsatellite and major histocompatibility complex variation. Trans. Am. Fish. Soc. 134: 1124-1146.
- Beacham, T.D., J.R. Candy, K.J. Supernault, M. Wetklo, B. Deagle, K. Labaree, J.R. Irvine, K.M. Miller, R.J. Nelson, and R.W. Withler. 2003a. Evaluation and application of microsatellites for population identification of Fraser River chinook salmon (*Oncorhynchus tshawytscha*). Fish. Bull. 101: 243-259.
- Beacham, T.D., J.R. Candy, K.J. Supernault, T. Ming, B. Deagle, A. Schultz, D. Tuck, K. Kaukinen, J.R. Irvine, K.M. Miller and R. E. Withler. 2001. Evaluation and application of microsatellite and major histocompatibility complex variation for stock identification of coho salmon in British Columbia. Trans. Am. Fish. Soc. 130: 1116-1155.
- Beacham, T.D., J.R. Candy, K.L. Jonsen, K.J. Supernault, M. Wetklo, L. Dend, K.M. Miller, R.E. Withler, and N. Varnavskaya. 2006. Estimation of stock composition and individual identification of Chinook salmon across the Pacific Rim by use of microsatellite variation. Trans. Am. Fish. Soc. 135: 861-888.
- Beacham, T.D., K.J. Supernault, M. Wetklo, B. Deagle, K. Labaree, J.R. Irvine, J.R. Candy, K.M. Miller, R.J. Nelson, and R.W. Withler. 2003b. The geographic basis for population structure in Fraser River chinook salmon (*Oncorhynchus tshawytscha*). Fish. Bull. 101: 229-242.
- Beacham, T.D., M. Lapointe, J.R. Candy, K.M. Miller, and R.E. Withler. 2004a. DNA in action: rapid application of DNA variation to sockeye salmon fisheries management. Cons. Gen. 5: 411-416.

- Beacham, T.D., M. Lapointe, J.R. Candy, B. McIntosh, C. MacConnachie, A. Tabata, K. Kaukinen, L. Deng, K.M. Miller, and R.E. Withler. 2004b. Stock identification of Fraser River sockeye salmon using microsatellites and major histocompatibility complex variation. *Trans. Am. Fish. Soc.* 133: 1117-1137.
- Beamish, R.J., and C. Mahnken. 2001. A critical size and period hypothesis to explain natural regulation of salmon abundance and the linkage to climate and climate change. *Prog. Oceanogr.* 49: 423-437.
- Beamish, R.J., C. Mahnken, and C.M. Neville. 2004a. Evidence that reduced early marine growth is associated with lower marine survival of coho salmon. *Trans. Am. Fish. Soc.* 133: 26-33.
- Beamish, R.J., D.J. Noakes, G.A. McFarlane, L. Klyashtorin, V.V. Ivanov and V. Kurashov. 1999. The regime concept and natural trends in the production of Pacific salmon. *Can. J. Fish. Aquat. Sci.* 56: 516-526.
- Beamish, R.J., D.J. Noakes, G.A. McFarlane, W. Pinnix, R. Sweeting, and J. King. 2000. Trends in coho marine survival in relation to the regime concept. *Fish. Oceanogr.* 9: 114-119.
- Beamish, R.J., J.T. Schnute, A.J. Cass, C.M. Neville, and R.M. Sweeting. 2004b. The influence of climate on the stock and recruitment of pink and sockeye salmon from the Fraser River, British Columbia, Canada. *Trans. Am. Fish. Soc.* 133: 1396-1412.
- Beers, D.E. 2003. Production of coho salmon from Slippery Creek, 2000-2001. Alaska Department of Fish and Game, Fishery Data Series No. 03-08.
- Boisclair, D., and J.B. Rasmussen. 1996. Empirical analysis of environmental variables on perch growth, consumption and activity rates. *Ann. Zool. Fenn.* 33: 507-515.
- Bokma, F. 2004. Evidence against universal allometry of metabolic rate. *Funct. Ecol.* 18: 184-187.
- Bottom, D.L., B.E. Riddell, and J.A. Lichatowich. 2006. The estuary, plume, and marine environments, pp. 507-569. In: *Return to the River: Restoring salmon to the Columbia River*. Williams, R.N. (ed), Elsevier Academic Press, Amsterdam.
- Boyd, P.W., and 37 co-authors. 2004. The decline and fate of an iron-induced subarctic phytoplankton bloom. *Nature* 428: 549-553.
- Bradford, M.J., G.C. Taylor, and J.A. Allan. 1997. Empirical review of coho salmon smolt abundance and the prediction of smolt production at the regional level. *Trans. Am. Fish. Soc.* 126: 49-64.
- Bradford, M.J., J.A. Grout, and S. Moodie. 2001. Ecology of juvenile chinook salmon in a small non-natal stream of the Yukon River drainage and the role of ice conditions on their distribution and survival. *Can. J. Zool.* 79: 2043-2054.
- Brannon, E.L., M.S. Powell, T.P. Quinn, and A. Talbot. 2004. Population structure of Columbia River Basin Chinook salmon and steelhead trout. *Rev. Fish. Sci.* 12: 99-232.
- Brodeur, R.D., G.W. Boehlert, E. Casillas, M.B. Eldridge, J.H. Helle, W.T. Peterson, W.R. Heard, S.T. Lindley, and M.H. Schiewe. 2000. A coordinated research plan for estuarine and ocean research on Pacific salmon. *Fisheries* 25: 7-16.
- Brodeur, R.D., E.A. Daly, M.V. Sturdevant, T.W. Miller, J.H. Moss, M. Thiess, M. Trudel, L.A. Weitkamp, J. Armstrong, and E.C. Norton. 2007a. Regional comparisons of juvenile salmon feeding in coastal marine waters off the west coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 183-203.
- Brodeur, R.D., E.A. Daly, R.A. Schabetsberger, and K.L. Mier. 2007b. Interannual and interdecadal variability in juvenile coho salmon (*Oncorhynchus kisutch*) diets in relation to environmental changes in the northern California Current. *Fish. Oceanogr.* 16: 395-408.
- Brown, R.F., M.S. Elson, and L.W. Steigenberger. 1976. Catalogue of aquatic resources of the Upper Yukon River drainage (Whitehorse area). Fisheries Marine Service Technical Report PACT/T-76-4. 149 pp.

- Carlson, H.R., E.V. Farley, Jr., and K.W. Myers. 2000. The use of thermal otolith marks to determine stock-specific ocean distribution and migration patterns of Alaskan pink and chum salmon in the North Pacific Ocean 1996–1999. North Pacific Anadromous Fish Commission Bulletin 2: 291–300.
- Chavez, F.P., J. Ryan, S.E. Lluch-Cota, and C.M. Niquen. 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science* 299: 217–221.
- Cooke, K., and C. Groot. 1990. Data record of juvenile sockeye salmon and other fish species captured by purse seine in Alberni Inlet and Barkley Sound in April, May, and June, 1987 and 1988. Can. Dat. Rep. Fish. Aquat. Sci. No. 813.
- Costello, D.J., D.B. Molyneaux, and C. Goods. 2006. Takotna River salmon studies, 2005. Alaska Department of Fish and Game, Fishery Data Series No. 06-06.
- Crossin, G.T., S.G. Hinch, A.P. Farrell, D.A. Higgs, and M.C. Healey. 2004. Somatic energy of sockeye salmon *Oncorhynchus nerka* at the onset of upriver migration: a comparison among ocean climate regimes. *Fish. Oceanogr.* 13: 345–349.
- Dawley, E.M., R.D. Ledgerwood, and A.L. Jensen. 1985. Beach and purse seine sampling of juvenile salmonids in the Columbia River estuary and ocean plume, 1977–1983. Vol. I–II. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-74.
- DFO, 2006. 2005 Pacific Region State of the Ocean. DFO Science Ocean Status Report 2006.
- Drucker, B. 1972. Some life history characteristics of coho salmon of the Karluk River system, Kodiak Island, Alaska. *Fish. Bull.* 70: 79–94.
- Ericksen, R.P. 2001. Smolt production and harvest of coho salmon from the Chilkat River, 1999–2000. Alaska Department of Fish and Game, Fishery Data Series No. 01-17.
- Ericksen, R.P. 2002. Smolt production and harvest of coho salmon from the Chilkat River, 2000–2001. Alaska Department of Fish and Game, Fishery Data Series No. 02-18.
- Ericksen, R.P. 2003. Production of coho salmon from the Chilkat River, 2001–2002. Alaska Department of Fish and Game, Fishery Data Series No. 03-28.
- Farley, E. V., Jr., J. Murphy, A. Middleton, L. Eisner, J. Moss, J. Pohl, O. Ivanov, N. Kuznetsova, M. Trudel, M. Drew, C. Lagoudakis, and G. Yaska. 2004. Eastern Bering Sea (BASIS) coastal research (August - October 2003) on juvenile salmon. (NPAFC Document 816) Auke Bay Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, 11305 Glacier Highway, Juneau, AK 99801-8626. 29 p.
- Fisher, J.P., and W.G. Pearcy. 1995. Distribution, migration, and growth of juvenile chinook salmon, *Oncorhynchus tshawytscha*, off Oregon and Washington. *Fish. Bull.* 93: 274–289.
- Fisher, J.P., and W.G. Pearcy. 2005. Seasonal changes in growth of coho salmon (*Oncorhynchus kisutch*) off Oregon and Washington and concurrent changes in the spacing of scale circuli. *Fish. Bull.* 103: 34–51.
- Fisher, J., M., Trudel, A. Ammann, J. Orsi, J. Piccolo, C. Bucher, J. Harding, E. Casillas, B. MacFarlane, R. Brodeur, J. Morris, and D. Welch. 2007. Regional comparisons of distribution and abundance of juvenile salmon along the West Coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 31–80.
- Fleming, D.F. 2005. Production of coho salmon from Slippery Creek, 2001–2002. Alaska Department of Fish and Game, Fishery Data Series No. 05-08.
- Freeman, G. 2003. Smolt production and adult harvest of coho salmon from the Naha River, 1998–2000. Alaska Department of Fish and Game, Fishery Data Series No. 03-07.
- Fresh, K.L., E. Casillas, L.L. Johnson, and D.L. Bottom. 2005. Role of the estuary in the recovery of Columbia River Basin salmon and steelhead: an evaluation of the effects of selected factors on salmonid population viability. NOAA Technical Memorandum NMFS-NWFSC-69.
- Gargett, A.E. 1997. The optimal stability ‘window’: a mechanism underlying decadal fluctuations in North Pacific salmon stocks? *Fish. Oceanogr.* 6: 109–117.

