

AN ABSTRACT OF THE DISSERTATION OF

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Title: Sandy Beach Surf Zones: What is their Role in the Early Life History of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*)?

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Early life stages of many marine and diadromous fish species use sandy beach surf zones, which occur along >50% of the world's marine coastlines. This extensive habitat can provide juvenile fishes with an abundant supply of potential prey and the ability to hide from predators in its shallow turbid waters. Chinook salmon is an anadromous species that migrates to the ocean during their first (subyearlings) or second (yearlings) year of life. The majority of subyearlings reside in estuaries during their first summer season; however, a small number of juveniles also use surf zones. Early marine residence is considered a critical period for Chinook salmon due to high mortality rates; however the role of surf zones in Chinook salmon life history is unclear. Therefore, I determined the distribution of juvenile Chinook salmon on beaches of the eastern North Pacific, compared the migration and growth patterns observed in surf zones and estuaries, identified the factors that accounted for variation in juvenile surf zone catch, explored the factors

that influence growth rate variation in surf zones and estuaries, and modeled how growth rates in these coastal habitats may vary in the near future with predicted changes in climate.

The majority (94%) of juveniles were caught in surf zones adjacent to estuaries with trough areas, which are beach sections where sand moved by currents and waves produce a trench-like shape. Surf zone fish were collected in significantly lower numbers than estuarine juveniles but entered brackish/ocean waters at similar sizes. Juveniles in surf zones consumed similar organisms (gammarid amphipods, crustacean larvae and insects) as in estuaries. Furthermore, stomach fullness indices (average = 2% of body weight) and growth rates (average = 0.4 mm day^{-1}) were similar in surf zones and estuaries. At one surf zone, juvenile catch was positively correlated to short-term specific growth rates (14 days prior to capture). A bioenergetics modeling approach indicated that given current conditions, consumption rates accounted for more of the variation in growth than prey energetic content and temperature. Climate models predict future increases in fresh water temperature (1.5 to 5.8°C), sea surface temperature (1.2°C) and wave height (0.75 m) that could influence estuarine and surf zone use. Therefore, I developed a local mixing model based on these predictions to estimate future surf zone and estuarine water temperatures in two of the watersheds studied. Based on these temperature projections and the bioenergetics model, I predicted how juvenile specific growth rates would vary in both habitats. I determined that increases in water temperature in both habitats would reduce specific growth rates by 9 to 40% in surf zones and

estuaries if diet composition and consumption rates remain similar to present conditions. To compensate for the decline in growth, juveniles may increase their consumption rates or consume more energetically rich prey, if available. If they are not able to compensate, their size at the end of the season may be reduced, which could reduce their overall survival. These results confirm that a small number of suyearling Chinook salmon use sandy beach surf zones, mostly adjacent to estuary mouths, where they experience growth conditions comparable to estuaries. My findings indicate that, in certain situations, juvenile Chinook salmon surf zone use can be influenced by surf zone growth conditions, while variation in growth rates are themselves most strongly influenced by variation in consumption rates in surf zones and estuaries. Predicted changes in coastal western North American climate will likely modify juvenile growth conditions in the next 50 years, and potentially reduce overall survival. Additional insights into the potential impacts of climate change on juvenile salmon will require estimates of changes in the composition, energetic quality and abundance of prey communities inhabiting coastal environments.

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Sandy Beach Surf Zones: What is their Role in the Early Life History of Juvenile
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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Jose R. Marin Jarrin, Author

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CONTRIBUTION OF AUTHORS

Dr. Miller was involved in the project development, data collection and analysis, and writing of Chapters 2, 3 and 4. David Teel aided with the analysis of genetic region of origin and writing Chapter 2. Dr. David Noakes, Dr. Robert Emmett and Dan Bottom provided guidance in the development of Chapters 2, 3 and 4.

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CHAPTER 1: INTRODUCTION

Sandy beach surf zones are semi-enclosed environments (McLachlan 1980a) and have been well studied around the world, e.g. Belgium, Brazil, The Netherlands, and South Africa (McLachlan and Brown 2006). These studies have found the surf zone fish community to be composed mostly of larvae and juveniles, which may be using the area as a habitat or as a migratory path to other habitats (McLachlan and Brown 2006). Potential benefits associated with surf zone residence include an abundant supply of potential prey and refuge from predators in its shallow turbid waters. Other factors found to positively influence fish abundance and species richness on sandy beach surf zones include the presence of estuaries or river mouths, structure within surf zones, greater abundance of detached macrophytes, and water temperature appropriate for relatively high growth rates (Allen and Pondella II 2006; McLachlan and Brown 2006).

Sandy beaches are categorized into reflective, dissipative (both opposite extremes) and intermediate beaches based on physical characteristics such as their sand grain size, beach slope and tidal range (Short and Wright 1983). Reflective beaches are those where sediment is coarse, tidal excursion is small, slope is steep, and the energy of the wave is reflected (McLachlan and Brown 2006). Dissipative beaches are the complete opposite, sediment particle size is fine, the tidal excursion is large, and the beach slope is flat allowing the wave energy to be consumed in the surf zone before reaching the beach. Differences in beach physical characteristics may also influence the species composition of the different communities that inhabit

this environment (McLachlan 1980b; McLachlan and Dorvlo 2005). Reflective beach communities, which include burrowing macrofauna (polychaetes and crustaceans) and meiofauna (nematodes), can be characterized by low species richness. Dissipative beaches usually have communities with relatively high species richness, which include zooplankton and fish species besides macro and meiofauna (McLachlan and Brown 2006).

Sandy beaches comprise over 50% of the world's marine coastlines (McLachlan and Brown 2006). In Washington and Oregon, sandy beaches comprise over 60% of the marine coastline (Komar 1997; Don et al. 2006). Coastlines in Oregon and Washington are divided into littoral cells, which are stretches of sandy beach bordered by rocky headlands. These headlands act as boundaries for the water circulation cells (i.e. littoral cells) that form within them and restrict transfer of sediment to offshore regions or to other cells (Komar 1997). Washington and Oregon beaches experience mixed semidiurnal tides, with a mean of 2 m and maximum daily amplitude of 3.6 m. Wave action is extreme during the winter (average wave height: 3-4 m) and moderate in the summer (average wave height: 1-2 m) when sand accretion may transform dissipative into intermediate beaches (Komar et al. 1976). This accretion produces sand bars that propagate shoreward during summer. Eventually, the sand bars develop finger-like structures that weld to the shoreline producing sheltered trough areas (hereafter referred to as "troughs") and adjacent flat surf areas where the topography was not affected by sand bars (referred to as "flat areas"), before completely fusing with the beach shoreline (Short and Wright 1983;

Alexander and Holman 2004; Ruggiero et al. 2005). Higher fish abundances and species richness have been observed in trough waters when compared to flat areas, potentially due to the differences in wave conditions and water circulation produced by these sand bars (Harvey 1998; Watt-Pringle and Strydom 2003; Janssen et al. 2008).

Anadromous fish species are common in many temperate areas potentially due to the high productivity of the surrounding oceans where juveniles and pre-spawning adults can experience enhanced growth rates (McDowall 1988; Bertness et al. 2001). During their ontogenetic migrations, anadromous fish encounter a suite or portfolio of habitats in which they may encounter different foraging and growth opportunities (Healey and Prince 1995; Hilborn et al. 2003; Fodrie et al. 2009; Schindler et al. 2010; Fulford et al. 2011; Dantas et al. 2012; Schein et al. 2012). Diversity in habitat use may spread the risk of mortality among individuals by reducing the risk of a catastrophic event eliminating the whole cohort (Hilborn et al. 2003; Secor 2007; Schindler et al. 2010).

Chinook salmon (*Oncorhynchus tshawytscha*) is an anadromous fish species that spawns in most river systems of western North America (Healey 1991). The majority of juveniles initiate their migration to the ocean during their first or second year of life during which they are termed subyearlings or yearlings, respectively (Healey 1983). Subyearling Chinook salmon reside in their natal rivers for several weeks to months prior to migrating to estuaries during their first spring, summer or

fall of life (Healey 1991). During this early life stage, estuaries are considered a nursery habitat for subyearling Chinook salmon due to the potential for enhanced growth, refugia from predation and physiological acclimation to marine waters (reviewed in Simenstad et al. 1982; Bottom et al. 2005). Exceptions to estuaries serving as nurseries to juvenile Chinook salmon are in river systems with small or non developed estuaries (e.g. Rogue and Klamath rivers), where growth conditions may not be as favorable (Cramer and Lichatowich 1978). For reasons that are not yet clear, some juveniles will also reside in sandy beach surf zones before moving to deeper coastal waters (Marin Jarrin et al. 2009).

Over 25 years ago, Healey (1983) hypothesized that subyearling Chinook salmon stayed close to shore (< 5 km) when they first entered the ocean. This hypothesis has been tested repeatedly (e.g. Fisher and Pearcy 1995; Schabesberger et al. 2003; Brodeur et al. 2004), but not fully supported. Reimers (1973) collected sub-yearling Chinook salmon in the sandy beach surf zones located to the north and south of the Sixes River on the Oregon coast, however he did not further investigate. Dawley et al. (1981) caught large numbers of small fish (< 13 cm fork length, FL) in shallow marine waters just outside the surf zone, which led him to suggest that subyearlings were present in the surf zone of sandy beaches. Fisher et al. (2007), Trudel et al. (2009) and Tucker et al. (2011) sampled as close as 1 km offshore and found that smaller Chinook salmon were present closer to shore and/or at shallower depths, suggesting fish size influenced habitat distribution. These studies further support the hypothesis that surf zones are a habitat for subyearling Chinook salmon.

For juvenile salmonids, early marine residence is considered a critical period due to high potential for mortality (reviewed in Healey 1991; Pearcy 1992; Quinn 2005). Growth rates during this critical marine period can influence subsequent survival, with larger faster growing juveniles often surviving at a higher rate than smaller slower growing fish (Beamish and Mahnken 2001; Reed et al. 2010; Tomaro et al. 2012). Potential reasons for differences in mortality are that larger/faster growing fish should be less prone to predation because they can more successfully avoid predators (i.e. bigger is better hypothesis, Butler and Pickett 1988; Miller et al. 1988), fewer predators are able to ingest them (i.e. gape-limited predation hypothesis, Zaret 1980), and they remain susceptible to predation for a shorter period of time (i.e. stage-duration hypothesis, Houde 1987). Larger fish are also less prone to starvation because larger fish can more efficiently capture prey and accumulate more energy reserves that will enable them to survive the less productive winter months (i.e. Growth-mortality hypothesis, Ware 1975; Shepherd and Cushing 1980). In juvenile salmonids, growth rates are most strongly influenced by water temperature, consumption rates, and the energetic quality of their prey (Brett 1979; Wootton 1998; Trudel et al. 2002; Beauchamp et al. 2007; Beauchamp and Duffy 2011). Therefore, habitat choice for juvenile Chinook salmon during early marine residence may be influenced by growth conditions as well as predation risk.

Prior research conducted at one beach during 2006 and 2007 found that juvenile Chinook salmon were present in the surf zone during the summer where they fed on the local prey field (Marin Jarrin et al. 2009; Marin Jarrin, unpublished

data). I therefore built on these findings by evaluating the role of sandy beach surf zones for subyearling Chinook salmon. In Chapter 2, I defined juvenile Chinook salmon distribution on beaches of the western North American coast, and determined if their presence and diet were consistent among beaches and years, and between trough and flat areas. I then compared the role of sandy beach surf zones and estuaries, a known nursery habitat. Specifically, I determined their catch, migration patterns, diet and growth. I observed similar growth rates between surf zones and estuaries (Chapter 3). Therefore I determined what factors could lead juveniles to move to surf zones, studied the factors that account for variation in growth rates in surf zones and estuaries, and modeled how growth rates in these coastal habitats may vary in the near future with predicted changes in climate.