- Hare, S.R., and N.J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Prog. Oceanogr.* 47: 103-145.
- Hare, S.R., N.J. Mantua and R.C. Francis. 1999. Inverse production regimes: Alaska and West Coast Pacific salmon. *Fisheries* 24: 6-14.
- Hartman, G. F., and J. C. Scrivener. 1990. Impact of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. *Can. Bull. Fish. Aquat. Sci.* 223.
- Hartt, A.C., and M.B. Dell. 1986. Early oceanic migrations and growth of juvenile Pacific salmon and steelhead trout. *Int. N. Pac. Fish. Comm. Bull.* 51, 92 p.
- Healey, M.C. 1991. Life history of Chinook salmon (*Oncorhynchus tshawytscha*). In *Pacific salmon life histories. Edited by Groot, C., and Margolis, L.* University of British Columbia Press, Vancouver, British Columbia. pp. 313-393.
- Hinch, S.G., M.C. Healey, R.E. Diewert, and M.A. Henderson. 1995. Climate change and ocean energetics of Fraser River sockeye (*Oncorhynchus nerka*). *Can. Spec. Pub. Fish. Aquat. Sci.* 121: 439-445.
- Holtby, L.B., B.C. Anderson, and R.K. Kadowaki. 1988. Importance of smolt size and early ocean growth to interannual variability in marine survival of coho salmon (*Oncorhynchus kisutch*). *Can. J. Fish. Aquat. Sci.* 47: 2181-2194.
- Hoof, R.C., and W.T. Peterson. 2006. Copepod biodiversity as an indicator of changes in ocean and climate conditions of the northern California current ecosystem. *Limnol. Oceanogr.* 51: 2607-2620.
- ISRP 2005-14. Retrospective report 1997-2005. Northwest Power Planning Council, 851 SW 6th Avenue, Suite 1100, Portland, Oregon, 97204.
- Kiljunen, M., J. Grey, T. Sinisalo, C. Harrod, H. Immonen, and R.I. Jones. 2006. A revised model for lipid-normalizing $\delta^{13}\text{C}$ values from aquatic organisms, with implications for isotope mixing models. *J. Appl. Ecol.* 43: 1213-1222.
- Levin, P.S. 2003. Regional differences in responses of Chinook salmon populations to large-scale climatic patterns. *J. Biogeogr.* 30: 711-717.
- Logerwell, E.A., N. Mantua, P.W. Lawson, R.C. Francis, and V.N. Agostini. 2003. Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival. *Fish. Oceanogr.* 12: 554-568.
- Mackas, D.L., R. Goldblatt, and A.G. Lewis. 1998. Interdecadal variation in developmental timing of *Neocalanus plumchrus* populations at Ocean Station P in the subarctic North Pacific. *Can. J. Fish. Aquat. Sci.* 55: 1878-1893.
- Mackas, D.L., R.E. Thompson, and M. Galbraith. 2001. Changes in the zooplankton community of the British Columbia continental margin, 1985-1999, and their covariation with oceanographic conditions. *Can. J. Fish. Aquat. Sci.* 58: 685-702.
- Mackas, D.L., S. Batten, and M. Trudel. 2007. Effects on zooplankton of a warmer ocean: recent evidence from the Northeast Pacific. *Prog. Oceanogr.* 75: 223-252.
- Mackas, D.L., W.T. Peterson, and J.E. Zamon. 2004. Comparisons of interannual biomass anomalies of zooplankton communities along the continental shelf margins of British Columbia and Oregon. *Deep-Sea Res. II* 51: 875-896.
- MacPherson, S.A., D.R. Bernard, and M.S. Kelley. 1997. Production of coho salmon from the Taku River, 1995-1996. Alaska Department of Fish and Game, Fishery Data Series No. 97-24.
- Martin, D.J., C.A. Simenstad, D.A. Milward, E.C. Volk, M.L. Stevenson, P. Nunes, M. Savoie, and R.A. Grotefendt. 1986. Distribution, seasonal abundance, and feeding dependencies of juvenile salmon and non-salmonid fishes in the Yukon River Delta. Final Report, Outer Continental Shelf Environmental Assessment Program, Research Unit 660, Dames and Moore, Seattle, Washington.
- Matthews, B., and A. Mazumder. 2005. Temporal variation in body composition (C:N) helps explain seasonal patterns of zooplankton $\delta^{13}\text{C}$. *Freshwat. Biol.* 50: 502-515.

- McConnauey, T. and C.P. McRoy. 1978. Food-web structure and the fractionation of carbon isotopes in the Bering Sea. *Mar. Biol.* 53: 257-262.
- McCurdy, S.J. 2005. Production of coho salmon from Chuck Creek in Southeast Alaska, 2001-2003. Alaska Department of Fish and Game, Fishery Data Series No. 05-28.
- McCurdy, S.J. 2006. Production of coho salmon from Chuck Creek in Southeast Alaska, 2003-2004. Alaska Department of Fish and Game, Fishery Data Series No. 06-10.
- McGowan, J.A., D.R. Cayan, and L.M. Dorman. 1998. Climate-ocean variability and ecosystem response in the Northeast Pacific, *Science* 281: 210-217.
- McGowan, J.A., S.J. Bograd, R.J. Lynn, and A.J. Miller. 2003. The biological response to the 1977 regime shift in the California Current. *Deep-Sea Res. II* 50: 2567-2582.
- McKinnell, S.M., C.C. Wood, D.T. Rutherford, K.D. Hyatt, and D.W. Welch. 2001. The demise of Owikeno Lake sockeye salmon. *N. Am. J. Fish. Manag.* 21: 774-791.
- Meehan, W.R., and D.B. Siniff. 1962. A study of the downstream migrations of anadromous fishes in the Taku River, Alaska. *Trans. Am. Fish. Soc.* 91: 399-407.
- Moodie, S., J.A. Grout, and A. von Finster. 2000. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) utilization of Croucher Creek, a small non-natal tributary of the Upper Yukon River during 2003. *Can. Man. Rep. Fish. Aquat. Sci.* 2531.
- Morris, J.F.T., M. Trudel, M. Thiess, R.M. Sweeting, J. Fisher, S. Hinton, E.A. Fergusson, J.A. Orsi, E.V. Farley, Jr., and D.W. Welch. 2007. Stock-specific migrations of juvenile coho salmon derived from coded-wire tag recoveries on the continental shelf of western North America. *Am. Fish. Soc. Symp. Ser.* 57: 81-104.
- Moss, J.H., D.A. Beauchamp, A.D. Cross, K. Myers, E.V. Farley Jr., J.M. Murphy, and J.H. Helle. 2005. Evidence for size-selective mortality after summer of ocean growth by pink salmon. *Trans. Am. Fish. Soc.* 134: 1313-1322.
- Murphy, M.L., K.V. Koski, J.M. Lorenz, J.F. Thedinga. 1997. Downstream migrations of juvenile Pacific salmon (*Oncorhynchus* spp.) in a glacial transboundary river. *Can. J. Fish. Aquat. Sci.* 54: 2837-2846.
- Nass, B.L. 1996. Enumeration and coded-wire tagging of coho salmon smolts at Zolzap Creek, and enumeration of coho salmon smolts at Seaskinnish and Ginlulak Creeks, 1992. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2376.
- Nass, B.L. 1997a. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 1994. *Can. Man. Rep. Fish. Aquat. Sci.* 2420.
- Nass, B.L. 1997b. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 1995. *Can. Man. Rep. Fish. Aquat. Sci.* 2423.
- Nass, B.L. 2001. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 1996. *Can. Man. Rep. Fish. Aquat. Sci.* 2564.
- Nass, B.L., and H.R. Frith. 2001. Adult and juvenile coho salmon enumeration and coded-wire tag recovery analysis for Zolzap Creek, BC, 1997. *Can. Man. Rep. Fish. Aquat. Sci.* 2565.
- Nielsen, E.E., M.M. Hansen, C. Schmidt, D. Meldrup, and P. Grønkjær. 2001. Population of origin of Atlantic cod. *Nature* 413: 272.
- National Oceanographic and Atmospheric Administration. 2009. National Climatic Data Center. [www.ncdc.noaa.gov/oa/climate/research/anomalies/index.php]
- National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. National Academy Press, Washington D.C.
- Orsi, J.A., and H.W. Jaenicke. 1996. Marine distribution and origin of prerecruit chinook salmon *Oncorhynchus tshawytscha*, in Southeastern Alaska. *Fish. Bull.* 94: 482-497.
- Pazzia, I., M. Trudel, M., Ridgway, and J.B. Rasmussen. 2002. Influence of food web structure on the growth and bioenergetics of lake trout (*Salvelinus namaycush*). *Can. J. Fish. Aquat. Sci.* 59: 1593-1605.
- Pearcy, W. G. 1992. Ocean ecology of North Pacific salmonids. University of Washington Press, Seattle, WA.

- Pearcy, W.G., and J.P. Fisher. 1988. Migrations of coho salmon, *Oncorhynchus kisutch*, during their first summer in the ocean. Fish. Bull. 86: 173-195.
- Pella, J., and M. Masuda. 2001. Bayesian methods for analysis of stock mixtures from genetic characters. Fish. Bull. 99: 151-167.
- Peterson, W.T., and F.B. Schwing. 2003. A new climate regime in the northeast Pacific ecosystem. Geophys. Res. Lett. 30, 1986, doi:10.1029/2003GL017528.
- Peterson, W.T., R.C. Hoof, C.A. Morgan, K.L. Hunter, E. Casillas, and J.W. Ferguson. 2006. Ocean conditions and salmon survival in the northern California Current. 52 p. (www.nwfsc.noaa.gov/research/divisions/fed/ecosysrep.pdf).
- PICES. 2004. Marine ecosystems of the North Pacific. PICES Spec. Pub. 1, 280 p.
- Phillipson, J. 1964. A miniature bomb calorimeter for small biological samples. Oikos 15:130-139.
- Post, D.M. 2002a. The long and short of food chain length. TREE 17: 269-277.
- Post, D.M. 2002b. Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology 83: 703-718.
- Post, D.M., C.A. Layman, D.A. Arrington, G. Takimoto, J. Quattrochi, C.G. Montaña. 2007. Getting to the fat of the matter: models, methods, and assumptions for dealing with lipids in stable isotope analyses. Oecologia 152: 179-189.
- Post, J.R., and D.O. Evans. 1989. Size-dependent overwinter mortality of young-of-the-year yellow perch (*Perca flavescens*): Laboratory, in situ enclosure, and field experiments. Can. J. Aquat. Sci. 53: 910-923.
- Raymond, H.L. 1988. Effects of hydroelectric development and fisheries enhancement on spring and summer Chinook salmon and steelhead in the Columbia River Basin. N. Am. J. Fish. Manag. 8: 1-24.
- Ricker, W.E. 1979. Growth rates and models. In Fish Physiology Edited by Hoar W.S., Randall D.J. and Brett J.R. Vol. VIII, Academic Press, New York, pp. 677-743.
- Rowan, D.J., and J.B. Rasmussen. 1995. The elimination of radiocaesium from fish. J. Appl. Ecol. 32: 739-744.
- Rowan, D. J., and Rasmussen, J. B. 1996. Measuring the bioenergetic cost of fish activity using a globally dispersed radiotracer (¹³⁷Cs). Can. J. Fish. Aquat. Sci. 53: 734-745.
- Ruckelshaus, M.H., P. Levin, J.B. Johnson, and P.M. Kareiva. 2002. The Pacific salmon wars: What science brings to the challenge of revering species? Ann. Rev. Ecol. Syst. 33: 365-706.
- Schaller, H.A., C.E. Petrosky, and O.P. Langness. 1999. Contrasting patterns of productivity and survival rates for stream-type chinook salmon (*Oncorhynchus tshawytscha*) populations of the snake and Columbia Rivers. Can. J. Fish. Aquat. Sci. 56: 1031-1045.
- Schaller, H., P. Wilson, S. Haeseker C. Petrosky, E. Tinus, T. Dalton, R. Woodin, E. Weber, N. Bouwes, T. Berggren, J. McCann, S. Rassk, H. Franzoni, and P. McHugh. 2007. Comparative Survival Study (CSS) of PIT-tagged spring/summer Chinook and steelhead in the Columbia River Basin: Ten-year retrospective summary report. Report Contract # 19960200. Prepared by Fish Passage Center and Comparative Survival Study Oversight Committee representing the Columbia Basin Fish and Wildlife Agencies and Columbia Basin Tribes. 675 pp. (<http://www.fpc.org/documents/CSS.html>).
- Scheuerell, M.D., and J.G. Williams. 2005. Forecasting climate-induced changes in the survival of Snake River spring/summer Chinook salmon (*Oncorhynchus tshawytscha*). Fish. Oceanogr. 14: 448-457.
- Seeb, L.W., P.A. Crane, C.M. Kondzela, R.L. Wilmot, S. Urawa, N.V. Varnavskaya, and J.E. Seeb. 2004. Migration of Pacific Rim chum salmon on the high seas: insights from genetics data. Environmental Biology of Fishes 69: 21-36.