I sampled beaches across a broad geographic range that includes several distinct Chinook salmon populations (Seeb et al. 2007). I visited 11 sandy beaches along the Oregon and Washington coast, including nine beaches that were within 1 km of estuaries and three distant beaches (>15km from an estuary). These sites were chosen to represent estuary type (drowned river mouth and river dominated), different levels of human development, origin of juveniles (hatchery- and natural-origin), access and availability of samples from within the estuary (collaboration with Oregon Department of Fish and Wildlife).

Chinook salmon are an important fisheries species whose populations have declined throughout western North America over the last century (Emmett et al. 2000; Katz et al. 2012). This has led to several Chinook salmon Evolutionary

Significant Units (ESUs) being listed under the U.S. Endangered Species Act (Gustafson et al. 2007). Declining ESUs have led to an increase in research attempting to further understand the ecology of Chinook salmon, of which surf zone use is one of the many poorly studied phases. The present study is important because it will define the relative importance of surf zones for juvenile Chinook salmon that have just entered the ocean, a period which is considered critical for survival to adulthood. It will also provide a robust analysis of the potential alterations the growth rates of juveniles residing in coastal habitats may undergo in the near future due to climate change.

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CHAPTER 2

DISTRIBUTION, ABUNDANCE AND DIET OF AGE-0 CHINOOK SALMON IN
SANDY BEACH SURF ZONES

Jose R. Marin Jarrin

ABSTRACT

Early life stages of many marine and diadromous fish species use sandy beach surf zones. Chinook salmon (*Oncorhynchus tshawytscha*), an economically and ecologically important anadromous species, can use surf zones during its juvenile life stage but the extent of habitat use and feeding behavior in sandy beaches is unclear. We investigated the distribution, abundance and diet of juvenile Chinook salmon in 11 Oregon and southern Washington surf zones (USA) during 2008-2010. We collected 329 subyearling (0-age) Chinook salmon (average: 3 ± 8 SD individuals 100 m^{-2}) at 8 beaches. Subyearling fish were present in surf zones every year from late June to early September, and ranged from 5.9 to 14.4 cm fork length. The majority of these juveniles were collected at beaches adjacent to estuary mouths, and genetic stock identification and coded wire tag data indicated that the majority of juveniles had exited from those adjacent estuaries. Juvenile salmon were collected in significantly greater numbers within trough areas, which are beach sections where sand moved by currents and waves produces a trench-like shape, compared to flatter beach areas (4 ± 2 vs. 1 ± 2 ind. 100 m^{-2} , respectively). The only beach adjacent to an estuary where juveniles were not collected was also the only beach at which trough

areas did not form. Overall, stomach fullness averaged 2% ($\pm 2\%$ SD) of body weight and did not vary among beaches or years but was, on average, 25% higher for fish collected in troughs ($n = 155$) compared with flat areas ($n = 88$, $p = 0.02$). A total of 57 taxa were identified during stomach content analysis, most of which were gammarid amphipods, dipteran insects, mysids and fish. There were more insects in the stomachs of juveniles collected in troughs than in flat areas (17.8 ± 25.5 vs. 0.1 ± 0.4 individuals per stomach, respectively). These data indicate that, during summer, 0-age juvenile Chinook salmon inhabit surf zones adjacent to estuaries that present trough areas where they feed on a diverse community of invertebrate and vertebrate prey. In order to further understand the role of surf zones for juvenile salmon in the future we will make direct comparisons of abundance, growth and migration characteristics with juveniles present in estuaries, a known nursery habitat.

INTRODUCTION

Habitat use is thought to reflect a choice behavior, where animals react to a set of stimuli and select a habitat that would increase the fitness of the individual (Morin 2011). In fish ecology this theoretical concept has historical legacy (Pianka 1966; Morris 1987) and empirical support (e.g. Werner et al. 1983a, b; Fausch 1984; Grand and Dill 1997; Taylor et al. 2007). These studies have found that individuals can choose their habitat based on stimuli such as water temperature, salinity, dissolved oxygen, habitat complexity, prey availability, predation pressure or density of conspecifics (reviewed in Wootton 1998). In the case of anadromous fish, the

stimuli influencing habitat choice are difficult to study during early life history stages as the fish are migrating towards the ocean.

Chinook salmon (*Oncorhynchus tshawytscha*) is an anadromous species that spawns in most rivers of the west coast of North America north of San Francisco, California (Quinn 2005). The majority of juveniles migrates to the ocean during their first or second year of life and are referred to as subyearlings (0-age) or yearlings (1-age), respectively (Healey 1983). On the west coast of continental USA, most Chinook salmon migrate to the ocean as subyearlings (Rich 1920; Reimers 1973; Nicholas and Hankin 1988). Subyearling Chinook salmon reside in their natal rivers for several weeks to months prior to migrating to estuaries during their first spring, summer or fall of life (Healey 1991). During this early life stage, estuaries are considered a nursery habitat for subyearlings due to the potential for enhanced growth, refugia from predation and physiological acclimation to marine waters (reviewed in Simenstad et al. 1982; Bottom et al. 2005a). For reasons that are not yet clear, after using estuaries, some juveniles can also use sandy beach surf zones for an unknown period of time, before moving to deeper coastal waters (Marin Jarrin et al. 2009).

Sandy beach surf zones are semi-enclosed environments that extend from the shoreline to the outermost breakers. These environments are inhabited by a fish community mostly composed of larvae and juveniles (reviewed in McLachlan and Brown 2006). Possible reasons for surf zone residence include an abundant supply of

potential prey and, due to the turbid shallow waters, shelter from predators. Other factors found to positively influence fish abundance and species richness on sandy beach surf zones include the presence of estuaries or river mouths, structure within surf zones, greater abundance of detached macrophytes, and water temperature appropriate for relatively high growth rates (Allen and Pondella II 2006; McLachlan and Brown 2006).

Very little is known about the role of sandy beach surf zones as a habitat for juvenile Chinook salmon. Recently, Marin Jarrin et al. (2009) confirmed that subyearling (0-age) Chinook salmon can use surf zones in Oregon where they were collected at one beach during all tides, and throughout the day during summer. Juvenile Chinook salmon residence in estuaries (e.g. Healey 1980; Kjelson et al. 1982; Dawley et al. 1986; Bottom et al. 2005b) and coastal waters (e.g. Fisher and Pearcy 1995; Schabetsberger et al. 2003; Peterson et al. 2010; Tucker et al. 2011) has been more thoroughly studied than in surf zones (Marin Jarrin et al. 2009). In estuaries and coastal waters, Chinook salmon habitat use is influenced by various factors, including: water depth, with smaller juveniles present in shallower habitats than larger juveniles; habitat structure, with juveniles being more abundant in the presence of overhanging vegetation; and current speed, with individuals often selecting areas of slow moving water that are close to fast moving water (reviewed in Healey 1991; Bottom et al. 2005a; Quinn 2005).

For juvenile salmonids, early marine residence is considered a critical period due to high mortality rates (reviewed in Healey 1991; Pearcy 1992; Quinn 2005). During this critical marine period, diet composition and consumption rates may influence growth rates and potentially subsequent survival (Trudel et al. 2002; Beauchamp and Duffy 2011). Habitat choice for juvenile Chinook salmon during early marine residence may be influenced by prey quantity and quality as well as temperature and predation risk. However, very little is known about the diet of juvenile Chinook salmon in surf zones. Marin Jarrin et al. (2009) found that juveniles foraged primarily on gammarid amphipods and to a lesser degree, on insects and fish, and they exhibited a diet shift from invertebrates to fish as they increased in size. However, these observations are from collections at only one surf zone in 2006.

Sandy beaches comprise over 60% of the marine coastline in Washington and Oregon (Komar 1997; Don et al. 2006). The Oregon and Washington coastline is divided into littoral cells, which are stretches of sandy beach bordered by rocky headlands. These headlands act as boundaries for water circulation cells that form within them and restrict transfer of sediment to offshore regions or to other cells (Komar 1997). Oregon and Washington beaches experience mixed semidiurnal tides, with a mean of 2 m and maximum daily amplitude of 3.6 m. Wave action is extreme during the winter (>3m) and moderate in the summer (average wave height: 1-2 m). Smaller summer waves allow sand to accrete close to shore transforming beaches from dissipative (i.e., shallower slope) to intermediate (Komar et al. 1976). Sand accretion produces sand bars that propagate shoreward during summer. Eventually,

the sand bars develop finger-like structures that weld to the shoreline producing sheltered trough areas (hereafter referred to as “troughs”) and adjacent flat surf areas where the topography was not affected by sand bars (referred to as “flat areas”), before completely fusing with the beach shoreline (Short and Wright 1983; Alexander and Holman 2004; Ruggiero et al. 2005). In each littoral cell, one to five sand bars may form each year (average two to three), mostly during the summer season. These bars can form 100 to 1500 m offshore at water depths that vary from three to eight and a half meters, are one to three and a half meters tall, and modify water circulation and wave condition along the beach profile (Alexander and Holman 2004; Ruggiero et al. 2005). Higher fish abundances and species richness have been observed in trough waters when compared to flat areas, potentially due to the differences in wave conditions and water circulation produced by these sand bars (Harvey 1998; Watt-Pringle and Strydom 2003; Janssen et al. 2008).

Prior research conducted at one beach during 2006 found that juvenile Chinook salmon can use sandy beach surf zones throughout the summer where they feed on the resident and allocthonous prey species (Marin Jarrin et al. 2009); however it is unclear if juveniles use all sandy beaches. Therefore, we examined the distribution of juvenile Chinook salmon on sandy beaches and determined if patterns in presence and diet are similar among beaches of western North America. We determined (1) the timing and size at capture of juveniles using surf zones; whether (2) juveniles were present at all sandy beaches or only those adjacent to estuary

mouths and (3) if catch, stomach fullness and diet composition varied among beaches and years, or within beaches, i.e., between trough and flat areas.

MATERIALS AND METHODS

Study Region

This study was conducted at 11 dissipative sandy beaches (McLachlan 1980; Short and Wright 1983) located in six littoral cells in Oregon and Washington, USA (Fig. 2.1). Eight of these beaches were pairs of sites located directly to the north and south of the Columbia River, Tillamook Bay, Alsea Bay and Coos Bay. The other three beaches were randomly selected, located at least 15 km away from an estuary mouth and were termed “distant beaches”. Nine of the eleven beaches are located in littoral cells with watersheds that produce Chinook salmon, while the other two beaches are in littoral cells without Chinook-inhabited watersheds (Fig. 2.1).

Physical size, origin of juveniles, estuary type and classification based on human development of the four estuaries vary considerably and are detailed in Table 2.1.

Juvenile Collection and Analysis

A prior study conducted at a beach during 2006 found that juvenile Chinook salmon were present in the surf zone only during the summer (Marin Jarrin et al. 2009). Therefore, to determine if residence times and juvenile size in sandy beaches is similar among beaches and years we sampled from June 1 to September 30 in 2008-2010 at multiple beaches (Table 2.2) using a beach seine (1.5 m high and 15 m

wide with a 1.0-cm mesh) (see Marin Jarrin and Shanks 2011 for additional sampling details). Briefly, three people carried the net into the surf to a depth of approximately 1.5 m where the net was opened parallel to the shoreline and in a V-shape after which it was pulled to shore. Beach nomenclature indicates the proximate estuary and which side of the estuary the beach is located (e.g. Coos South). The three distant beaches are referred to as detailed in Fig. 2.1. Each year, we sampled between two and nine different beaches to determine if distribution, residence times and diet varied spatially and temporally (Table 2.2). However, our sampling design was also influenced by the results from the preceding year. In 2008, we sampled 6 beaches immediately to the north and south of Coos, Tillamook and Alsea bays, and 3 distant beaches to determine if juveniles were present at all sandy beaches or only those adjacent to estuary mouths (Table 2.2). Due to low catches at distant beaches (< 10 juveniles), we did not sample distant sites in 2009 or 2010. In 2009, we sampled beaches on only one side of Coos, Tillamook and Alsea bays to increase sample frequency. We also sampled beaches on both sides of the Columbia River, which we had not visited previously. In 2010, we sampled only two beaches (Coos and Alsea South) to further increase the temporal frequency of our sampling (Table 2.2).