- Simpkins, D.G., W.A. Hubert, C.M. Del Rio, and D.C. Rule. 2003. Physiological responses of juvenile rainbow trout to fasting and swimming activity: effects on body composition and condition indices. *Trans. Am. Fish. Soc.* 132: 576-589.
- Spence, B.C. 1995. Geographic variation in timing of fry emergence and smolt migration of coho salmon (*Oncorhynchus kisutch*). Doctoral Dissertation, Oregon State University, Corvallis, 201p.
- Sweeting, C.J., N.V.C. Polunin, S. Jennings. 2006. Effects of chemical lipid extraction and arithmetic lipid correction on stable isotope ratios of fish tissues. *Rap. Comm. Mass Spec.* 20: 595-601.
- Teel, D.J., D.M. Van Doornik, D.R. Kuligowski, and W.S. Grant. 2003. Genetic analysis of juvenile coho salmon (*Oncorhynchus kisutch*) off Oregon and Washington reveals few Columbia River wild fish. *Fish. Bull.* 101: 640-652.
- Trudel, M., and D.W. Welch. 2005. Modeling the oxygen consumption rates of Pacific salmon and steelhead trout: model development. *Trans. Am. Fish. Soc.* 134: 1542-1561.
- Trudel, M., and J.B. Rasmussen. 2001. Predicting mercury concentration in fish using a mass balance model. *Ecol. Appl.* 11: 517-529.
- Trudel, M., and J.B. Rasmussen. 2006. Bioenergetics and mercury dynamics in fish: a modelling perspective. *Can. J. Fish. Aquat. Sci.* 63: 1890-1902.
- Trudel, M., A. Tremblay, R. Schetagne, and J.B. Rasmussen. 2000. Estimating food consumption rates of fish using a mercury mass balance model. *Can. J. Fish. Aquat. Sci.* 57: 414-428.
- Trudel, M., D.W. Welch, J.F.T. Morris, J.R. Candy, and T.D. Beacham. 2004. Using genetic markers to understand the coastal migration of juvenile coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*). *N. Pac. Anadr. Fish. Comm. Tech. Rep.* 5: 52-54.
- Trudel, M., J. Fisher, J.A. Orsi, J.F.T. Morris, M.E. Thiess, R.M. Sweeting, S. Hinton, E.A. Ferguson, E.V. Farley, Jr., and D.W. Welch. 2009. Distribution and migration of juvenile Chinook salmon derived from coded-wire tag recoveries along the continental shelf of western North America. *Trans. Am. Fish. Soc.* (submitted in September 2008).
- Trudel, M., J. Morris, M. Thiess, T. Zubkowski, and D. Mackas. 2007c. Annual report of the Canada-USA Salmon Shelf Survival Study submitted to the Bonneville Power Administration. 92 pages.
- Trudel, M., S. Tucker, J.E. Zamon, J.F.T. Morris, D.A. Higgs, and D.W. Welch. 2002. Bioenergetic response of coho salmon to climate change. *N. Pac. Anadr. Fish Comm. Tech. Rep.* 4: 59-61.
- Trudel, M., S. Tucker, J.F.T. Morris, D.A. Higgs, and D.W. Welch. 2005. Indicators of energetic status in juvenile coho salmon (*Oncorhynchus kisutch*) and chinook salmon (*Oncorhynchus tshawytscha*). *N. Am. J. Fish. Manag.* 25: 374-390.
- Trudel, M., S.R.M. Jones, M.E. Thiess, J.F.T. Morris, D.W. Welch, R.M. Sweeting, J.H. Moss, B.L. Wing, E.V. Farley, Jr., J.M. Murphy, R.E. Baldwin, and K.C. Jacobson. 2007a. Infestations of motile salmon lice on Pacific salmon along the west coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 157-182.
- Trudel, M., M.E. Thiess, C. Bucher, E.V. Farley, Jr., B. MacFarlane, E. Casillas, J.F.T. Morris, J.M. Murphy, and D.W. Welch. 2007b. Regional variation in the marine growth and energy accumulation of juvenile Chinook salmon and coho salmon along the west coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 205-232.
- Van Doornik, D.M., D.J. Teel, D.R. Kuligowski, C.A. Morgan, and E. Casillas. 2007. Genetic analyses provide insight into the early ocean stock distribution and survival of juvenile coho salmon (*Oncorhynchus kisutch*) off the coasts of Washington and Oregon. *North American Journal of Fisheries Management* 27: 220-237.
- Vander Zanden, M.J., and J.B. Rasmussen. 1999. Primary consumer $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ and the trophic position of consumers. *Ecology* 80: 1395-1404.

- Vander Zanden, M.J., and J.B. Rasmussen. 2001. Variation in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ trophic fractionation: implications for aquatic food web studies. *Limnol. Oceanogr.* 46: 2061-2066.
- Veefkind, R.J. 2003. Carbon isotope ratios and composition of fatty acids: tags and trophic markers in pelagic organisms. Thesis Dissertation, University of Victoria, Victoria, British Columbia. 271 p.
- Walker, C.E. 1976. Studies on the freshwater and anadromous fishes of the Yukon River within Canada. Fisheries Marine Service Technical Report PAC/T-73-12. 52 pp.
- Waples, R.S., D.J. Teel, J.M. Myers, and A.R. Marshall. 2004. Life-history divergence in chinook salmon: historic contingency and parallel evolution. *Evolution* 58: 386-403.
- Ware, D.W., and R.E. Thomson. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Nature* 308: 1280-1284.
- Welch, D.W., B.R. Ward, B.D. Smith and J.P. Eveson. 2000. Temporal and spatial responses of British Columbia steelhead (*Oncorhynchus mykiss*) populations to ocean climate shifts. *Fish. Oceanogr.* 9: 17-32.
- Welch, D.W., E.L. Rechisky, M.C. Melnychuk, A.D. Porter, C.J. Walters, S. Clements, B.J. Clemens, R.S. McKinley, and C. Schreck. 2008. Survival of migrating salmon smolts in large rivers with and without dams. *PLoS Biol* 6(10): e265. doi:10.1371/journal.pbio.0060265.
- Welch, D.W., M. Trudel, J. Zamon, J. Morris, and M. Thiess. 2002. Potential interrelationships between patterns of migration and marine survival in Pacific salmon. *N. Pac. Anadr. Fish Comm. Tech. Rep.* 4: 62-64.
- Whitney, F.A., and D.W. Welch. 2002. Impact of the 1997-1998 El Niño and 1999 La Niña on nutrient supply in the Gulf of Alaska. *Prog. Oceanogr.* 54: 405-422.
- Whitney, F.A., W.R. Crawford, and P.J. Harrison. 2005. Physical processes that enhance nutrient transport and primary productivity in the coastal and open ocean of the subarctic NE Pacific. *Deep-Sea Res. II* 52: 681-706.
- Williams, B., M. Nemeth, S. Kinneen, and B. Bocking. 2006. Abundance of juvenile coho salmon in the Nome River. Annual report prepared for the Norton Sound Disaster Relief Fund by LGL Alaska Research Associates, Inc. and Norton Sound Economic Development Corporation. 31 p. + appendix.
- Williams, J.G., S.G. Smith, R.W. Zabel, W.D. Muir, M.D. Scheuerell, B.P. Sandford, D.M. Marsh, R.A. McNatt, and S. Archord. 2005. Effects of the Federal Columbia River power system on salmon population. NOAA Tech. Memo. NMFS-NWFSC-63, 99p.
- Williams, J.G., S.G. Smith, and W.D. Muir. 2001. Survival estimates for downstream migrant yearling juvenile salmonids through the Snake and Columbia Rivers hydropower system, 1966-1980 and 1993-1999. *N. Am. J. Fish. Manag.* 21: 310-317.
- Wirth, T., and L. Bernatchez. 2001. Genetic evidence against panmixia in the European eel. *Nature* 409: 1037-1040.
- Withler, R.E., K.D. Le, R.J. Nelson, K.M. Miller, and T.D. Beacham. 2000. Intact genetic structure and high levels of genetic diversity in bottlenecked sockeye salmon, *Oncorhynchus nerka*, populations of the Fraser River, British Columbia, Canada. *Can. J. Fish. Aquat. Sci.* 57: 1985-1998.
- Yannusz, R.J., S.A. MacPherson, D.R. Bernard, and I.M. Boyce. 2000. Production of coho salmon from the Taku River, 1998-1999. Alaska Department of Fish and Game, Fishery Data Series No. 00-31.
- Zamon, J.E., and D.W. Welch. 2005. Rapid shift in zooplankton community composition on the northeast Pacific shelf during the 1998-99 El Niño-La Niña event. *Can. J. Fish. Aquat. Sci.* 62: 133-144.
- Zhang, Z., and R.J. Beamish. 2000. Use of otolith microstructure to study life history of juvenile chinook salmon in the Strait of Georgia in 1995 and 1996. *Fish. Res.* 52: 344-352.