We collected juveniles during lower low spring tides in the morning for safety reasons and to match the timing of collections of juveniles in estuaries for a related study. We considered this approach reasonable given that prior research observed no differences in juvenile catches among tides or times of day (Marin Jarrin 2007). Each day, we completed 4 to 6 tows with 2-3 in trough and flat areas,

respectively, wherever possible. Troughs were identified visually by variation in topography and wave height, i.e. deeper water depth and reduced wave height compared to flat areas (Short and Wright 1983).

Juvenile Chinook salmon were euthanized with MS-222 (tricaine methanesulfonate, Argent Chemical Laboratories, 150 mg l⁻¹) buffered with baking soda (sodium bicarbonate, 300 mg l⁻¹) and transported back to the laboratory on ice. All other species were identified, counted and released on site (Appendix Table 1). We retained up to three individuals of each new species for a voucher collection (Carlton 2007, Lamb and Edgell 2010). We calculated juvenile catch (individuals 100 m⁻²) by estimating the area sampled using the distance from the shoreline to the point at which the beach seine was opened and the width of the mouth of the seine when opened in a V-shape.

In the lab, juvenile Chinook salmon were measured (fork length, 0.1 cm) and weighed (0.1 g). We collected tissue samples for genetic analysis, checked for fin clips and coded wire tags (CWTs, Jefferts et al. 1963), and extracted stomachs and otoliths (data not presented). We then identified and counted stomach contents to the lowest taxonomic level possible. Stomach fullness (SF) was calculated as the percentage of juvenile body weight as follows:

$$SF = \frac{\text{Stomach content weight (g)}}{(\text{Juvenile weight (g)} - \text{Stomach content weight (g)})} \times 100$$

(1)

To determine the genetic stock of origin of each fish, we used standard genetic stock identification methods (Manel et al. 2005). Samples were processed as detailed in Teel et al. (2009) using PCR amplifications of the 13 Chinook salmon microsatellite DNA loci and a baseline of population data compiled from the Genetic Analysis of Pacific Salmonids (GAPS) consortium (Seeb et al. 2007). The baseline included data for Chinook salmon populations ranging from northern California to southern British Columbia, which allowed us to differentiate among the major genetic stocks of Chinook salmon that would potentially contribute to our samples of juveniles (Seeb et al. 2007). We only present data on individuals that were assigned to a stock with a probability >0.90 .

Statistical Analysis

We compared juvenile size and collection timing using data from all beaches during 2008-2010, but to compare presence, catch and diet we only used data from the three beaches we sampled multiple years, i.e. Coos South, Tillamook North and Alsea South in 2008 and 2009. To determine if juvenile Chinook salmon were present at all sandy beaches or only those adjacent to estuaries, we compared the percentage of days in which we collected juveniles in adjacent and distant beaches with a Fisher's exact test using day as the sampling unit (Ramsey and Schafer 2002). We used a two-way analysis of variance (ANOVA) to determine if juvenile catch or stomach fullness varied among years and beaches: year and beach were fixed factors and day was the sampling unit. Parametric assumptions for the ANOVA were met

after $\log_{10}(x + 1)$ transformation. Assumptions were tested using normal probability (quantile–quantile) plots and boxplots of residuals versus fitted values (Ramsey and Schafer 2002). When main level effects were significant, we conducted pair-wise comparisons using the Tukey HSD test.

To determine if there were differences in diet among beaches, we compared diet composition by calculating the Percent Similarity Index (PSI, see Hurlbert 1978, for review) with day as the sampling unit:

$$PSI = \sum_i \min(P_{xi}, P_{yi}) \quad (2)$$

where P_{xi} = numerical percentage of prey_{*i*} in surf zone and P_{yi} = numerical percentage of prey_{*i*} in estuary.

In this analysis, a value of 0 and 100 signify no and complete similarity, respectively.

We also compared catch, stomach fullness and diet composition of juvenile Chinook salmon between troughs and adjacent flat areas using one-way ANOVA and PSI as detailed above. For these analyses we pooled data from Coos South, Tillamook North and Alsea South collected during 2008 and 2009 because we observed insignificant differences in catch and diet among beaches and years (see results section).

RESULTS

We collected 329 juvenile Chinook salmon at eight sandy beaches, and Coos South accounted for the majority of the catch (67%, Fig. 2.1). Juveniles (99%) were

primarily captured between July 1 and September 1 (Fig. 2.2). Of all juveniles collected, 38 had adipose fin clips and were therefore considered of hatchery-origin. Size of the juveniles in the surf zone ranged from 5.9 to 14.4 cm fork length (FL) with the majority (63%) between 9 and 11 cm FL. Based on their size, CWTs and genetic analysis, all juveniles were categorized as subyearlings (Fisher et al. 2007). The largest juveniles (12.5 ± 1.9 SD cm FL) were collected at Distant Beach 3, which was located 15 km north of Coos Bay and was the only distant beach that was located within a littoral cell with Chinook-inhabited estuaries (Fig. 2.1). No juveniles were collected at Distant Beaches 1 and 2 or Columbia South (Table 2.2). Columbia South was also the only beach at which we did not observe trough areas.

We collected juveniles during more days and tows at beaches adjacent to estuary mouths (16 days, 31 tows) than at beaches distant from estuary mouths (1 day, 2 tows) (Table 2.2). We also collected juveniles on a significantly higher percentage of days in adjacent (53%) than distant beaches (10%) (Fisher's exact test, $p = 0.03$). At beaches adjacent to estuaries, juveniles were collected on both the north (47%) and south sides (43%), with the exception of Columbia South during 2009. Juvenile catches averaged 3 ± 8 ind. 100 m^{-2} (\pm SD) and were highly variable among days and tows (coefficient of variation >123 and 300% , respectively). There were no significant differences in juvenile catch among years ($F_{1,30} < 4.17$, $p > 0.05$), beaches ($F_{2,30} < 3.32$, $p > 0.05$) or a significant interaction between these two factors ($F_{2,30}$, $p > 0.05$) (Table 2.3).

Of the 298 juveniles analyzed for genetic stock of origin, 223 (75%) had assignment probabilities >0.90 . The majority of those juveniles (95%) were collected within the littoral cell that included their region of origin (Fig. 2.3). Most of the juveniles that were collected in a littoral cell that did not encompass their region of origin came from an adjacent region (69%, $n = 16$). The beaches surrounding Coos and Alsea bays are part of the Mid- and Northern-Oregon Coast genetic stock group, respectively, which each includes multiple estuaries (Fig. 2.1). We evaluated our assumption that juveniles had exited from the estuary closest to beach of capture within the fish's genetic region of origin by comparing our determinations with information obtained from CWTs, which provide information on fish origin, and size and date at tagging (<http://www.rmmpc.org>). We collected 15 juveniles with CWTs, and 13 of these juveniles exited Coos Bay and were collected at Coos South. The other two fish were (1) released in Willapa Bay watershed, Washington, and collected at Columbia North, which is within the same littoral cell, and (2) released in central Columbia River and collected at Tillamook North, which is in a different littoral cell (Fig. 2.1).

Stomach fullness ranged from 0.02 to 11.88% of body weight (mean \pm SD: $2.1 \pm 2.1\%$, Table 2.3). There were also no significant differences in stomach fullness between years ($F_{1,11} < 4.84$, $p > 0.05$) or among beaches ($F_{2,11} < 3.98$, $p > 0.05$) (Table 2.3). Juveniles fed on 57 taxa, most of which were amphipods (70% of taxa), dipteran insects (14%), mysids (6%), crab megalopae (5%), isopods (1%), and larval and juvenile fish (1%) (Table 2.4). The most abundant prey taxon was a gammarid

amphipod, *Jassa* spp. (42% of all prey items). Diet composition was most dissimilar between Tillamook North and the other two beaches (mean PSI = $33 \pm 12\%$ SD) (Table 2.5). Differences in diet composition were mostly due to the larger number of *Jassa* spp. consumed by juveniles at Coos and Alsea South compared to those collected at Tillamook North, where juveniles preyed heavily on insects and the mysid *Archaeomysis grebnitzkii* (Fig. 2.5a). Interannual differences in PSI values at Coos and Alsea South and Tillamook North averaged $40 \pm 14\%$ (\pm SD), and were largely due to the higher numbers of *Archaeomysis grebnitzkii* and *Cancer magister* megalopa, and lower numbers of insects, and the amphipod, *Atylus tridens*, in diets at all three beaches during 2008 compared to 2009 (Fig. 2.5a).

Given the insignificant spatial and temporal variation in catch and diet, we pooled all years and sites to compare catch and diet in trough and flat areas. Juveniles catches were significantly higher in troughs than in flat areas (mean: 4 ± 2 SD vs. 1 ± 2 ind. 100 m^{-2} , $F_{1,32} = 6.0$, $p < 0.05$, Fig. 2.6a). Juveniles were also collected in more tows (33 vs. 15) and on a greater percentage of days (23 vs. 12%) in trough than in flat areas. Stomach fullness was also significantly higher in trough than in flat areas (2.1 ± 0.8 vs. $1.5 \pm 0.6\%$, $F_{1,32} = 4.82$, $p < 0.05$, Fig. 2.6b), and diet composition PSI between trough and flat areas was 47%. Juveniles collected in troughs consumed more insects and fewer *Cancer magister* megalopae and unidentified fish species than juveniles collected in flat areas (Fig. 2.5b).

DISCUSSION

Juvenile Chinook salmon were collected in surf zones throughout the summer in every year of our study (99% of the collections occurred between July 1 and September 1). These results indicate surf zones are a consistent summer habitat for subyearling Chinook salmon, at least in this portion of their range. Juvenile Chinook salmon are usually present in estuaries of western North America between April and September at sizes similar to those observed in this study (Reimers 1973; Fisher and Pearcy 1990; Bottom et al. 2005b). Therefore, it is possible that subyearling Chinook salmon may exhibit a spatially split cohort (for review see Skúlason and Smith 1995), which means that a group of fish of the same age use multiple habitats during the same time period. Utilizing multiple habitats may increase population resilience by spreading the risk of mortality among individuals by increasing the possibility of fish encountering favorable growth conditions and reducing the risk of a catastrophic event eliminating the whole cohort (Hilborn et al. 2003; Secor 2007; Schindler et al. 2010). In the case of subyearling Chinook salmon, using estuaries and surf zones may allow them to forage on different prey fields while staying in habitats where they are hypothesized to experience low predation pressure (Simenstad et al. 1982; Bottom et al. 2005a; McLachlan and Brown 2006; Marin Jarrin et al. 2009).

Our data indicate that some juveniles exiting Oregon estuaries initially remain close to their natal estuary, potentially due to their relatively small body size (< 13 cm FL) and the presence of rocky headlands. In estuaries and the coastal ocean, the depth and distance from shore at which juveniles are present has been positively related to their size (Kjelson et al. 1982; Myers and Horton 1982; Healey

1983; Levings et al. 1986; Trudel et al. 2009; Tucker et al. 2011). During summers in Oregon and Washington, shallow coastal habitats usually present warmer waters (Marin Jarrin and Peterson J. unpublished data, Ryer et al. 2012), higher densities of potential prey items (i.e. benthic amphipods and insects, Reimers et al. 1978; Bottom 1984; Miller and Simenstad 1997; Gray et al. 2002; Marin Jarrin et al. 2009), and fewer piscivorous fish than deeper waters (Myers and Horton 1982; Brodeur et al. 2005; McLachlan and Brown 2006; Marin Jarrin 2007). The highly turbid and dynamic nature of surf zones has also been hypothesized to reduce predation by diving marine birds (McLachlan and Brown 2006). Therefore, by using shallow habitats, such as sandy beach surf zones, juvenile Chinook salmon may be increasing their growth rates while minimizing the predation risk that comes with increasing their foraging activities (i.e. Heincke's Law, sensu Cushing 1975; Ryer et al. 2010).