9. Publications involving the Canada-USA Salmon Shelf Survival Study during FY04-FY08**9.1. Primary publication**

1. Farley, E.V., Jr., and Trudel, M. 2009. Growth rate potential of juvenile sockeye salmon in warm and cool years on the eastern Bering Sea shelf. *J. Mar. Biol.* (submitted in February 2009).
2. Tucker, S., M. Trudel, D.W. Welch, J.R. Candy, J.F.T. Morris, M.E. Thiess, C. Wallace, D.J. Teel, W. Crawford, E.V. Farley, Jr., and T.D. Beacham. 2009. Using DNA-based stock identification to elucidate coastal migration of juvenile sockeye salmon (*Oncorhynchus nerka*). *Trans. Am. Fish. Soc.* (submitted in October 2008).
3. Trudel, M., J. Fisher, J.A. Orsi, J.F.T. Morris, M.E. Thiess, R.M. Sweeting, S. Hinton, E.A. Ferguson, E.V. Farley, Jr., and D.W. Welch. 2009. Distribution and migration of juvenile Chinook salmon derived from coded-wire tag recoveries along the continental shelf of western North America. *Trans. Am. Fish. Soc.* (submitted in September 2008).
4. Mackas, D.L., Batten, S., and Trudel, M. 2007. Effects on zooplankton of a warmer ocean: recent evidence from the Northeast Pacific. *Prog. Oceanogr.* 75: 223-252.
5. Fisher, J., Trudel, M., Ammann, A., Orsi, J., Piccolo, J., Bucher, C., Harding, J., Casillas, E., MacFarlane, B., Brodeur, R., Morris, J., and Welch, D. 2007. Regional comparisons of distribution and abundance of juvenile salmon along the West Coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 31-80.
6. Morris, J.F.T., Trudel, M., Thiess, M., Sweeting, R.M., Fisher, J., Hinton, S., Fergusson, E.A., Orsi, J.A., Farley, E.V., Jr., and Welch, D.W. 2007. Stock-specific migrations of juvenile coho salmon derived from coded-wire tag recoveries on the continental shelf of western North America. *Am. Fish. Soc. Symp. Ser.* 57: 81-104.
7. Orsi, J.A., Harding, J.A., Pool, S.S., Brodeur, R.D., Halderson, L.J., Murphy, J.M., Moss, J.H., Farley, E.V., Jr., Sweeting, R.M., Morris, J.F.T., Trudel, M., Beamish, R.J., Emmett, R.L., and Fergusson, E.A. 2007. Epipelagic fish assemblages associated with juvenile Pacific salmon in neritic waters of the California Current and Alaska Current. *Am. Fish. Soc. Symp. Ser.* 57: 105-155.
8. Trudel, M., Jones, S.R.M., Thiess, M.E., Morris, J.F.T., Welch, D.W., Sweeting, R.M., Moss, J.H., Wing, B.L., Farley, E.V., Jr., Murphy, J.M., Baldwin, R.E., and Jacobson, K.C. 2007. Infestations of motile salmon lice on Pacific salmon along the west coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 157-182.
9. Brodeur, R.D., Daly, E.A., Studervant, M.V., Miller, T.W., Moss, J.H., Thiess, M., Trudel, M., Weitkamp, L.A., Armstrong, J., and Norton, E.C. 2007. Regional comparisons of juvenile salmon feeding in coastal marine waters off the West Coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 183-203.
10. Trudel, M., Thiess, M.E., Bucher, C., Farley, E.V., Jr., MacFarlane, B., Casillas, E., Morris, J.F.T., Murphy, J.M., and Welch, D.W. 2007. Regional variation in the marine growth and energy accumulation of juvenile Chinook salmon and coho salmon along the west coast of North America. *Am. Fish. Soc. Symp. Ser.* 57: 205-232.
11. Brodeur, R.D., Ralston, S., Emmett, R.L., Trudel, M., Auth, T.D., and Phillips, A.J. 2006. Recent trends and anomalies in pelagic nekton abundance, distribution, and apparent recruitment in the Northeast Pacific Ocean. *Geophys. Res. Lett.* Doi:10.1029/2006GL026614.
12. Trudel, M., Tucker, S., Morris, J.F.T., Higgs, D.A., and Welch, D.W. 2005. Indicators of energetic status in juvenile coho salmon (*Oncorhynchus kisutch*) and chinook salmon (*Oncorhynchus tshawytscha*). *N. Am. J. Fish. Manag.* 25: 374-390.
13. Trudel, M., and D.W. Welch. 2005. Modeling the oxygen consumption rates of Pacific salmon and steelhead trout: model development. *Trans. Am. Fish. Soc.* 134: 1542-1561.

14. Beacham, T.D., J.R. Candy, B. McIntosh, C. MacConnachie, A. Tabata, K. Kaukinen, L. Deng, K.M. Miller, R.E. Withler, and N. Varnawskaya. 2005. Estimation of stock composition and individual identification of sockeye salmon on a Pacific Rim basis using microsatellite and major histocompatibility complex variation. *Trans. Am. Fish. Soc.* 134: 1124-1146.
15. Ware, D.W., and R.E. Thomson. 2005. Bottom-up ecosystem trophic dynamics determine fish production in the Northeast Pacific. *Nature* 308: 1280-1284.
16. Whitney, F.A., W.R. Crawford, and P.J. Harrison. 2005. Physical processes that enhance nutrient transport and primary productivity in the coastal and open ocean of the subarctic NE Pacific. *Deep-Sea Res. II* 52: 681-706.
17. Zamon, J.E., and Welch, D.W. 2005. Rapid shift in zooplankton community composition on the northeast Pacific shelf during the 1998-99 El Niño-La Niña event. *Can. J. Fish. Aquat. Sci.* 62: 133-144.
18. Trudel, M., Geist, D.R., and Welch, D.W. 2004. Modeling the oxygen consumption rates of Pacific salmon and steelhead trout: an assessment of current models and practices. *Trans. Am. Fish. Soc.* 133: 326-348.
19. Mackas, D.L., W.T. Peterson, and J.E. Zamon. 2004. Comparisons of interannual biomass anomalies of zooplankton communities along the continental shelf margins of British Columbia and Oregon. *Deep-Sea Research II* 51: 875-896.

9.2. Conference proceedings

20. Beamish, R.J., Trudel, M., and Sweeting, R. 2007. Canadian coastal and high seas juvenile Pacific salmon studies. North Pacific Anadromous Fish Commission Technical Report 7: 1-4.
21. Trudel, M., Thiess, M.E., Morris, J.F.T., Candy, J.R., Beacham, T.D., Higgs, D.A., and Welch, D.W. 2007. Overwinter mortality and energy depletion in juvenile Pacific salmon off the west coast of British Columbia and Alaska. North Pacific Anadromous Fish Commission Technical Report 7: 61-63.
22. Trudel, M., Welch, D.W., Morris, J.F.T., Farley, E.V. Jr., and Murphy, J. 2005. Influence of the marine feeding area on lipid accumulation in juvenile coho salmon. *N. Pac. Anadr. Fish. Comm. Tech. Rep.* 6: 94-95.
23. Harrison, P.J., Whitney, F., Mackas, D., Beamish, R., Trudel, M., and Perry, I. 2004. Changes in coastal ecosystems in the NE Pacific Ocean. Proceedings of International Symposium on long-term variations in the coastal environments and ecosystems, 27-28 September 2004, Matsuyama, Japan, pp 17-35.
24. Trudel, M., D.W. Welch, J.F.T. Morris, J.R. Candy, and T.D. Beacham. 2004. Using genetic markers to understand the coastal migration of juvenile coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*). *N. Pac. Anadr. Fish. Comm. Tech. Rep.* 5: 52-54.
25. Welch, D.W., Trudel, M., Beacham, T.D., Morris, J.F.T., and Candy, J.R. 2004. DNA-based stock identification of coastal sockeye salmon: evidence for stock-specific migration behaviour of central coast (Rivers Inlet) sockeye salmon. *N. Pac. Anadr. Fish. Comm. Tech. Rep.* 5: 65-66.

9.3. Data reports

26. Morris, J. F. T., Trudel, M., Thiess, M. E., Boyle, C. A., Zubkowski, T. B., and Maclean, H. R. 2008. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, November 7 - December 5, 2006. *Can. Data Rep. Fish. Aquat. Sci.* 1199: 144 p.

27. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., Boyle, C. A., and Maclean, H. R. 2008. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, June 21-30, 2006. Can. Data Rep. Fish. Aquat. Sci. 1198: 145 p.
28. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., and MacLean, H. R. 2007. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, June 12-19, 2004. Can. Data Rep. Fish. Aquat. Sci. 1194: 150 p.
29. Morris, J. F. T., Trudel, M., Welch, D. W., Thiess, M. E., Zubkowski, T. B., and MacLean, H. R. 2007. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, February 13- 28, 2004. Can. Data Rep. Fish. Aquat. Sci. 1193: 47p.
30. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., Boyle, C. A., and MacLean, H. R. 2007. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, February 28 - March 27, 2006. Can. Data Rep. Fish. Aquat. Sci. 1191: 73 p.
31. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., and MacLean, H. R. 2007. *CFV Frosti* Gulf of Alaska salmon survey, June 28 - July 7, 2005. Can. Data Rep. Fish. Aquat. Sci. 1187: 125 p.
32. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., Boyle, C. A., and MacLean, H. R. 2007. *CFV Frosti* Gulf of Alaska salmon survey, October 27 - November 20, 2005. Can. Data Rep. Fish. Aquat. Sci. 1186: 136 p.
33. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., and MacLean, H. R. 2007. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, March 4-25, 2005. Can. Data Rep. Fish. Aquat. Sci. 1185: 83 p.
34. Morris, J. F. T., Trudel, M., Thiess, M. E., Zubkowski, T. B., and MacLean, H. R. 2007. CCGS *W.E. Ricker* Gulf of Alaska salmon survey, October 20 – November 21, 2004. Can. Data Rep. Fish. Aquat. Sci. 1184: 121 p.
35. Myers, K.W., Davis, N.D., Celewycz, A.G., Farley, E.V., Jr., Morris, J.F.T., Trudel, M., Fukuwaka, M.-A. 2005. High seas salmonid coded-wire tag recovery data, 2005. North Pacific Anadromous Fisheries Commission Document No. 905.
36. Morris, J.F.T., M. Trudel, D.W. Welch, M.E. Thiess, and T.B. Zubkowski. 2004. Canadian Highseas Salmon surveys: CWT recoveries from juvenile Chinook and coho salmon on the continental shelf of British Columbia and southeast Alaska from 1998 to 2003. North Pacific Anadromous Fish Commission Document No. 823.
37. Morris, J.F.T., Trudel, M., Welch, D.W., Thiess, M.E., Zubkowski, T.B., and MacLean, H.R.C.. 2004. Canadian Highseas Salmon surveys in the fall of 2003 and the winter of 2004: seasonal changes in the distributions of juvenile salmon on the continental shelf off British Columbia and Southeast Alaska. N. Pac. Anadr. Fish. Comm. Doc. No. 780.
38. Morris, J.F.T., Welch, D.W., Winchell, P.M., Thiess, M.E., Trudel, M., Zubkowski, T.B., and H.R.C. MacLean. 2004. The joint USA - Canada echo integration - trawl survey from June 24 to September 8, 2003: a report on the catch and biological data collected for Pacific salmon off Southeast Alaska. Can. Data Rep. Fish. Aquat. Sci. 1151: 43 p.
39. Morris, J.F.T., Welch, D. W., Thiess, M.E., Trudel, M., Ladouceur, A.R., Jacobs, M.C., and Zubkowski, T.B. 2004. The joint USA-Canada echo integration-trawl survey in 2001: a report on the catch and biological data collected for Pacific salmon from July 28 to August 18. Can. Data Rep. Fish. Aquat. Sci. 1150: 110 p.
40. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Zubkowski, T.B., Jacobs, M.C., and MacLean, H. R. 2004. F.V. Ocean Selector Gulf of Alaska Salmon Survey, June 16-28, 2002. Can. Data Rep. Fish. Aquat. Sci. 1146: 71 p.
41. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Jacobs, M.C., Zubkowski, T.B., and MacLean, H. R. 2004. CCGS *W.E. Ricker* Gulf of Alaska Salmon Survey, October 8-27, 2003. Can. Data Rep. Fish. Aquat. Sci. 1145: 116 p.

42. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Zubkowski, T.B., Jacobs, M.C., Winchell, P.M., and MacLean, H. R. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, June 9-11, 2003. Can. Data Rep. Fish. Aquat. Sci. 1144: 54 p.
43. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Jacobs, M.C., Zubkowski, T.B., Winchell, P.M., and MacLean, H. R. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, February 27 to March 17, 2002. Can. Data Rep. Fish. Aquat. Sci. 1143: 56 p.
44. Welch, D. W., Morris, J.F.T., Thiess, M.E., Zamon, J.E., Trudel, M., Ladouceur, A.R., Jacobs, M.C., Zubkowski, T.B., Demers, E., and Robert, M. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, March 9-24, 2001. Can. Data Rep. Fish. Aquat. Sci. 1142: 67 p.
45. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Zubkowski, T.B., Jacobs, M.C., Winchell, P.M., and MacLean, H. R. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, February 14- 26, 2003. Can. Data Rep. Fish. Aquat. Sci. 1139: 63 p.
46. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Zubkowski, T.B., Jacobs, M.C., Winchell, P.M., and MacLean, H. R. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, October 17 to November 9, 2002. Can. Data Rep. Fish. Aquat. Sci. 1138: 120 p.
47. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Jacobs, M.C., Zubkowski, T.B., and MacLean, H.R. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, August 15- 26, 2002. Can. Data Rep. Fish. Aquat. Sci. 1137: 119 p.
48. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Zubkowski, T.B., MacLean, H.R., Jacobs, M.C., and Winchell, P.M. 2004. CCGS W.E. Ricker Gulf of Alaska salmon survey, October 9 to November 5, 2001. Can. Data Rep. Fish. Aquat. Sci. 1136: 143 p.
49. Welch, D. W., Morris, J.F.T., Thiess, M.E., Trudel, M., Ladouceur, A.R., Jacobs, M.C., Zubkowski, T.B., Demers, E., and Zamon, J.E. 2004. CCGS W.E. Ricker Gulf of Alaska Salmon Survey, June 14- 24, 2001. Can. Data Rep. Fish. Aquat. Sci. 1135: 84 p.

9.4. Other documents

50. DFO, 2008. 2007 Pacific Region State of the Ocean. DFO Science Ocean Status Report 2007 (2008). [http://www.dfo-mpo.gc.ca/csas/Csas/Publications/ResDocs-DocRech/2008/2008_013_e.pdf].
51. DFO, 2007. 2006 Pacific Region State of the Ocean. DFO Science Ocean Status Report 2006 (2007). [http://sci.info.pac.dfo.ca/PSARC/OSR's/State-of_ocean-2006-Full_E.pdf].
52. DFO, 2006. 2005 Pacific Region State of the Ocean. DFO Science Ocean Status Report 2005 (2006). [<http://sci.info.pac.dfo.ca/PSARC/OSR's/StateofOceans2005fnl.pdf>].
53. DFO, 2005. 2004 Pacific Region State of the Ocean. DFO Science Ocean Status Report 2004 (2005). [<http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/StateofOceans2004fnl.pdf>].
54. DFO, 2004. 2003 Pacific Region State of the Ocean. DFO Science Ocean Status Report 2003 (2004). [<http://sci.info.pac.dfo.ca/PSARC/OSR's/OceanStatus2003.pdf>].

10. TABLES

Table 1. Juvenile salmon surveys conducted by the High Seas Salmon Program off the west coast of British Columbia and southeast Alaska from inception to present.

Sampling date	Oceanographic station	Plankton station	Fish station
June 2–18, 1998	32	20	25
July 16–25, 1998	42	40	49
August 25 – September 3, 1998	51	26	30
October 5–21, 1998	63	25	58
May 17–30, 1999	40	38	59
June 18–26, 1999	48	27	43
October 2–15, 1999	63	25	71
June 27 – July 6, 2000	43	11	43
October 4–30, 2000	136	120	127
March 9–24, 2001	91	69	92
June 14–24, 2001	74	71	70
July 28 – August 18, 2001	8	0	8
October 9 – November 5, 2001	149	138	147
February 27 – March 17, 2002	86	84	91
June 16–28, 2002	63	58	69
August 15–26, 2002	61	62	63
October 17 – November 9, 2002	123	115	122
February 14 – 26, 2003	74	76	75
June 9–11, 2003	21	21	21
August 27, 2003	9	8	5
October 9 – 26, 2003	98	97	95
February 13 – 28, 2004	77	77	63
June 13–19, 2004	47	47	45
October 20 – November 21, 2004	125	123	126
March 4–25, 2005	126	120	119
June 30 – July 6, 2005	39	36	39
October 27 – November 20, 2005	129	129	130
March 1 – March 26, 2006	132	129	129
June 21 – June 30, 2006	62	60	64
November 8 – December 2, 2006	116	111	117
February 28 – March 23, 2007	120	119	119
June 20 – July 5, 2007	109	107	108
October 11 – November 3, 2007	158	146	158
March 1 – March 22, 2008	148	118	111
June 19 – July 3, 2008	106	132	132
Total	2,869	2,585	2,823

Table 2. Size range of juvenile subyearling and yearling Chinook determined from coded-wire tag recoveries off Oregon to Alaska. Modified from Fisher et al. (2007).

Months	Subyearling Chinook	Yearling Chinook
Jun - Jul	<125 mm	125-275 mm
Oct – Nov	125-250 mm	250-350 mm
Feb - Mar	200-300 mm	300-400 mm

Table 3. Empirical models of energy density for juvenile coho and Chinook salmon collected at sea from the Oregon Coast to Alaska between 1996 and 2002. *ED*: energy density ($\text{kJ} \cdot \text{g}^{-1}_{\text{wet}}$); *PDRY*: percent dry weight of whole fish (%); *PDRY_{muscle}*: percent dry weight of fish muscle (%); *LIP*: lipid concentration ($\text{mg} \cdot \text{g}^{-1}_{\text{wet}}$); *n*: sample size; *S_{x,y}*: standard error of the estimate. From Trudel et al. (2005).

Model	Equation	r^2	<i>n</i>	<i>S_{x,y}</i>
Chinook salmon				
A1	$ED = -3.07 + 0.35 \cdot PDRY$	0.93	569	0.16
A2	$\log_{10} ED = -1.50 + 1.62 \cdot \log_{10} PDRY$	0.93	569	0.014
A3	$ED = -8.79 + 0.63 \cdot PDRY_{\text{muscle}}$	0.70	62	0.42
A4	$\log_{10} ED = -2.93 + 2.70 \cdot \log_{10} PDRY_{\text{muscle}}$	0.70	62	0.036
A5	$LIP = -108.3 + 6.0 \cdot PDRY$	0.76	104	5.5
Coho salmon				
B1	$ED = -3.18 + 0.35 \cdot PDRY$	0.93	467	0.19
B2	$\log_{10} ED = -1.51 + 1.61 \cdot \log_{10} PDRY$	0.94	467	0.015
B3	$ED = -10.81 + 0.69 \cdot PDRY_{\text{muscle}}$	0.63	83	0.42
B4	$\log_{10} ED = -3.44 + 3.04 \cdot \log_{10} PDRY_{\text{muscle}}$	0.63	83	0.034
B5	$LIP = -103.2 + 5.5 \cdot PDRY$	0.73	224	7.2
B6	$LIP = -271.1 + 13.1 \cdot PDRY_{\text{muscle}}$	0.55	75	9.4

Table 4. Timing and size at ocean entry for coho salmon and Chinook salmon smolts. FL_{OE}: Fork length at ocean entry (mm); DY_{OE}: Day of ocean entry (from Trudel et al. 2007b).

Latitude	Region	FL _{OE}	DY _{OE}	Source
Subyearling Chinook salmon				
48-52°	WCVI	75	Jun-21	1-4
44-48°	ORWA	90	Jul-01	4-6
37-41°	CA	87	Jun-01	7
Yearling Chinook salmon				
62-66°	NBS	90	Jun-15	8-12
60-62°	SBS	85	Jun-06	13-14
53-58°	SEAK	75	May-24	15
44-48°	ORWA	160	May-12	4, 5
Coho salmon				
62-66°	NBS	105	Jun-22	16
60-62°	SBS	105	Jun-13	14, 17-21
53-58°	SEAK	100	May-27	15, 17, 22-33
48-52°	WCVI	105	May-19	4, 17, 33-34
44-48°	ORWA	128	May-8	4, 17, 35-36

1. Cooke and Groot (1990); 2. Beacham (1990) 3. Zhang and Beamish (2000); 4. www.rmpc.org; 5. www.fpc.org; 6. Fresh et al. (2005); 7. R.B. MacFarlane (unpublished); 8. Martin et al. (1986); 9. Brown et al. (1976); 10. Walker (1976); 11. Moodie et al. (2000); 12. Bradford et al. (2001); 13. C. Zimmerman (USGS, personal communication); 14. Costello et al. (2006); Van Doornick et al. (2007); 15. P. Etherton (DFO, personal communication); 16. Williams et al. (2006); 17. Spence (1996); 18. Yannusz et al. (2000); 19. MacPherson et al. (1997); 20. Murphy et al. (1997); 21. Meehand and Siniff (1962); 22. Drucker (1972); 23. Ericksen (2001, 2002, 2003); 24. McCurdy (2005, 2006); 25. Beers (2003); 26. Fleming (2005); 27. Nass (1996, 1997a, 1997b, 2001); 28. Nass and Frith (2001); 29. Baxter et al. (2001); 30. Baxter and Stephens (2002a, 2002b, 2002c, 2004, 2005); 31. Baxter (2003); 32. Freeman (2003); 33. Bradford et al. (1997); 34. Hartman and Scrivener (1990); 35. Fisher and Percy (2005); 36. Dawley et al. (1985)

Table 5. Recovery location of juvenile coded-wire tagged (CWT) Chinook and coho salmon originating from the Columbia River caught during FY05 to FY08 as part of the Shelf Survival Study. SEAK/NBC: Southeast Alaska/Northern British Columbia; HS/QCI: Hecate Strait/Queen Charlotte Islands; WCVI: West coast of Vancouver Island.

Region	FY05	FY06	FY07	FY08*	Total
Chinook salmon					
SEAK/NBC	2	3	0	1	6
HS/QCI	0	7	19	5	31
WCVI	7	37	21	3	68
Total	9	47	40	9	105
Coho salmon					
SEAK/NBC	1	3	0	0	4
HS/QCI	0	0	1	0	1
WCVI	6	28	4	0	38
Total	7	31	5	0	43

*This table excludes the June/July 2008 CWT recoveries, as not all of the 2008 release codes are available in the RMIS database. A total of 185 juvenile CWT Chinook salmon and 25 juvenile CWT coho salmon were recovered during that survey. As of March 2, 2009, 98% (130 out of 132) of juvenile Chinook salmon for which we were able to retrieve the release information originated from the Columbia River, compared to 10% (2 out of 21) for juvenile coho salmon. Ninety-eight percent of these fish (150 out of 153) were caught off the west coast of Vancouver Island.

Table 6. Recovery of juvenile coded-wire tagged (CWT) Chinook salmon originating from the Columbia River caught during FY05 to FY08 as part of the Shelf Survival Study by release basin and run timing. CECR: Mid Columbia River; CRGN: Columbia River General; LOCR: Lower Columbia River; SNAKE: Snake River; UPCR: Upper Columbia River.

Basin	Spring runs	Summer runs	Fall runs	Total
CECR	4	0	1	5
CRGN	0	9	0	9
LOCR	10	0	1	11
SNAKE	12	7	10	27
UPCR	30	21	0	51
Total	56	37	12	105

*This table excludes the June/July 2008 CWT recoveries, as not all of the 2008 release codes are available in the RMIS database. As of March 2, 2009, 98% (130 out of 132) of juvenile Chinook salmon for which we were able to retrieve the release information originated from the Columbia River, compared to 10% (2 out of 21). The majority of these fish (144 out of 130 fish) were spring-summer Snake River and Upper Columbia River Chinook salmon.

Table 7. Number of coded-wire tag Chinook and coho salmon released in the Columbia River Basin between 1998 and 2008. Data compiled from the Regional Mark Processing Center (<http://www.rmhc.org/>).