Subyearling Chinook salmon diet composition varied among surf zone beaches. Diet differences were mostly due to variation in the relative abundance of benthic amphipods and mysids and insects in stomachs. This variation in diet composition may be due to differences in wave action, which has been found to influence sandy beach community composition (Dexter 1992; McLachlan and Dorvlo 2005). The degree of beach exposure can be estimated by the length of a beach and sediment grain size, with longer beaches with larger sand grain size being more exposed than shorter beaches with smaller sand grains (McLachlan 1980). Tillamook North is a longer beach (19 vs. 3 and 6 km, respectively) with larger average sand grain size (0.27 vs. 0.19 and 0.19 mm, Peterson et al. 1994) than Coos

or Alsea South. Longer beaches that are more exposed to waves can maintain larger populations of sand burrowing species such as *Archaeomysis grebnitzkii* that are common in highly dynamic environments (Carlton 2007) and were heavily preyed upon at Tillamook North during 2008. At more protected beaches surrounded by rocky habitat, benthic and swimming amphipods, such as *Jassa* spp., may also be abundant (Carlton 2007; Marin Jarrin, unpublished data). Therefore, differences in beach exposure may lead to diverse prey fields on which juvenile Chinook salmon, a known opportunistic feeder (Healey 1991; Schabetsberger et al. 2003) may forage. The difference in diet composition we observed may therefore be due to differences in beach exposure among the three beaches.

Few studies have compared faunal assemblages in troughs and flat areas (Harvey 1998; Layman 2000; Watt-Pringle and Strydom 2003; Janssen et al. 2008). We collected subyearlings in higher numbers with greater stomach fullness in troughs compared to flat areas. Harvey (1998) found that several fish species were more abundant in trough than in flat areas throughout the tidal cycle, and proposed that this difference was due to higher abundances of fish prey and lower abundance of predators in the troughs. Several other studies have also observed significantly higher species richness and fish abundance in trough waters than in flat sites (Layman 2000; Watt-Pringle and Strydom 2003; Janssen et al. 2008). However, these authors suggest it was due to the more protected nature of troughs produced by reduced current speed and wave height. In our sites, we observed circulation patterns within troughs that were not perceived in flat areas. Therefore differences in catch

and stomach fullness observed in our study may be due to the spatial distribution of prey and/or calmer waters in troughs than in flat areas. Similar tactics have been described for salmonids in pools of rivers where the energy requirements for maintaining position is relatively low, and where drift insects from adjacent riffles provide ample foraging opportunities (Fausch 1984).

In the present study, we sampled during lower low tides when through areas are most accesible. Prior reseach collected juvenile Chinook salmon in surf zones at all tides and times of day (Marin Jarrin 2007; Marin Jarrin et al. 2009), and determined that sand bars migrate across shore through the whole beach profile and throughout the summer (Alexander and Holman 2004; Ruggiero et al. 2005). Therefore we think that our low tide catches in trough and flat areas are representative of conditions throughout the day. Intertidal sand bars that produce trough and flat areas are common on the Oregon and Washington coast and are the primary mechanism for sand accretion on a seasonal scale (Komar 1997; Ruggiero et al. 2005). Therefore, higher number of juveniles in trough than in flat areas may be a common pattern along the coast of western North America.

Coos South was the beach at which we collected most subyearling Chinook salmon. Certain physical characteristics of Coos South likely contributed to these higher catches; this beach is short in length (~3 km long) with a rocky headland and a jetty on the south and north side of the beach, respectively. These characteristics may concentrate juveniles between the headlands and jetty as well as promote

development of circulation cells that trap prey in the surf zone (Marin Jarrin 2007). An additional possibility is that juveniles were attracted to Coos South due to the low interspecific competition for prey (i.e. underused resources, Skúlason and Smith 1995). For example, silver surfperch, *Hyperprosopon ellipticum*, whose diet is very similar to Chinook salmon in surf zones (Marin Jarrin 2007), were often collected at all beaches except Coos South. Therefore, reduced competition may have influenced surf zone residence at Coos South.

We estimated the proportion of the Coos Bay population that used sandy beach surf zones using a “back-of-the-envelope” calculation. First, we determined the proportion of Coos South that was trough area during summer 2009 (19%, Marin Jarrin, unpublished data). Based on this proportion and our surf zone catch estimates, we then estimated the abundance of juvenile Chinook salmon at Coos South. Finally, using annual hatchery releases in the Coos watershed as a minimum estimate of juvenile production, we estimated that 0.3 to 10% of emigrating juvenile Chinook salmon were present within shallow waters of Coos South on any given day. We expect that our net efficiency was less than one, similar to other studies that used similar methods (Healey 1980; Bottom et al. 2005b). Therefore our results are likely an underestimation. Overall, it appears that a small but consistent proportion of subyearling Chinook salmon populations use shallow sandy beach surf zones during their first ocean summer.

The only beach adjacent to an estuary at which we did not collect juveniles was Columbia South, potentially due to an absence of trough areas at this site. Alternatively, the lack of collections at Columbia South may have been due to the relatively long jetty on the south side of the Columbia River (~10.4 km) and relatively deep waters at the end of this jetty (>10 m), which may provide habitat for large piscivorous fish that could deter juveniles from accessing surf zones. The absence of collections could also be due to the large amount of rearing habitat available within the estuary or to physical transport processes. Unlike the other three estuaries adjacent to our sampling sites, the Columbia River estuary has significant river flow and a large coastal plume (Table 2.1, Burla et al. 2010). The river flow may therefore have quickly directed juveniles away from the estuary mouth. Our lack of catches at Columbia South was most likely not due to the presence of jetties, habitat availability within the estuary or physical transport since we collected juveniles at beaches adjacent to other estuaries with jetties (i.e. Coos and Tillamook Bay) and at Columbia North. Therefore, the absence of juvenile collections at Columbia South was most likely due to the nonexistence of troughs. The absence of troughs at Columbia South appears to be a common pattern since they were not present during 2011 or 2012 (<http://www.oregongeology.org/sub/Nanoos1/index.htm>).

Climate change is predicted to significantly influence aquatic habitats throughout the world in the near future. There are predictions for an increase in fresh water temperature (1.5 to 5°C), sea surface temperature (1.2°C) annual precipitation

(1 to 2%), sea surface height (0.2 to 1.3 m) and wave height (0.75 m) in western North America in the next 50 years (Mantua et al. 2009; Mote and Salathé 2009; Ruggiero et al. 2010). Some researchers predict local upwelling winds will either not change (Mote and Mantua 2002; Mote and Salathé 2009) or increase in strength and variability in the near future (Di Lorenzo et al. 2005; Bakun et al. 2010; García-Reyes and Largier 2010). All of these changes could impact conditions in surf zones and estuaries, thus changing the role of both habitats for juvenile Chinook salmon. In western North America, estuaries are considered to be particularly vulnerable to climate because of impacts they have already sustained from human development, introduction of exotic species, and an inability for these habitats to move inland due to the steep coastal topography (Emmett et al. 2000; Galbraith et al. 2002). Habitat conditions in sandy beach surf zones may also be altered. For example, if increasing wave height changes sediment movement and the development of trough areas, juveniles may encounter less preferred areas within surf zones thus potentially reducing growth rates.

In conclusion, a small number of naturally- and hatchery- reared subyearling Chinook salmon are present in sandy beach surf zones that are adjacent to estuaries and present trough areas during the summer season, where they feed mostly on amphipods, insects and crustacean larvae. In surf zones, juvenile abundance and diet varies with the presence of troughs and flat areas, and the length of the beach. The role of sandy beach surf zones may change under future climate scenarios, which could influence growth conditions in coastal habitats throughout the Pacific

Northeast. Further understanding of the relative importance of surf zones for juvenile Chinook salmon will require direct comparisons of growth conditions in surf zones and estuaries, a known nursery habitat.

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Table 2.1: Size, type and classification based on human development of estuaries adjacent to sandy beaches where we collected juvenile Chinook salmon during 2008-2010. Origin of juveniles and approximate number of hatchery juveniles released in each watershed (Hatchery production) are also presented.

Characteristics	Columbia River	Coos Bay	Tillamook Bay	Alsea Bay
Size (km ²) ¹	327	54	37	10
Type ²	River dominated	← Drowned river mouth →		
Classification ²		Draft development (maintained jetties and channels)		Conservation (minor development)
Juvenile Origin ³	← Natural - Hatchery →			Natural
Hatchery production ³	>100,000,000	500,000	2,000,000	-

¹Oregon Coastal Atlas: <http://www.coastalatlantlas.net/>

²Cortright et al. 1987

³Regional Mark Processing Center: <http://www.rmpec.org/>

Table 2.2. Number of days sampled (a), and total number of days and numbers of juveniles that were collected and used in analyses. Data used for (b) determination of timing and size, spatial distribution, and genetic origin, and (c) comparison of catch, stomach fullness and diet composition among beaches and years, and between troughs and flat areas. Beaches are located immediately adjacent to the north or south of each estuary listed. Distant beaches were at least 15 km from an estuary mouth. Data from 2010 were not included in analyses due to low sample sizes at Alsea South (2 juveniles) and because we did not sample at Tillamook North in order to increase sampling frequencies at Coos and Alsea South. * Location of distant beaches in Fig. 2.1.

Collections	Columbia River		Tillamook Bay		Alsea Bay		Coos Bay		Distant beaches*		
	North	South	North	South	North	South	North	South	1	2	3
a)	Number of days sampled										
2008			6	6	6	6	6	6	3	3	4
2009	6	6	6			6		6			
2010						10		10			
b)	Number of days juveniles were collected (total # of juveniles)										
2008			3 (16)	2 (6)	3 (32)	4 (6)	2 (12)	2 (50)	0 (0)	0 (0)	1 (8)
2009	3 (10)	0 (0)	3 (12)			2 (5)		3 (10)			
2010						2 (2)		9 (160)			
c)	Comparison of catch, stomach fullness and diet composition										
2008			3 (16)			4 (6)		2 (50)			
2009			3 (10)			2 (5)		3 (10)			
2010						2 (2)		9 (160)			

Table 2.3. Mean (\pm SD) annual catch (ind. 100m^{-2}) and stomach fullness (SF) of juveniles in surf zones located immediately to the south of Coos Bay mouth (Coos South), north of Tillamook Bay mouth (Tillamook North) and south of Alsea Bay mouth (Alsea South).

Year	Coos South		Tillamook North		Alsea South	
	Catch	SF	Catch	SF	Catch	SF
2008	3.2 (5.8)	4.4 (3.6)	0.8 (3.3)	1.9 (1.1)	0.09 (0.14)	1.6 (0.8)
2009	0.3 (0.4)	1.9 (0.1)	0.1 (0.3)	1.8 (1.1)	0.14 (0.56)	1.9 (0.5)

Table 2.4. Prey taxa observed in juvenile Chinook salmon collected at eight sandy beach surf zones on the Oregon and Washington coast. Life history stage (Stage), group, number of beaches in which the taxa was observed (Beaches) and percent frequency (Freq.) are also presented.