Release year	Above Bonneville	Below Bonneville	Total
Subyearling Chinook salmon			
1998	5,794,125	3,087,501	8,881,626
1999	3,731,280	1,810,786	5,542,066
2000	4,378,874	1,756,012	6,134,886
2001	4,310,650	1,954,260	6,264,910
2002	4,326,671	1,468,297	5,794,968
2003	5,734,535	1,371,551	7,106,086
2004	4,810,639	1,855,388	6,666,027
2005	6,695,609	1,330,646	8,026,255
2006	5,820,126	1,476,401	7,296,527
2007	3,225,606	1,473,890	4,699,496
2008	2,588,164	1,398,639	3,986,803
Total	51,416,279	18,983,371	70,399,650
Yearling Chinook salmon			
1998	6,926,391	2,692,314	9,618,705
1999	9,538,311	6,841,254	16,379,565
2000	7,500,539	1,784,480	9,285,019
2001	8,802,011	1,874,220	10,676,231
2002	9,111,971	2,246,946	11,358,917
2003	9,525,941	1,759,531	11,285,472
2004	9,638,310	1,873,139	11,511,449
2005	9,670,175	2,197,810	11,867,985
2006	9,677,975	1,759,916	11,437,891
2007	7,876,491	1,347,686	9,224,177
2008	7,114,858	1,143,242	8,258,100
Total	95,382,973	25,520,538	120,903,511
Coho salmon			
1998	979,604	1,051,766	2,031,370
1999	740,183	1,306,620	2,046,803
2000	1,697,824	1,839,174	3,536,998
2001	1,330,808	1,590,731	2,921,539
2002	1,438,745	1,420,638	2,859,383
2003	2,113,262	1,139,650	3,252,912
2004	1,709,551	1,155,072	2,864,623
2005	1,470,761	1,008,172	2,478,933
2006	1,814,285	946,143	2,760,428
2007	1,789,931	1,019,539	2,809,470
2008	1,630,944	941,628	2,572,572
Total	16,715,898	13,419,133	30,135,031

Table 8. Recovery location of juvenile Redfish Lake sockeye salmon and estimated migration distance and dispersion speed.

Tag code	Recovery Date	FL (mm)	Latitude	Longitude	Distance (km)	Speed (km/d)
10-82-77	07/01/2007	162	54°15' N	131°41' W	2,515	46.5
10-17-81	06/21/2008	138	49°03' N	126°07' W	1,800	40.0
09-46-29	06/28/2008	193	54°28' N	131°36' W	2,530	48.6

Table 9a. Mean ($\bar{x}$) and variance (s^2) of the fork length (mm) of juvenile Chinook salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) during October-November and February-March. n : sample size.

Region	Year	October-November			Year	February-March		
		$\bar{x}$	s^2	n		$\bar{x}$	s^2	n
WCVI	1998	225	734	71	1999	--	--	--
	1999	205	1288	181	2000	--	--	--
	2000	183	524	17	2001	240	1142	470
	2001	158	366	144	2002	240	940	193
	2002	173	976	338	2003	222	451	153
	2003	178	942	233	2004	242	1041	138
	2004	169	1088	281	2005	213	1750	518
	2005	172	325	740	2006	230	873	309
	2006	170	895	1668	2007	217	1046	342
	2007	151	623	720	2008	--	--	--
SEAK	1998	--	--	--	1999	--	--	--
	1999	--	--	--	2000	--	--	--
	2000	280	545	222	2001	288	680	155
	2001	248	906	239	2002	288	434	67
	2002	268	625	111	2003	--	--	--
	2003	258	1737	34	2004	277	1031	103
	2004	258	1052	274	2005	289	845	114
	2005	229	900	296	2006	279	1282	67
	2006	258	1182	185	2007	271	704	88
	2007	261	1777	177	2008	--	--	--

Table 9b. Mean ($\bar{x}$) and variance (s^2) of the fork length (mm) of juvenile coho salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) during October-November and February-March. n : sample size.

Region	Year	October-November			Year	February-March		
		$\bar{x}$	s^2	n		$\bar{x}$	s^2	n
WCVI	1998	262	298	139	1999	--	--	--
	1999	289	385	75	2000	--	--	--
	2000	282	549	105	2001	331	935	163
	2001	283	608	53	2002	319	718	143
	2002	303	479	125	2003	317	686	69
	2003	279	794	130	2004	309	867	92
	2004	307	485	191	2005	335	1279	42
	2005	233	1496	19	2006	336	836	41
	2006	318	1009	91	2007	342	1309	307
	2007	309	1154	85	2008	--	--	--
SEAK	1998	324	399	49	1999	--	--	--
	1999	298	417	92	2000	--	--	--
	2000	308	585	110	2001	--	--	--
	2001	301	697	101	2002	--	--	--
	2002	318	691	64	2003	330	--	1
	2003	303	483	115	2004	--	--	--
	2004	331	715	60	2005	--	--	--
	2005	343	1119	85	2006	407	479	9
	2006	333	1062	17	2007	--	--	--
	2007	296	772	118	2008	--	--	--

Table 10. Mean ($\bar{x}$) and variance (s^2) of the fork length (mm) of marked and unmarked juvenile Chinook and coho salmon caught off the west coast of Vancouver Island during June-July. n : sample size.

Species	Year	Marked			Year	Unmarked		
		$\bar{x}$	s^2	n		$\bar{x}$	s^2	n
Chinook	1998	182	585	11	1998	173	463	13
	1999	181	440	67	1999	175	755	41
	2000	204	292	41	2000	187	220	12
	2001	202	2345	9	2001	136	2373	18
	2002	183	173	18	2002	176	535	11
	2003	184	449	28	2003	197	1224	4
	2004	191	839	16	2004	180	2352	3
	2005	208	189	6	2005	--	--	--
	2006	191	567	65	2006	164	743	10
	2007	188	686	57	2007	203	1174	9
	2008	195	325	521	2008	185	500	165
Coho	1998	226	697	16	1998	209	199	12
	1999	212	216	89	1999	206	180	51
	2000	213	501	248	2000	196	859	186
	2001	198	505	59	2001	188	1396	107
	2002	--	--	--	2002	244	--	1
	2003	188	408	9	2003	206	1440	10
	2004	223	358	7	2004	195	443	6
	2005	207	403	14	2005	195	1955	49
	2006	197	296	186	2006	183	610	79
	2007	209	805	83	2007	206	960	167
	2008	228	881	151	2008	203	1438	180

Table 11a. Mean ($\bar{x}$) and variance (s^2) of the energy density ($\text{kJ}\cdot\text{g}^{-1}_{\text{wet}}$) of juvenile Chinook salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) during October-November and February-March. n : sample size.

Region	Year	October-November			Year	February-March		
		$\bar{x}$	s^2	n		$\bar{x}$	s^2	n
WCVI	1998	4.30	0.09	71	1999	--	--	--
	1999	4.68	0.24	117	2000	--	--	--
	2000	3.98	0.04	9	2001	4.38	0.22	28
	2001	3.91	0.10	19	2002	4.40	0.21	33
	2002	4.35	0.19	59	2003	4.26	0.22	30
	2003	4.48	0.15	55	2004	4.53	0.23	63
	2004	4.62	0.20	50	2005	4.11	0.21	63
	2005	4.22	0.07	190	2006	4.29	0.11	127
	2006	4.37	0.24	297	2007	4.20	0.28	302
	2007	3.88	0.16	322	2008	4.45	0.22	151
SEAK	1998	--	--	--	1999	--	--	--
	1999	--	--	--	2000	--	--	--
	2000	5.23	0.38	32	2001	4.77	0.26	30
	2001	4.91	0.27	20	2002	4.84	0.09	25
	2002	5.31	0.28	51	2003	--	--	--
	2003	4.77	0.25	34	2004	4.77	0.23	86
	2004	5.20	0.43	53	2005	4.57	0.22	56
	2005	4.78	0.22	110	2006	4.84	0.17	67
	2006	5.12	0.37	146	2007	4.61	0.25	81
	2007	4.87	0.37	160	2008	--	--	--

Table 11b. Mean ($\bar{x}$) and variance (s^2) of the energy density ($\text{kJ}\cdot\text{g}^{-1}_{\text{wet}}$) of juvenile coho salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) during October-November and February-March. n : sample size.

Region	Year	October-November			Year	February-March		
		$\bar{x}$	s^2	n		$\bar{x}$	s^2	n
WCVI	1998	4.47	0.11	101	1999	--	--	--
	1999	5.11	0.16	76	2000	--	--	--
	2000	4.82	0.36	36	2001	4.51	0.21	27
	2001	4.94	0.66	13	2002	4.31	0.10	29
	2002	5.28	0.41	38	2003	4.70	0.27	28
	2003	5.22	0.73	61	2004	4.92	0.19	48
	2004	4.94	0.30	59	2005	4.59	0.17	42
	2005	4.91	0.45	19	2006	4.77	0.12	36
	2006	5.94	0.45	85	2007	4.44	0.14	121
	2007	5.07	0.37	137	2008	--	--	--
SEAK	1998	5.32	0.23	62	1999	--	--	--
	1999	4.94	0.23	89	2000	--	--	--
	2000	5.47	0.56	110	2001	--	--	--
	2001	5.28	0.45	99	2002	--	--	--
	2002	5.55	0.56	42	2003	--	--	--
	2003	5.43	0.30	96	2004	--	--	--
	2004	5.11	0.34	59	2005	--	--	--
	2005	5.83	0.57	50	2006	--	--	--
	2006	6.23	0.35	17	2007	--	--	--
	2007	5.48	0.64	32	2008	--	--	--

11. FIGURES

Figure 1. Locations of the stations surveyed by the *Canada-USA Salmon Shelf Survival Study* in FY05-FY08.

Figure 2. Distribution of juvenile Chinook salmon caught in British Columbia and southeast Alaska during fall (October-November), winter (February-March), and summer (June-July) of the 2005, 2006, 2007, and 2008 BPA fiscal years. The summer catches represent only Columbia River Chinook salmon (based on DNA). Juvenile salmon were caught using a rope trawl towed at the surface for 30 minutes at 5 knots. Except for a few stations, sampling effort was limited to the continental shelf, as previous surveys indicated that juvenile salmon were restricted to the continental shelf at this time of year.

Figure 3. Distribution of juvenile coho salmon caught in British Columbia and southeast Alaska during fall (October-November), winter (February-March), and summer (June-July) of the 2005, 2006, 2007, and 2008 BPA fiscal years. Juvenile salmon were caught using a rope trawl towed at the surface for 30 minutes at 5 knots. Except for a few stations, sampling effort was limited to the continental shelf, as previous surveys indicated that juvenile salmon were restricted to the continental shelf at this time of year.

Figure 4. Distribution of juvenile sockeye salmon caught in British Columbia and southeast Alaska during fall (October-November), winter (February-March), and summer (June-July) of the 2005, 2006, 2007, and 2008 BPA fiscal years. Juvenile salmon were caught using a rope trawl towed at the surface for 30 minutes at 5 knots. Except for a few stations, sampling effort was limited to the continental shelf, as previous surveys indicated that juvenile salmon were restricted to the continental shelf at this time of year.

Figure 5. Catch-per-unit-effort (CPUE) of juvenile chum, sockeye, coho and Chinook salmon on the continental shelf off the west coast of Vancouver Island in June-July 1998-2008. Average CPUE and 95% confidence intervals were obtained by bootstrap.

Figure 6. Proportion of marked juvenile Chinook and coho salmon on the continental shelf off the west coast of Vancouver Island in June-July and October-November.

Figure 7. Stock composition of juvenile Chinook salmon caught off southern British Columbia (49-51°N) and off northern British Columbia and southeast Alaska (54-58°N) in July-August, October-November, and February-March 1998-2008 determined using microsatellite DNA. Upper Columbia River and Snake River spring Chinook salmon represented approximately 20% and 50%, of the Columbia River juvenile Chinook salmon caught during summer surveys, respectively.

Figure 8. Spring (May to Mid-June) and summer (Mid-June to August) distribution of juvenile sockeye salmon originating from the Columbia River Basin determined from coded-wire tag recoveries and DNA analyses.

Figure 9. Sea surface temperature (SST, °C) measured during winter (Feb-Mar), spring-summer (Jun-Jul), and fall (Oct-Nov) in 2001-2008 off the west coast of Vancouver Island and Southeast Alaska. The blue bars are for the inlets and inside waters, while the purple bars are for the continental shelf waters. SST could not be recovered from the CTD cast performed in June 2002 due to equipment failure. Furthermore, no data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2·SE.

Figure 10. Nitrate concentration (mg · L⁻¹) measured at the surface during winter (Feb-Mar), spring-summer (Jun-Jul), and fall (Oct-Nov) in 2001-2008 off the west coast of Vancouver Island and Southeast Alaska. The blue bars are for the inlets and inside waters, while the purple bars are for the continental shelf waters. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2·SE.

Figure 11. Mixed-layer depth (m) measured during winter (Feb-Mar), spring-summer (Jun-Jul), and fall (Oct-Nov) in 2001-2008 off the west coast of Vancouver Island and Southeast Alaska. The blue bars are for the inlets and inside waters, while the purple bars are for the continental shelf waters. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2*SE.

Figure 12. Chlorophyll a concentration ($\text{mg} \cdot \text{L}^{-1}$) measured at the surface during winter (Feb-Mar), spring-summer (Jun-Jul), and fall (Oct-Nov) in 2001-2008 off the west coast of Vancouver Island and Southeast Alaska. The blue bars are for the inlets and inside waters, while the purple bars are for the continental shelf waters. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are $2 \cdot SE$.

Figure 13. Zooplankton biomass ($\text{g}_{\text{dry}}/1000 \text{ m}^3$) measured during winter (Feb-Mar), spring-summer (Jun-Jul), and fall (Oct-Nov) in 2001-2008 off the west coast of Vancouver Island and Southeast Alaska. The blue bars are for the inlets and inside waters, while the purple bars are for the continental shelf waters. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2-SE.

Figure 14. Relationship between sea surface temperature (SST), nitrate concentration, phytoplankton biomass (chlorophyll a), and zooplankton biomass collected on the continental shelf off the west coast of Vancouver Island and southeast Alaska in 2001-2008. The green squares represent the values measured in FY08.

Figure 15. 1979-2008 time series of zooplankton biomass anomalies along the southern Vancouver Island continental margin for three copepod species groups, pteropods, two euphasiids groups. Boreal shelf and Southern copepods had near-mirror-image anomaly patterns ($r=-0.57$). During the warm 1992-1998 interval, the boreal shelf species had much lower-than-average biomass and abundance, while the southern species had strong positive anomalies. The signs reversed briefly 1999-2002, but have subsequently returned to the mid 1990s patterns. No sampling was done in 1982 and 1984. Modified from Mackas et al. (2009).

Figure 16. C:N ratio measured in two size-classes of zooplankton during spring-summer (Jun-Jul) and fall (Oct-Nov) off the west coast of Vancouver Island and Southeast Alaska. The blue circles are for 0.25-1.0 mm zooplankton and the red squares are for 1.0-1.7 mm zooplankton. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2-SE.

Figure 17. Average copepod diversity (Shannon-Weaver Diversity Index) determined on the zooplankton community collected on three standard transects during summer and fall 1998-2008: Estevan Point (49°15'N), Triangle Island (51°N), and Hecate Strait (52°20'N). The error bars are 2·SE.

Figure 18. Zooplankton biomass anomalies along the southern Vancouver Island continental margin for three copepod species groups and euphausiids in relation to the carbon to nitrogen ratio measured in small zooplankton (0.25-1.7 mm) during spring-summer (Jun-Jul). The C:N ratio obtained in 2000 was excluded from the analysis, as it was based on a single value, while it was averaged over five values for all the other years.

Figure 19. Diet composition by major prey categories of juvenile coho salmon from the west coast of Vancouver Island and southeast Alaska in June-August, October-November, and February-March 1999-2006.

Figure 20. Diet composition by major prey categories of juvenile Chinook salmon from the west coast of Vancouver Island and southeast Alaska in June-August, October-November, and February-March 1999-2006. Legend as in Figure 19.

Figure 21. $\delta^{13}\text{C}$ measured in two size-classes of zooplankton during spring-summer (Jun-Jul) and fall (Oct-Nov) off the west coast of Vancouver Island and Southeast Alaska. The blue circles are for 0.25-1.0 mm zooplankton and the red squares are for 1.0-1.7 mm zooplankton. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2·SE.

Figure 22. $\delta^{15}\text{N}$ measured in two size-classes of zooplankton during spring-summer (Jun-Jul) and fall (Oct-Nov) off the west coast of Vancouver Island and Southeast Alaska. The blue circles are for 0.25-1.0 mm zooplankton and the red squares are for 1.0-1.7 mm zooplankton. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2-SE.

Figure 23. $\delta^{13}\text{C}$ measured in juvenile Chinook and coho salmon during and fall (Oct-Nov) in the inlets/straits (blue circles) and open shelf (red squares) off the west coast of Vancouver Island and Southeast Alaska. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2·SE.

Figure 24. $\delta^{15}\text{N}$ measured in juvenile Chinook and coho salmon during fall (Oct-Nov) in the inlets/straits (blue circles) and open shelf (red squares) off the west coast of Vancouver Island and Southeast Alaska. No data were collected in southeast Alaska during June 2003, as the ship broke down before reaching these areas. The error bars are 2·SE.

Figure 25. Average fork length of marked and unmarked juvenile Chinook and coho salmon caught on the continental shelf off the west coast of Vancouver Island in June-July 1998-2008. The error bars are 2·SE.

Figure 26. Average fork length of juvenile Chinook salmon caught off the west coast of Vancouver Island and Southeast Alaska in October-November and February-March 1998-2008. The error bars are 2·SE.

Figure 27. Average fork length of juvenile coho salmon caught off the west coast of Vancouver Island and Southeast Alaska in October-November and February-March 1998-2008. The error bars are 2·SE.

Figure 28. Average energy density of juvenile Chinook salmon caught off the west coast of Vancouver Island and Southeast Alaska in October-November and February-March 1998-2008. The error bars are 2·SE.

Figure 29. Average energy density of juvenile coho salmon caught off the west coast of Vancouver Island and Southeast Alaska in October-November and February-March 1998-2008. The error bars are 2*SE.

Figure 30. Growth rates (mm/d) of juvenile Chinook salmon coho salmon caught off the west coast of Vancouver Island (red squares) and in southeast Alaska (blue circles) in 1998-2007. The error bars represent 2·SE.

Figure 31. Relationship between juvenile Chinook and coho salmon growth caught off the west coast of Vancouver Island (red squares) and in southeast Alaska (blue circles) in 1998-2007. The two outliers correspond to the two lowest growth rates observed in juvenile coho salmon and were excluded from the regression analysis. Both outliers were associated with exceptionally warm water conditions off the west coast of Vancouver Island.

Figure 32. Food consumption rates (% body weight·d⁻¹) of juvenile Chinook salmon coho salmon caught off the west coast of Vancouver Island (red squares) and in southeast Alaska (blue circles) in 1998-2006. The error bars represent 2·SE, and were estimated using Monte Carlo simulations.

Figure 33. Relationship between growth rates and food consumption rates of juvenile salmon coho salmon caught off the west coast of Vancouver Island and in southeast Alaska in 1998-2006.

Figure 34. Growth rates and growth residuals of coho salmon off the west coast of Vancouver Island (WCVI) in relation to juvenile coho salmon growth, boreal copepod anomaly, and the carbon to nitrogen (C:N) ratio in small zooplankton off WCVI. Growth residuals were estimated as the difference between observed and predicted growth from consumption rates using the equation presented in Fig. 33. The C:N ratio obtained in 2000 was excluded from the analysis, as it was based on a single value, while it was averaged over five values for all the other years.

Figure 35. Relationship between the apparent winter growth (mean winter size minus mean fall size) and fall size in juvenile Chinook salmon (CK) and coho salmon (CO) caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) in 2000-2007.

Figure 36. Ratio of mean winter fork length (mm) to mean fall fork length (mm) in juvenile Chinook salmon and coho salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) in 2000-2008. We subtracted one from each ratio. Positive values of the ratio indicate that juvenile salmon are larger at the end of winter compared to those caught during fall. No juvenile salmon were collected in Southeast Alaska during the 2003 winter survey due to an engine failure.

Figure 37. Ratio of the variance winter fork length (mm) to the variance of fall fork length (mm) in juvenile Chinook salmon and coho salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) in 2000-2008. We subtracted one from each ratio. Positive values of the ratio indicate that the variance of winter size is larger than the variance of fall size. No juvenile salmon were collected in Southeast Alaska during the 2003 winter survey due to an engine failure.

Figure 38. Slopes of the relationship between the percentiles of winter fork length as a function of the percentiles of fall fork length for juvenile Chinook salmon and coho salmon caught off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) in 2000-2008. We subtracted one from each slope. Negative values indicate size-selective mortality against smaller fish. No juvenile salmon were collected in Southeast Alaska during the 2003 winter survey due to an engine failure.

Figure 39. Differences in the slope of the relationship between energy density ($\text{kJ}\cdot\text{g}^{-1}_{\text{wet}}$) and weight (g) of juvenile Chinook and coho salmon caught during fall and winter off the west coast of Vancouver Island (WCVI) and Southeast Alaska (SEAK) in 2000-2008. Positive values indicate that smaller fish deplete their energy reserves faster than larger fish. The error bars are $2\cdot\text{SE}$.

Figure 40. Marine survival of west coast of Vancouver Island (WCVI) and OPI coho salmon in relation to juvenile coho salmon growth, boreal copepod anomaly, and the carbon to nitrogen (C:N) ratio in small zooplankton off WCVI. The C:N ratio obtained in 2000 was excluded from the analysis, as it was based on a single value, while it was averaged over five values for all the other years.

Figure 41. Number of adult Chinook and coho salmon returning to the Bonneville Dam in relation to juvenile coho salmon growth, boreal copepod anomaly, and the carbon to nitrogen (C:N) ratio in small zooplankton off WCVI. Adult counts were offset by two years for Chinook salmon, as Columbia River Chinook spend 2-3 years at sea before maturing, and by one year for coho salmon. The C:N ratio obtained in 2000 was excluded from the analysis, as it was based on a single value, while it was averaged over five values for all the other years. The blue circle and the green square represent the forecast for the 2007 and 2008 smolt year respectively.

Figure 42. Marine survival of Chinook salmon returning to the Bonneville Dam and OPI coho salmon in relation to juvenile coho salmon growth, boreal copepod anomaly, and the carbon to nitrogen (C:N) ratio in small zooplankton off WCVI. Adult counts were offset by two years for Chinook salmon, as Columbia River Chinook spend 2-3 years at sea before maturing, and by one year for coho salmon. The C:N ratio obtained in 2000 was excluded from the analysis, as it was based on a single value, while it was averaged over five values for all the other years. The blue circle and the green square represent the forecast for the 2007 and 2008 smolt year respectively.