Taxa	State	Group	Beaches	Freq.
<i>Allorchestes angusta</i>	Adult	Amphipoda	2	12
<i>Americhelidium micropleon</i>	Adult	Amphipoda	1	1
<i>Ampithoe lacertosa</i>	Adult	Amphipoda	2	8
<i>Atylus tridens</i>	Adult	Amphipoda	6	101
Caprellidea spp.	Adult	Amphipoda	6	64
<i>Carinonajna barnardi</i>	Adult	Amphipoda	1	1
<i>Corophium</i> spp.	Adult	Amphipoda	1	1
<i>Dogielinotus loquax</i>	Adult	Amphipoda	5	96
<i>Eohaustorius washingtonianus</i>	Adult	Amphipoda	2	9
<i>Eusiroidea</i> sp.	Adult	Amphipoda	1	2
<i>Eyakia</i> sp.	Adult	Amphipoda	1	1
Gammaridea spp.	Adult	Amphipoda	5	44
<i>Hartmanodes hartmanae</i>	Adult	Amphipoda	1	1
<i>Jassa</i> spp.	Adult	Amphipoda	7	224
<i>Mandilophoxus</i> sp.	Adult	Amphipoda	1	1
<i>Megalorchestia pugettensis</i>	Adult	Amphipoda	1	14
<i>Pleustidae</i> sp.	Adult	Amphipoda	1	1
<i>Tiron biocellata</i>	Adult	Amphipoda	1	1
Araneae spp.	Adult	Araneae	1	2
Cephalopod sp.	Larvae	Cephalopoda	1	2
Calanus sp.	Adult	Copepoda	1	1
Unidentified crustacean	Adult	Crustacea	3	4
Cumacea spp.	Adult	Cumacea	3	3
<i>Cancer magister</i>	Megalopa	Decapoda	8	25
<i>Cancer</i>	Juvenile	Decapoda	1	1
<i>orogenensis/productus</i>	Megalopa	Decapoda	1	14
Crangonidae sp. 1	Juvenile/Postlarva	Decapoda	1	6
Crangonidae sp. 2	Megalopa	Decapoda	3	9

Crangonidae sp. 3	Megalopa	Decapoda	1	2
Crustacea spp.	Larvae	Decapoda	1	1
<i>Emerita analoga</i>	Zoea	Decapoda	1	1
<i>Euphausia pacifica</i>	Adult	Decapoda	5	10
<i>Lissocrangon stylirostris</i>	Adult	Decapoda	2	2
<i>Lophopanopeus bellus</i>	Megalopa	Decapoda	3	42
Paguridea sp.	Zoea	Decapoda	1	1
Porcellanidae spp.	Megalopa	Decapoda	1	1
Porcellanidae spp.	Zoea	Decapoda	1	5
<i>Upogebia pugettensis</i>	Megalopa	Decapoda	1	1
Insecta spp.	Larvae	Insecta	1	4
Insecta spp.	Adult	Insecta	7	116
Insecta spp.	Pupae	Insecta	1	1
<i>Gnorimosphaeroma oregonensis</i>	Adult	Isopoda	1	2
Idotea spp.	Adult	Isopoda	3	3
<i>Lycaeopsis themistoides</i>	Adult	Isopoda	3	55
<i>Munna</i> sp.	Adult	Isopoda	2	2
<i>Stenolhoides burkanki</i>	Adult	Isopoda	1	1
<i>Excirrolana chiltoni</i>	Adult	Isopoda	4	37
<i>Archaeomysis grebnitzkii</i>	Adult	Mysidacea	7	94
<i>Holmesimysis sculpta</i>	Adult	Mysidacea	2	93
Unidentified mysid	Adult	Mysidacea	1	1
<i>Ammodytes hexapterus</i>	Juvenile	Osteichthyes	1	4
<i>Clinocottus embryum</i>	Larvae	Osteichthyes	1	2
<i>Engraulis mordax</i>	Larvae	Osteichthyes	2	13
Fish spp.	Egg	Osteichthyes	1	1
<i>Leptocottus armatus</i>	Larvae	Osteichthyes	2	10
Fish spp.	Larvae	Osteichthyes	4	17
Pycnogonida sp.	Adult	Pycnogonida	1	1

Table 2.5. Percent similarity index (PSI) of diet composition of juvenile Chinook salmon collected at surf zones located immediately to the south of Coos Bay mouth (Coos South), north of Tillamook Bay mouth (Tillamook North) and south of Alsea Bay mouth (Alsea South) during 2008 and 2009.

Comparison	2008	2009
Coos South vs. Alsea South	57.05	56.88
Coos South vs. Tillamook North	18.40	47.60
Alsea South vs. Tillamook North	31.10	39.14
Coos South 08 vs. 09	41.64	
Tillamook North 08 vs. 09	35.32	
Alsea South 08 vs. 09	41.54	

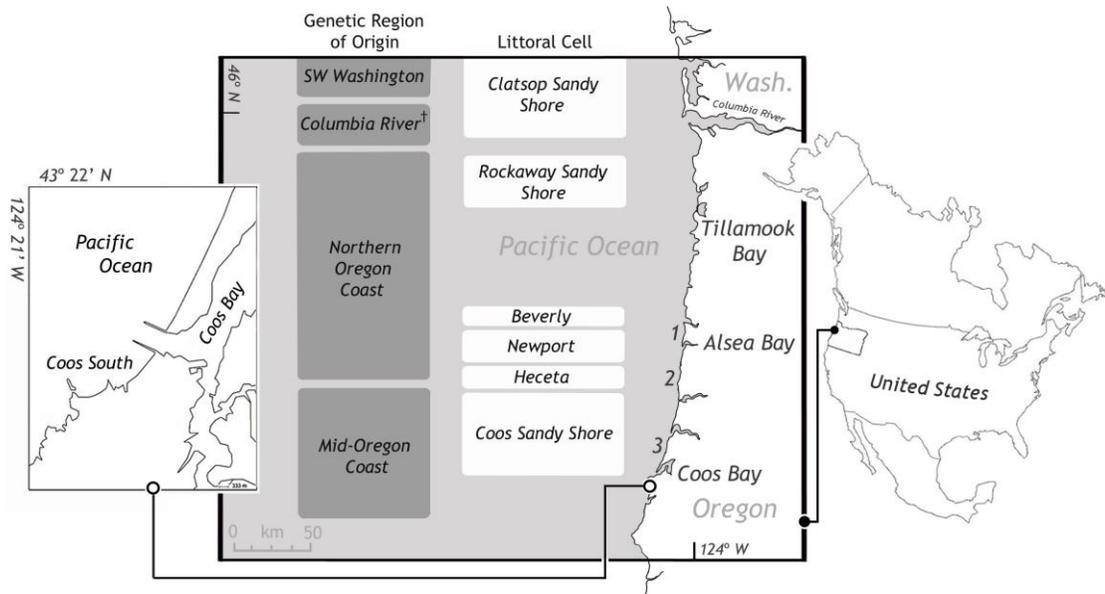


Fig. 2.1. Map with location of collection sites. Eight beaches were located immediately to the north and south of the four estuaries shown in figure. Three distant beaches are indicated as numbers and were defined as beaches located at least 15 km from an estuary mouth. Genetic region of origin, littoral cell of the beaches, and an inset of the beach south of Coos Bay where most of the juveniles were collected are also shown. †Columbia River genetic stock groups collected = Upper Columbia Summer and Fall, and Spring Creek Group Fall.

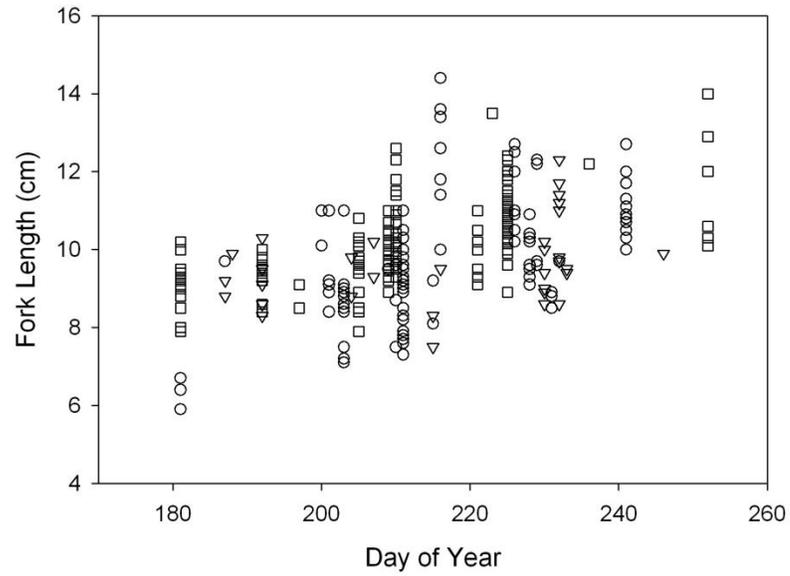


Fig. 2.2. Plot of fork length (cm) and day of capture for juvenile Chinook salmon collected at eight sandy beach surf zones during the summers of 2008-2010. Circles = 2008, triangles = 2009, squares = 2010.

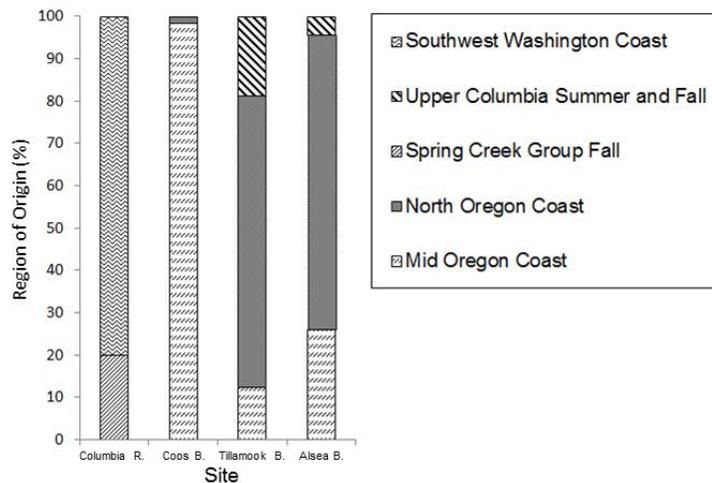


Fig. 2.3. Genetic region of origin of juvenile Chinook salmon collected at beaches surrounding four estuaries during summer of 2008-2010. Juveniles collected at beach located immediately to north of Columbia River (Columbia R, n = 5), north and south of Coos Bay, and Distant Beach 3 located 15 km north of Coos Bay (Coos B., n = 179), north and south of Tillamook Bay (Tillamook B., n = 16), north and south of Alsea Bay (Alsea B., n = 23). *Upper Columbia Summer and Fall, and Spring Creek Group Fall are Columbia River genetic stock groups.

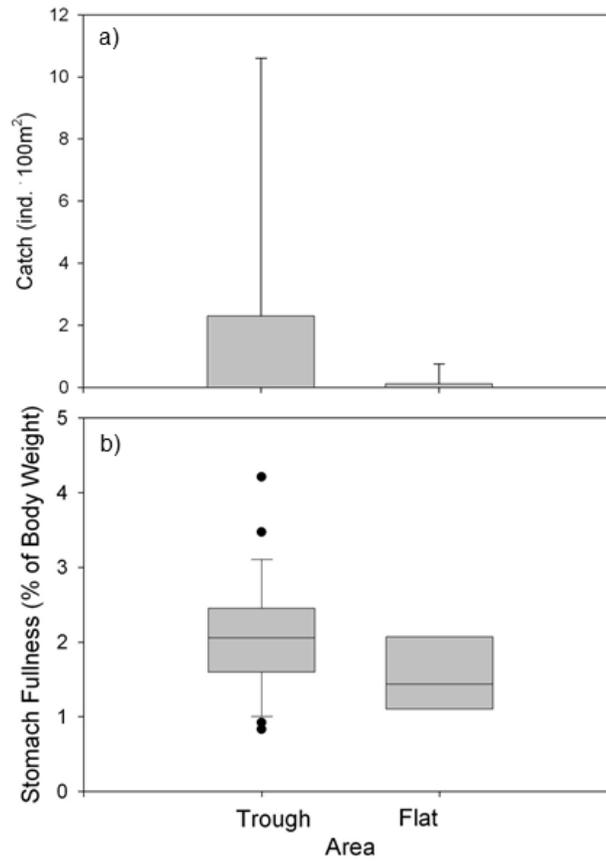


Fig. 2.4. Mean catch (a) and stomach fullness (b) of juvenile Chinook salmon collected in sheltered trough areas (Trough, $n = 155$) and adjacent flat surf areas (Flat, $n = 88$) of three sandy beach surf zones along the coast of western North America.

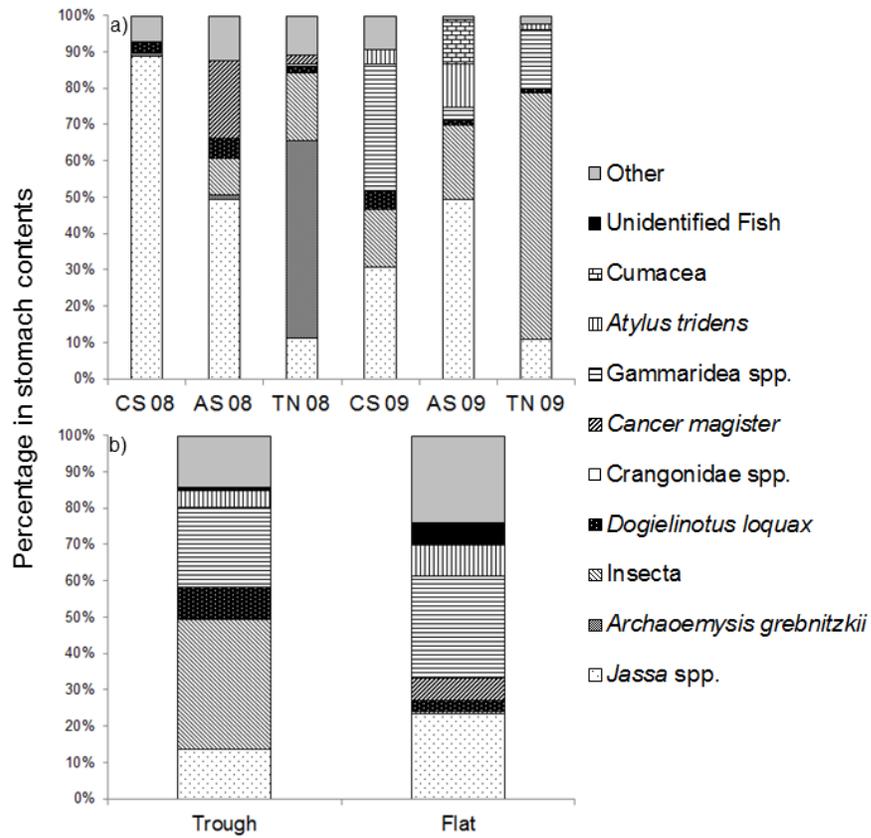


Fig. 2.5. Numerical percentage of juvenile Chinook salmon prey items collected in Coos South (CS), Tillamook North (TN) and Alsea South (AS) (a), and between trough and flat areas during 2008 and 2009 (b).

CHAPTER 3

THE ROLE OF SANDY BEACH SURF ZONES IN THE EARLY LIFE HISTORY
OF CHINOOK SALMON

Jose R. Marin Jarrin

ABSTRACT

Diversity in habitat use can increase population resilience by reducing the risk of a catastrophic event eliminating the whole cohort. Some anadromous species, such as Chinook salmon (*Oncorhynchus tshawytscha*), reside in different habitats during their early marine residence, a period that is considered critical due to high rates of mortality. Juvenile (0-age) Chinook salmon mostly inhabits estuaries, but also sandy beach surf zones and the coastal ocean, during their first months of marine life. However, despite the importance of this period, the role of surf zones for Chinook salmon is at present unclear. We directly compared catch, size, migration patterns, diet and growth of juveniles collected in two Oregon (USA) estuaries and surf zones. Juvenile catches were 10 to 50 times higher in estuaries than surf zones. Chinook salmon from both habitats were similar in size at capture (average 103 ± 15 SD mm fork length), size at marine entry (76 ± 13 mm FL), stomach fullness ($2 \pm 2\%$ body weight) and growth rates (0.4 ± 0.0 mm day⁻¹). Juveniles collected in estuaries entered brackish/ocean water significantly earlier than surf zone fish (17 ± 20 days earlier) and had different diet composition. Our results suggest that despite the small number of juvenile Chinook salmon that use surf zones, the role of this environment

is to provide favorable foraging and growth conditions during the summer for subyearlings that are similar to those present in estuaries in their size at entrance and residence in marine waters.

INTRODUCTION

Anadromous fish use a diversity of habitats throughout their life (Dadswell et al. 1987; McDowall 1988). This heterogeneity in habitat use can occur among and within life stages (Dadswell et al. 1987; McDowall 1988; Bertness et al. 2001). Within a habitat, fish may also use multiple microhabitats. For example, fishes present in streams may use pools, riffles, glides or side channels (Reeves et al. 1993; Guégan et al. 1998; Young 2001). Diversity in habitat use by anadromous fish may confer resilience to environmental variability, such as climate change and other anthropogenic impacts (Wood 1995; Sheaves et al. 2006; Secor 2007; Waples et al. 2009; Katz et al. 2012). Using multiple habitats may also increase the possibility of fish encountering favorable growth conditions and reducing the risk of a catastrophic event eliminating the whole cohort (Hilborn et al. 2003; Secor 2007; Schindler et al. 2010).

Chinook salmon (*Oncorhynchus tshawytscha*) is an anadromous species naturally distributed throughout the North Pacific Ocean that spawns in most rivers of western North America north of San Francisco, California (Quinn 2005). The majority of juveniles initiate their migration to the ocean as 0-age (sub-yearlings) or 1-age (yearlings). On the west coast of continental USA, most Chinook salmon migrate to the ocean as subyearlings (Rich 1920; Reimers 1973; Nicholas and

Hankin 1988). Subyearling Chinook salmon will reside in streams and main rivers for several months before migrating to the estuary during the spring, summer or fall of their first year of life (Reimers 1973; Healey 1991; Bottom et al. 2005a). Estuaries are considered a nursery for Chinook salmon due to the potential for enhanced growth, refugia from predation and physiological acclimation to marine waters (Reimers 1973; Healey 1980; Simenstad et al. 1982; Bottom et al. 2005b). Subyearlings may inhabit estuaries for up to 6 months before continuing their migration to the ocean (Hering et al. 2010; Volk et al. 2010). This early period of marine residence is considered critical due to the high levels of mortality sustained by juvenile salmonids (for review see Pearcy 1992).

During this important early marine residence period, sub-yearling Chinook salmon also inhabit sandy beach surf zones adjacent to estuary mouths (Reimers 1973; Healey 1980; Marin Jarrin et al. 2009). Reimers (1973) hypothesized that juveniles moved to surf zones potentially due to increasing population abundances and decreasing potential prey in the estuary. In surf zones, juveniles have been collected during all tides and times of day throughout the summer season where they feed on the diverse local zooplankton community and potentially seek refuge from predation in its shallow turbid waters (Reimers 1973; Healey 1980; Marin Jarrin et al. 2009). Marin Jarrin et al. (2009) hypothesized that surf zones may also be acting as a nursery habitat because of the high feeding potential, expected low predation rates (McLachlan and Brown 2006) and large area of sandy beaches available to juvenile Chinook salmon (>60% of Oregon marine coastline, Don et al. 2006).

However, we tested this hypothesis and found that only a small (< 10%) proportion of juveniles from Oregon and Washington populations use sandy beach surf zones (Marin Jarrin et al. in review). Marin Jarrin et al. (in review) also found that the size of subyearlings using surf zones was similar to those reported in western North American estuaries and hypothesized that similar sized Chinook salmon were using both habitats during this life history stage. Therefore, after using estuaries, some juveniles may reside in surf zones for an unknown time period before moving to deeper coastal waters. These authors also found that juveniles inhabiting surf zones along the Oregon coast fed on a relatively high abundance and diversity of prey when compared to studies conducted in other juvenile habitats (Simenstad et al. 1982; Healey 1991) but they did not determine growth rates.

We evaluated the relative importance of sandy beaches by comparing the role of surf zones and estuaries, a known nursery habitat. Previous studies suggest juvenile Chinook salmon are present in lower numbers in surf zones than in estuaries but that individuals present similar sizes, high prey diversity and stomach fullness (Reimers 1973; Fisher and Pearcy 1990; Bottom et al. 2005b; Marin Jarrin et al. 2009; Marin Jarrin et al. In review.). However, these studies were conducted during different years and sites. Therefore, in the present study we directly compared juvenile catch, size, migration patterns, diet and growth of individuals collected simultaneously in two estuaries and two adjacent surf zones.

MATERIALS AND METHODS

Study Region

This study was conducted at the lower portion of Coos and Alsea bays and their adjacent sandy beach surf zones (Coos and Alsea Surf) located in Oregon, USA during 2008-2010 (Fig. 3.1). Coos and Alsea Surf are dissipative (shallower slope) sandy beaches (McLachlan 1980; Short and Wright 1983) experiencing moderate wave height in the summer (average wave height: 1-2 m) when sand accretion may transform them into intermediate beaches (Komar et al. 1976). Coos Surf is located immediately to the south of Coos Bay and is approximately 3 km long while Alsea Surf is located immediately to the south of Alsea Bay and is approximately 10 km long. Coos and Alsea Bay are drowned river mouth estuaries, influenced by high fall and winter, and low summer stream flows, when inflow is close to zero and are therefore dominated by seawater (Emmett et al. 2000). Coos and Alsea Bay are different in their sizes, origin of Chinook salmon juveniles, extent of hatchery production and classification based on human development (Table 3.1).

Sampling

Prior research found that juvenile Chinook salmon were present in surf zones and estuaries during all tides and throughout the day during the summer (Reimers 1973; Healey 1980; Marin Jarrin 2007). Therefore, juveniles were collected in both habitats during lower low spring tide to reduce the number of micro-habitats where some fish may not be as easily collected at higher tides (e.g. salt marsh channels, Hering et al. 2010) and for safety reasons. Samplings were conducted from June 1 to September 30 of 2008-2010 at all sites (Table 3.2). During 2008, juveniles were also collected on the beach immediately to the north of Alsea Bay mouth, which is also

10 km long, and has similar physical characteristics as Alesia Surf (Marin Jarrin, unpublished data).

In surf zones we collected juvenile Chinook salmon using a small beach seine (15 m x 1.5 m x 1.0 cm) (Marin Jarrin and Shanks 2011). Briefly, three people carried the net into the surf to a depth of approximately 1.5 m where the net was opened parallel to the shoreline and in a V-shape after which it was pulled to shore. In estuaries, juveniles were collected by Oregon Department of Fish and Wildlife personnel using a 38 m x 4 m x 1.3 cm beach seine with a lead and cork line and a 2.5 m x 2.5 m x 1 cm bag in the center, which was extended from shore in a loop. Three to six tows were conducted in each habitat, and up to 30 juvenile Chinook salmon were euthanized with MS-222 (tricaine methanesulfonate, Argent Chemical Laboratories, $150 \text{ mg}\cdot\text{l}^{-1}$) buffered with baking soda (sodium bicarbonate, $300 \text{ mg}\cdot\text{l}^{-1}$) and then transported back to the laboratory on ice. Additional Chinook salmon were counted and measured (fork length, FL, mm) prior to release.

Juvenile catch, size and stomach content analysis

In the lab, juveniles were measured (FL, mm) and weighed (g), and stomachs and otoliths were extracted. Juvenile catch was estimated by determining the area sampled by each net (individuals 100m^{-2}). In estuaries the area sampled was calculated by assuming the length of the net was the perimeter of a circle, and in surf zones by using the distance from the shoreline to the point at which the beach seine was opened and the width of the mouth of the seine when opened in a V-shape. We

identified and counted stomach contents to the lowest taxonomic level possible. Stomach fullness (SF) was calculated as the percentage of juvenile body weight as follows:

$$SF = \frac{\text{Stomach content weight (g)}}{(\text{Juvenile weight (g)} - \text{Stomach content weight (g)})} \times 100$$

(1)

Otolith analysis: size at marine entry, timing of entrance and growth in marine waters

To determine size at marine entry, day of entry, residence and growth rates in marine waters we used otolith microstructure and microchemistry. Otoliths were extracted and prepared for analysis by grinding both sides using wet-or-dry paper and lapping film to expose the dorsal-ventral growth axis (Miller 2007). Otolith microstructure was analyzed using ImagePro Plus[®] software. Otoliths were photographed at 40 and 400x to measure otoliths and count increments. We obtained otolith chemical data (Sr:Ca and Ba:Ca) using laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS) at Oregon State University's WM Keck Collaboratory for Plasma Spectrometry, Corvallis, Oregon. The laser ablated designated transects at a pulse rate of 7 Hz with a 50- μm ablation spot size at a speed of 5 $\mu\text{m sec}^{-1}$. Transects were along the dorsal-ventral growth axis through the core at the widest location of the otolith. Background levels of Ca, Ba, and Sr, were measured 50 s prior to otolith ablation. Ca was used as an internal standard to account for variation in amount of material ablated and instrument variation. Ratios

were obtained for each element, except Ca, by converting normalized ion ratios using a glass standard from the National Institute of Standards and Technology (NIST 610) (Kent and Ungerer 2006; Miller 2007). Ratios are reported in mmol/mol. The mean percent relative standard deviation of NIST 610, used as a measure of instrument precision during data collection, were Ca = 2.3, Sr = 2.4 and Ba = 3.3%. To estimate accuracy, we used a calcium carbonate standard of known composition (US Geological Survey, MACS -2). Measured values were within 3% of known Sr:Ca and Ba:Ca values.