12. APPENDICES

Appendix A. Recovery location of ocean age-0 coded-wire tagged juvenile Chinook salmon released from the Columbia River. CEAK: Central Alaska; SEAK: Southeast Alaska; NBC: Northern British Columbia; CEBC: Central British Columbia; WCVI: West Coast of Vancouver Island; WA: Washington Coast; OR: Oregon Coast.

Stock	Recovery location						
	CEAK	SEAK	CEBC	WCVI [‡]	WA	CR	OR
Lower Columbia River Spring-Summer runs							
Cowlitz River (46°15')							
Cowlitz River* (46°15')				8	24	16	22
Kalama River* (46°04')		2		1	2	4	2
Lewis River* (45°54')		2	5	5	9	7	1
Lower Columbia River Fall runs							
Toutle River (46°22')							
Elochoman River (46°16')						1	
Cowlitz River (46°15')						1	
Columbia River (46°14')							
Big Creek (46°09')					7		
Abernathy Creek (45°57')							1
Lewis River (45°54')				1			
Spring Creek (45°44')				1	12		
Willamette River Spring-Summer runs							
Sandy River* (45°24')				1			
Clackamas River - Early (45°20')				1			
Clackamas River - Early* (45°20')	1	2	2	6	5	7	1
Clackamas River - Late* (45°20')					2	6	2
Santiam River (44°59')				1			
Santiam River* (44°59')	2	2	3	7	10	7	2
McKenzie River (44°51')				1			
McKenzie River* (44°51')	2	1		5	11	3	1
Willamette River (44°32')				1			
Willamette River* (44°32')		1		21	9	2	1
Willamette River Fall runs							
Santiam River (44°59')			1				
Central Columbia River Spring runs							
Carson River* (45°55')		1	2				
Umatilla River* (45°55')				1		1	
Nehalem River* (45°55')						1	1
Klickitat River (45°47')				1			
Klickitat River* (45°47')				1	3	1	1
Little White Salmon River* (45°46')		1		3	3		
Hood River* (45°36')		1	2	4	1	4	
Warm Springs* (44°52')		2	1	2	5	3	
Round Bute Hatchery* (44°52')					1	2	
Deschutes River* (44°47')	1	2	2	4	12	7	

Stock	Recovery location						
	CEAK	SEAK	CEBC	WCVI [‡]	WA	CR	OR
Central Columbia River Summer-Fall runs							
Mid Columbia River (46°42')					1		2
Bonneville Pool (46°02')					2	2	1
Nehalem River (45°55')					1		
Umatilla River (45°55')					7		
Umatilla River* (45°55')					1		
Little White Salmon River (45°46')					2		
Upper Columbia River Spring runs							
Chewuch River* (48°32')				2	1		1
Twisp River* (48°26')				2		1	
Methow River* (48°18')		2	2	5	16	15	1
Chiwawa River* (47°47')		3	4	13	10	5	
Entiat River* (47°42')				1	1	3	
Leavonworth Hatchery* (47°35')			2	9	14	14	
Yakima River* (47°14')			1	3	3	1	
Priest Rapids (45°58')			2				
Wind River* (45°42')	1	1	3	8	3	2	1
Upper Columbia River Summer-Fall runs							
Methow River* (48°18')		1	8	42	55	20	2
Wells Hatchery (47°52')					3	5	2
Wells Hatchery* (47°52')		1	7	40	92	36	8
Wenatchee River* (47°27')			4	50	77	29	6
Hanford Reach (46°40')							
Priest Rapids (45°58')				1	3	6	3
Washington Brights (45°55')					14	3	1
Upper Columbia River (45°51')			1		1	3	6
Upper Columbia River* (45°51')							
Snake River Spring-Summer runs							
Dworshak Hatchery* (46°30')	1		5	7	4	2	
Powel Rearing Ponds (46°29')					1		
Powel Rearing Ponds* (46°29')	1			1	2	3	
Tucannon River (46°29')					1		
Tucannon River* (46°29')				4		1	
Kooskia Creek* (46°08')		1	1	1	1	2	
Grande Rhonde River (46°05')							
Grande Rhonde River* (46°05')				6		2	
Clearwater River* (45°47')			1	17		2	
Rapid River* (45°41')		1	6	13	11	17	
Lostine River* (45°34')				6		1	
Imnaha River* (45°25')		3	1	7	1	3	
Catherine Creek* (45°17')			1			1	
Salmon River* (45°15')	1	1	4	20	4	6	
Johnson Creek* (44°58')						1	

Pahsimeroi Channel* (44°41')			10	1	1		
Stock	Recovery location						
	CEAK	SEAK	CEBC	WCVI*	WA	CR	OR
Snake River Fall runs							
Snake River - Lower River (46°22')				1	1	1	1
Snake River - Lower River* (46°22')			3	43	21	18	14
Lyons Ferry Hatchery (46°04')					15	7	1
Lyons Ferry Hatchery* (46°04')				13	21	20	18
Snake River (45°52')				1	3		
Snake River - Mixed Stocks (45°52')					1		1

*Include Juan de Fuca Strait and Queen Charlotte Strait

*Released as yearling

Appendix B. Recovery location of ocean age-1 coded-wire tagged juvenile Chinook salmon released from the Columbia River. CEAK: Central Alaska; SEAK: Southeast Alaska; NBC: Northern British Columbia; CEBC: Central British Columbia; WCVI: West Coast of Vancouver Island; WA: Washington Coast; OR: Oregon Coast.

Stock	Recovery location						
	CEAK	SEAK	CEBC	WCVI [†]	WA	CR	OR
Lower Columbia River Spring-Summer runs							
Cowlitz River (46°15')					2	1	2
Cowlitz River* (46°15')						1	
Kalama River* (46°04')				1			
Lewis River* (45°54')							
Lower Columbia River Fall runs							
Toutle River (46°22')				1			
Elochoman River (46°16')	1						
Cowlitz River (46°15')							
Columbia River (46°14')				1			
Big Creek (46°09')				2			
Abernathy Creek (45°57')				1			
Lewis River (45°54')							
Spring Creek (45°44')				1	2	1	
Willamette River Spring-Summer runs							
Sandy River* (45°24')							
Clackamas River - Early (45°20')							
Clackamas River - Early* (45°20')							
Clackamas River - Late* (45°20')							
Santiam River (44°59')							
Santiam River* (44°59')							
McKenzie River (44°51')				2	1		
McKenzie River* (44°51')	1						
Willamette River (44°32')	1						
Willamette River* (44°32')							
Willamette River Fall runs							
Santiam River (44°59')							
Central Columbia River Spring runs							
Carson River* (45°55')							
Umatilla River* (45°55')							
Nehalem River* (45°55')							
Klickitat River (45°47')							
Klickitat River* (45°47')							
Little White Salmon River* (45°46')							
Hood River* (45°36')							
Warm Springs* (44°52')							
Round Bute Hatchery* (44°52')							
Deschutes River* (44°47')							

Stock	Recovery location						
	CEAK	SEAK	CEBC	WCVI [‡]	WA	CR	OR
Central Columbia River Summer-Fall runs							
Mid Columbia River (46°42')				1			
Bonneville Pool (46°02')							
Nehalem River (45°55')							
Umatilla River (45°55')							
Umatilla River* (45°55')							
Little White Salmon River (45°46')							
Upper Columbia River Spring runs							
Chewuch River* (48°32')							
Twisp River* (48°26')							
Methow River* (48°18')	1			1			
Chiwawa River* (47°47')							
Entiat River* (47°42')							
Leavonworth Hatchery* (47°35')							
Yakima River* (47°14')							
Priest Rapids (45°58')							
Wind River* (45°42')							
Upper Columbia River Summer-Fall runs							
Methow River* (48°18')				1			
Wells Hatchery (47°52')				2	1		
Wells Hatchery* (47°52')		1		11			
Wenatchee River* (47°27')				5			
Hanford Reach (46°40')			1				
Priest Rapids (45°58')				1			
Washington Brights (45°55')					1		
Upper Columbia River (45°51')				1	1		
Upper Columbia River* (45°51')				1			
Snake River Spring-Summer runs							
Dworshak Hatchery* (46°30')							
Powel Rearing Ponds (46°29')						1	
Powel Rearing Ponds* (46°29')							
Tucannon River (46°29')							
Tucannon River* (46°29')							
Kooskia Creek* (46°08')							
Grande Rhonde River (46°05')			1				
Grande Rhonde River* (46°05')							
Clearwater River* (45°47')							
Rapid River* (45°41')							
Lostine River* (45°34')							
Imnaha River* (45°25')							
Catherine Creek* (45°17')				2			
Salmon River* (45°15')						1	
Johnson Creek* (44°58')							
Pahsimeroi Channel* (44°41')							

Stock	Recovery location						
	CEAK	SEAK	CEBC	WCVI [‡]	WA	CR	OR
	Snake River Fall runs						
Snake River - Lower River (46°22')							
Snake River - Lower River* (46°22')				9			
Lyons Ferry Hatchery (46°04')				1	1		
Lyons Ferry Hatchery* (46°04')				8			
Snake River (45°52')				1			
Snake River - Mixed Stocks (45°52')							

[‡]Include Juan de Fuca Strait and Queen Charlotte Strait

*Released as yearling

Appendix C. Number of Chinook and coho salmon smolts released in the Columbia River Basin between 1998 and 2008 used to estimate the marine survival of the salmon returning to the Bonneville Dam. Data compiled from the Regional Mark Processing Center (<http://www.rmpec.org/>).

Release year	Above Bonneville	Below Bonneville	Total
Subyearling Chinook salmon			
1998	41,230,587	37,935,405	79,165,992
1999	34,789,282	25,157,014	59,946,296
2000	38,908,060	26,855,488	65,763,548
2001	33,795,987	29,314,473	63,110,460
2002	41,794,115	32,627,049	74,421,164
2003	39,870,977	33,443,621	73,314,598
2004	35,743,238	26,683,218	62,426,456
2005	36,326,710	31,385,443	67,712,153
2006	33,941,877	30,420,830	64,362,707
2007	30,635,613	30,781,581	61,417,194
2008*	9,817,233	27,081,733	36,898,966
Total*	376,853,679	331,685,855	708,839,543
Yearling Chinook salmon			
1998	15,955,660	7,537,013	23,492,673
1999	21,885,757	8,611,968	30,497,725
2000	23,687,714	7,770,305	31,458,019
2001	17,488,349	8,150,674	25,639,023
2002	24,042,140	7,781,327	31,823,467
2003	23,797,563	8,158,745	31,956,308
2004	23,112,452	9,298,507	32,410,959
2005	23,068,708	9,309,455	32,378,163
2006	24,889,437	8,137,131	33,026,568
2007	20,258,447	7,905,128	28,163,575
2008*	14,597,087	7,078,528	21,675,615
Total*	232,783,314	89,738,781	322,522,095
Coho salmon			
1998	9,167,170	20,687,751	29,854,921
1999	9,378,699	24,799,540	34,178,209
2000	9,585,964	21,161,091	30,747,055
2001	8,961,613	17,946,893	26,878,506
2002	8,426,377	16,456,414	24,882,791
2003	7,428,785	15,485,017	22,913,802
2004	7,488,491	14,811,657	22,300,148
2005	6,695,033	12,772,297	19,467,330
2006	6,883,359	12,828,839	19,712,198
2007	5,764,671	14,029,365	19,794,036
2008	5,648,576	12,792,365	18,440,941
Total	85,428,738	183,741,199	269,169,937

*Incomplete record