To determine juvenile size and day of marine entry we relied on the fact that certain elements, such as Sr and Ba, are incorporated into an otolith in proportion to their water concentration (Kraus and Secor 2004; Zimmerman 2005; Miller et al. 2010). Strontium:calcium ratios are usually higher in ocean waters (>8 mmol/mol) when compared to fresh waters (< 5 mmol/mol). However, because Coos Bay Sr:Ca water values can be between 5-8 mmol/mol (Miller, unpublished data), we also included Ba:Ca ratios, which can be 10 to 50 times higher in fresh than in marine waters, including within the Coos watershed, and thus allow a more precise discrimination between these two water bodies (Miller 2011; Miller, unpublished data). Therefore, we used the inflection point at which Sr:Ca increased and Ba:Ca decreased to signify a transition from fresh to marine water. We use the term “marine water” because variation in Sr:Ca and Ba:Ca is limited above salinities of 9-10 (Kraus and Secor 2004; Zimmerman 2005; Miller et al. 2010), and therefore we are only able to discriminate between waters below and above this salinity cutoff level.

Prior research found that it may take two to three days after juvenile Chinook salmon have entered marine waters for Sr:Ca and Ba:Ca ratios to increase and decrease, respectively (Miller et al. 2011); therefore when otoliths had no discernible changes in Sr:Ca or Ba:Ca we used a conservative 1 d marine residence time.

To estimate day of entrance and residence times in marine waters, we counted the number of increments from the otolith edge to the increment laid the day the fish had entered marine waters. Based on the habitat transitions identified using otolith Sr:Ca and Ba:Ca data, we estimated juvenile size at marine entry using the proportional back-calculation method, which allows us to account for individual variability in fish size (Francis 1990). We used separate equations for each estuary/surf zone site during each year (Table 3.3) that were obtained by regressing juvenile FL against otolith width (OW) as described below:

$$\log_{10}(FL_C) = a + b * \log_{10}(OW_C)$$

(2)

where FL_C = fork length (mm) at capture and OW_C = otolith width (μm) at capture.

We then back-calculated fork length as described below

$$\log_{10}(FL_{BC}) = \frac{\log_{10}(FL_C)}{\log_{10}(FL_{EC})} * [a + b * \log_{10}(OW_{BC})]$$

(3)

where FL_{BC} = fork length (mm) at a back-calculated size, FL_{EC} = estimated fork length at capture (mm, estimated using equation 2), OW_{BC} = otolith width (μm) at a back-calculated size (See Francis 1990 for more detail).

We measured increment widths for the last 14 days of the fish's life to estimate their growth rates. We chose the last 14 days since we collected juveniles every 14 days and because prior analysis of individual otolith growth trajectories found no difference in average increment widths between the last 14 and 10, 7 or 3 days (paired t-test, $p > 0.05$, Fig. 3.2). Increment widths were measured twice at least a week apart and the difference in measurements recorded to estimate error (<5%). We then back-calculated size 14 days before capture using equation 3 and calculated recent growth rates with the following equation:

$$\text{Growth rates (mm)} = \frac{\text{Fork length at capture} - \text{Fork length 14 days earlier}}{14}$$

(4)

Statistical comparison of variables between surf zone and estuarine juveniles

We compared results for each surf zone and estuary site separately due to differences between estuaries (detailed above) that can influence juvenile salmonid ecology (Zhang and Beamish 2000; Weitkamp 2008; Chittenden et al. 2010). We found no significant difference in juvenile size at marine entry, day of marine entry, diet composition, stomach fullness and growth rates among months within each habitat/year (ANOVA and Analysis of Similarity, $p > 0.05$) with the exception of

Coos Bay during 2010 where growth rates were higher during June and July when compared to August and September. Therefore, we used day as the unit to compare all variables measured between habitats during each year. We compared surf zone and estuarine catch using a non-parametric rank-sum test during each year due to differences in sampling methodology and habitat type. Due to low catches in surf zones, in the following comparisons we only used data from 2008 and 2010 in Coos habitats and in 2008 at Alsea habitats. To compare surf zone and estuarine juvenile size at catch and at marine entry, day of marine entry, residence times in marine water, SF and growth rates we used two- and one-way ANOVA. At Coos sites we used two-way ANOVA with habitat (estuary and surf zone) and year (2008 and 2010) as fixed factors. At Alsea sites we used one-way ANOVA with habitat (estuary and surf zone) as the fixed factor. To account for the change in juvenile size with time, when comparing size at capture we only included days that had collections in both estuaries and surf zones within a week of each other (Fig. 3.3). Parametric assumptions for the ANOVA were met after $\log_{10}(x + 1)$ transformation. Assumptions were tested using normal probability (quantile–quantile) plots and boxplots of residuals versus fitted values (Ramsey and Schafer 2002). Tukey HSD test was used for pair-wise comparisons.

To compare diet composition between habitats we used the Percent Similarity Index (PSI, see Hurlbert 1978, for review) to determine if there were differences in diet composition between surf zones and estuaries.

$$PSI = \sum_i \min(P_{xi}, P_{yi})$$

(5)

where P_{xi} = numerical percentage of prey_{*i*} in surf zone and P_{yi} = numerical percentage of prey_{*i*} in estuary. In this analysis, a value of 0 and 100 signify no and complete similarity between habitats, respectively. Because this type of analysis does not provide a cut-off value for significant differences we also compared diet composition between the two estuaries and between the two surf zones to use as reference values. For this analysis we included 2009 data for both sites because prior analysis showed that 3 to 5 fish per year accurately captured the annual pattern (one-way analysis of similarity, $n = 3$ vs. $n = 10$, $p > 0.05$).

RESULTS

From 2008 to 2010, 265 and 9,638 juveniles were collected in surf zones and estuaries, respectively. Juveniles were collected during all days in estuaries but not in surf zones (Table 3.2). Overall, catches were 10 to 50 times higher in estuaries than they were in surf zones (Table 3.4). Differences in catch between surf zones and estuaries were significant in Coos and Alsea habitats during each year (Rank Sum test, $W \geq 15$, $n \geq 3$, $p < 0.05$). Juvenile size at capture ranged from 69 to 145 mm in FL (average 103 ± 15 mm SD) and was not significantly different between habitats ($F_{1,11} < 4.84$, $p > 0.05$), or years ($F_{1,11} < 4.84$, $p > 0.05$) at Coos sites (Fig. 3.3) or between habitats at Alsea sites during 2008 ($F_{1,8} < 5.32$, $p > 0.05$).

Overall, juveniles were between 48 and 112 mm in FL at marine entry (Average: Coos sites = 75 ± 14 mm, Alsea sites = 77 ± 12 mm). On average, juvenile size at marine entry was significantly different between years ($F_{1,12} = 61.65$, $p > 0.0001$, Fig. 3.4) but not habitats ($F_{1,12} < 4.75$, $p > 0.05$) at Coos sites. When we included data from all three years and pooled habitats, size at marine entry in Coos sites was significantly larger in 2010 than 2009 or 2008, and 2009 had significantly larger sizes than 2008 ($F_{2,20} = 30.42$, $p < 0.0001$, post-hoc test $p < 0.05$). At Alsea sites, differences in size at marine entry were not significantly different between habitats ($F_{1,7} < 5.59$, $p > 0.05$). Analysis of residence and timing of marine entry found that juveniles had been present in marine waters an average of 23 ± 4 days (1 – 53 days, Fig. 3.5). Juveniles continuously migrated to marine waters from May 14 to August 10, with average values of June 14 ± 15 days in surf zone and May 31 ± 9 days in estuarine fish. The majority of juveniles migrated from freshwater by early June ($> 50\%$ of fish). Residence times in marine waters were not significantly different between habitats ($F_{1,11} < 4.84$, $p > 0.05$) or years ($F_{1,11} < 4.84$, $p > 0.05$) at Coos sites (Table 3.4), or between habitats at Alsea sites ($F_{1,7} < 5.59$, $p > 0.05$). However, when comparing day of marine entry, we observed a significant interaction between habitat and year at Coos sites ($F_{1,11} = 10.05$, $p < 0.01$, Table 3.4). Post-hoc comparisons found that day of marine entry was earlier for Coos Bay than Coos Surf caught juveniles during 2008 ($p < 0.05$). Similar results were not observed at Coos habitats during 2010 ($p > 0.05$). At Alsea sites, day of marine entry in estuarine juveniles was also earlier than surf zone fish during 2008 ($F_{1,7} = 5.61$, $p = 0.05$).

Surf zone juveniles fed on 57 taxa, the most abundant of which was a gammarid amphipod, *Jassa* spp. (42% of total prey items). The main prey groups were amphipods (70% of taxa), dipteran insects (14%), mysids (6%), crab megalopae (5%), isopods (1%), and larval and juvenile fish (1%). In estuaries, juveniles fed on 49 taxa, the most abundant of which was *Corophium* spp. (60% of total prey items, Table 3.5). The main prey groups were amphipods (70% of taxa), crustacean zoea and megalopae (15%), cumaceans (5.3%) and insects (3.3%). Diet composition was most similar between the two estuaries (mean PSI = 60.27%) and then between the two surf zones (mean PSI = 44.00%) (Table 3.6). Composition was most dissimilar between surf zone and estuarine sites during all three years (mean PSI = 16.01%). Similarities between surf zones was due to the large abundance of *Jassa* spp. observed in juvenile stomachs during all three years, while in estuaries it was mostly due to *Corophium* spp. and Porcellanid zoea (Fig. 3.6).

Stomach fullness of juveniles in both habitats varied from 0.02 to 11.88% of body weight. There was no significant difference in juvenile stomach fullness between habitats ($F_{1,15} < 4.54$, $p > 0.05$) or years ($F_{1,15} < 4.54$, $p > 0.05$) at Coos sites (Table 3.4) or between habitats at Alsea sites ($F_{1,9} < 5.12$, $p > 0.05$).

Overall, juvenile growth rates ranged from 0.28 to 0.53 mm per day (average 0.4 ± 0.1 SD mm day⁻¹, Table 3.4). At Coos habitats, growth rates averaged 0.43 ± 0.01 mm day⁻¹ and were not significantly different between habitats ($F_{1,12} < 4.75$, $p > 0.05$) or years ($F_{1,12} < 4.75$, $p > 0.05$) (Table 3.4). At Alsea sites growth rates

averaged 0.40 ± 0.01 mm day⁻¹ and were not significantly different between surf zone and estuary during 2008 ($F_{1,7} < 5.59$, $p > 0.05$). Despite similar growth rates between habitats, we collected several juvenile Chinook salmon at Coos Surf in 2008 and Coos Bay in 2010 that had been growing at a higher rate than the other juveniles collected that year (Fig. 3.2). However, we can not account for this difference and did not observe a similar pattern at Alsea habitats during 2008.

DISCUSSION

The present study is the first to evaluate the relative importance of sandy beach surf zones to juvenile Chinook salmon by directly comparing migratory, foraging and growth characteristics of juveniles collected in surf zones and estuaries, a known nursery habitat (Reimers 1973; Simenstad et al. 1982; Bottom et al. 2005a). These comparisons confirm that besides using estuaries and the open ocean, a small number of juvenile Chinook salmon also reside in adjacent surf zones during the summer season (Marin Jarrin et al. In review.). This confirmation supports the hypothesis that juvenile Chinook salmon exhibit a spatially split cohort (Secor 2007), with individuals using a diversity of habitats when they enter marine waters. Diversity in habitat use may spread the risk of mortality among individuals for species that live in highly variable environments or in which inter- and intra-specific competition is high (Robinson and Wilson 1994; Skúlason and Smith 1995). In coastal environments of western North America, habitat conditions during the summer season are influenced by oceanic processes that may vary temporally at

multiple scales (Hickey and Banas 2003; Schwing et al. 2010). Large numbers of Chinook salmon of hatchery-origin are released in western North America every year (Rand et al. 2012). Juveniles of hatchery origin have been found to exhibit similar spatial distributions and diet than juveniles of wild origin in coastal habitats, therefore potentially allowing for competition for prey resources to take place between hatchery and wild individuals (Myers and Horton 1982; Daly et al. 2011; Rand et al. 2012). Consequently, using multiple habitats may allow juveniles to take advantage of multiple prey fields while staying in shallow habitats that are hypothesized to present low predation pressures (Simenstad et al. 1982; Bottom et al. 2005a; McLachlan and Brown 2006; Marin Jarrin et al. 2009).

Juvenile salmon collected in surf zones entered marine waters at similar sizes and had resided in marine waters for similar lengths of time as fish collected in estuaries. Similar patterns were also observed in prior studies conducted in Coos and Alsea Bay, where subyearling Chinook salmon were present from the end of May and early June (Fisher and Percy 1990; Bieber 2005; B. Buckman, ODFW, personal communication). The size at marine entry and length of residence was also similar for subyearlings present in other drowned river mouth estuaries such as the Sixes and Salmon River estuaries (Reimers 1973; Bottom et al. 2005a; Volk et al. 2010) and other types of estuaries in western North America (Cramer and Lichatowich 1978; Dawley et al. 1978, 1986; Healey 1980; Kjelson et al. 1982; Levings et al. 1986; Wallace and Collins 1997) where juveniles were found to reach the lower estuary in early to late April and reside throughout the summer. Therefore, these results suggest

the majority of subyearling Chinook salmon from western North America enter marine waters during their first spring and summer and use estuaries for extended periods of time, but that some juveniles will then also use adjacent surf zones.

Juveniles that used surf zones generally entered marine waters at a later time than estuarine caught fish. Otolith analysis does not allow us to discriminate individual residence times separately in estuaries and surf zones. However, because surf zone caught salmon must have encountered the estuary on its way to the ocean, both surf zone and estuarine caught fish use estuaries prior to their movement to the surf zone or coastal ocean. Therefore, surf zone caught juveniles would have entered marine waters and used estuaries after estuarine fish had entered marine waters. A potential reason for this difference in migration times between juveniles collected in the two habitats is that as subyearlings migrated down the river, the first arrivals may have established residence in estuaries thus forcing later arrivals to move to surf zones. This territorial behavior during migration of first arrivals outcompeting later arrivals for the preferred habitat is common in Atlantic salmon (*Salmo salar*) in freshwater environments, to the point where only a few days may decide which fish occupies a preferred territory (Metcalf and Thorpe 1992; Kvingedal and Einum 2011) (i.e. ideal despotic distribution, Fretwell and Lucas 1969).

Juveniles collected in surf zones and estuaries had migrated to marine water continuously throughout the late spring and summer. These results differ (Reimers 1973) and agree (Bottom et al. 2005b; Volk et al. 2010) with previous studies.

Reimers (1973) proposed four subyearling life history types in the Sixes River that migrated during specific time periods. Juveniles from Type 1 migrated downstream and into the ocean within a few weeks after emergence from the gravel in the winter season. Chinook salmon from Types 2 and 3 moved to the estuary during the spring and summer and then continued their migration to the ocean during the middle and late summer, respectively. Type 4 subyearlings stayed in the main river until early summer and then quickly migrated through the estuary and into the ocean. In more recent studies, researchers have suggested that subyearling Chinook salmon continuously migrate from fresh to marine waters from spring to fall (Bottom et al. 2005b; Volk et al. 2010) and therefore do not present distinct types as proposed by Reimers (1973). Our study supports the more recent works that found that subyearling Chinook salmon continuously migrate to marine waters during the spring and summer, but is unable to determine if there were any fall migrants in Coos and Alsea populations as collections ended before the fall season.

In the present study, there was only one instance in which juveniles collected in surf zones entered brackish waters at similar times as estuarine caught fish. This result was due to early marine entrance of a few surf zone juveniles that were collected on June 20, which is on average 10 days before we usually collect juveniles at sandy beaches (Marin Jarrin et al. in review). This early marine entrance may have occurred because during June 2010 there was a precipitation event in the Coos watershed that produced an increase in river flow (NERRS:<http://cdmo.baruch>

.sc.edu/QueryPages /viewstations. cfm? Site_ ID= sos) that may have flushed many juveniles to marine waters thus forcing them to use the surf zone earlier than usual.

Despite foraging on different prey items, the prey diversity of juvenile Chinook salmon collected in surf zones and estuaries was similarly high. High prey diversity has also been reported in previous studies conducted in various types of estuaries, and deeper exposed and protected oceanic waters (Reimers et al. 1978; Sibert and Kask 1978; Bottom 1984; Brodeur 1991; Busby and Barnhart 1995; Miller and Simenstad 1997; Gray et al. 2002; Schabetsberger et al. 2003; Koehler et al. 2006; Weitkamp and Sturdevant 2008; Daly et al. 2009; Duffy et al. 2010) and is hypothesized to be due in large part to the opportunistic feeding nature of juvenile Chinook salmon (Healey 1991; Schabetsberger et al. 2003). Differences in prey taxa between estuarine and surf zone caught juveniles may be due to the dissimilarities in wave action, sediment grain sizes and physical structure between surf zones and estuaries (Short and Wright 1983; Emmett et al. 2000; Hickey and Banas 2003; McLachlan and Brown 2006) that may produce different prey field assemblages. The influence of habitat characteristics on Chinook salmon diet is best exemplified by *Jassa* spp. and *Corophium* spp., the main juvenile prey items in surf zones and estuaries, respectively, in the present study. The *Jassa* genus are a group of tube building gammarid amphipods known to inhabit shallow, hard substrate, intertidal to subtidal marine environments with fast moving water (Carlton 2007) and to feed on phytoplankton blooms (Chess 1979). Off the coast of Northern California, individuals from this genus are known to migrate onshore in spring and summer,

where they may become highly abundant (Chess 1979), and therefore available to juvenile Chinook salmon in sandy beaches (Marin Jarrin et al. 2009). The *Corophium* genus are also tube building gammarid amphipods but in soft sediment (i.e. mostly mud and silt) and are very abundant on mud flats located in the lower portion of many estuaries of western North America (Wilson 1983, Carlton 2007). Therefore, our study suggests that surf zones provide Chinook salmon with a unique and highly diverse prey field that is similar to other juvenile habitats.

In surf zones, subyearling Chinook salmon may feed at rates comparable to estuaries given by the similar stomach fullness indices in both habitats. Similarity in stomach fullness may have occurred because primary production in coastal environments of western North America during the summer are most likely controlled by wind-derived coastal upwelling, whose variability is on the scale of 500 km, and should therefore have similarly influenced water processes in surf zones and estuaries (Hickey and Banas 2003). During the summer fish prey communities are mostly fueled by allochthonous nutrient sources (i.e. wind-driven coastal upwelling), with some autochthonous input (e.g. terrestrial, sea grass beds, algae, phytoplankton) (Simenstad et al. 1990; Levings 1994; Hickey and Banas 2003; McLachlan and Brown 2006). Consequently, juvenile Chinook salmon stomach fullness may not vary between surf zones and estuaries due to similar sources of nutrients in both environments that allowed for the availability of prey to vary coherently between habitats. Despite differences in collection timing, which may bias our analysis interpretation due to differences in the state of digestion and daily

feeding cycle (Bottom 1984; Duffy et al. 2010; Marin Jarrin, unpublished data), our stomach fullness values are equal or higher than those observed in other North American coastal studies with similar sized juveniles ($\geq 1\%$ of body weight, Schabesteger et al. 2003; Baldwin et al. 2008). Therefore our results suggest that surf zones and estuaries provide an abundant supply of potential prey for juvenile Chinook salmon, probably due to the similar sources of nutrients to both habitats.

Our annual juvenile growth rates in surf zones and estuaries were similar and were within the range (0.2 to >1 mm day⁻¹) observed in other estuarine and deeper oceanic waters (Reimers 1973; Healey 1980; Kjelson et al. 1982; Levy and Northcote 1982; Neilson et al. 1985; Fisher and Pearcy 1995; Koehler et al. 2006; MacFarlane 2010). Similar growth rates may have occurred because of the similar prey groups and stomach fullness fish experienced in both juvenile habitats. In surf zones, we expected that the more dynamic nature and lower water temperature would lead to reduced juvenile growth rates when compared to estuaries (Reimers 1973; Neilson et al. 1985; Hickey and Banas 2003; Marin Jarrin and Shanks 2011). However, the differences between habitats in temperature and water movement may have been offset by the higher energetic content of the surf zone prey when compared to the estuarine prey (Marin Jarrin, unpublished data). All of these variables (i.e. prey quality and quantity, water circulation and temperature) have been found to influence growth rates (Sommer et al. 2001; Trudel et al. 2002; Limm and Marchetti 2009; Jenkins and Keeley 2010; Duffy and Beauchamp 2011) and could therefore have influenced our results.

This study confirmed that subyearling Chinook salmon use estuaries and sandy beach surf zones during the summer season. However, the high interannual variability in surf zone use poses the question: what influences juveniles to use surf zones? Does juvenile Chinook salmon surf zone use increase when estuarine growth conditions are sub-optimum (Reimers 1973), or could the abundance of prey and shallow turbid waters where fish can hide from predators offered by surf zones attract juveniles (Marin Jarrin et al. 2009)? This question will be further explored by a study that correlated growth rates in estuaries and surf zones with juvenile surf zone catch.

Our results confirm that despite the small number of juvenile Chinook salmon that use surf zones, this environment provides an abundant and diverse prey field and favorable growth conditions to subyearlings that migrate to marine waters during the spring and summer at sizes similar to juveniles collected in the estuary. Surf zone and estuarine foraging and growth rates may be comparable due to similarities in habitat and fish characteristics, such as juvenile size, physical properties, and nutrient sources. Our study provides novel information on surf zones, a poorly studied habitat, and estuaries, a known nursery habitat for Chinook salmon during a critical period. Given our extensive data collection and comparison with a nursery habitat, our results provide a robust evaluation of the role of surf zones for the early life history of Chinook salmon.

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Table 3.1: Estuary size, type and classification based on human development, origin of juveniles, and number of hatchery juveniles released in watershed (\pm SD). - = no juveniles of hatchery-origin released

Characteristics	Coos Bay	Alsea Bay
¹ Size (km ²)	54	10
² Type	Drowned river mouth	
³ Classification	Draft Developmental (jetty and channels)	Conservation (minor development)
⁴ Juvenile Origin	Hatchery & Natural	Natural
⁴ Hatchery production	2,006,043 \pm 460,675	-

¹Oregon Coastal Atlas web-page: www.coastalatlantlas.net/

²Emmett et al. 2000

³Cortright et al. 1987

⁴Regional Mark Processing Center web-page: www.rmmpc.org

Table 3.2: Location, year, number of sampling days (Sample), number of days juveniles were collected (Collect), and total number of juveniles euthanized for analysis (n) in two estuaries (Coos and Alsea Bay) and two surf zones (Coos and Alsea Surf) during three years.

Location	Year	Sample	Collect	n
Coos Bay	2008	5	5	31
	2009	6	6	34
	2010	6	6	45
Coos Surf	2008	6	2	50
	2009	6	3	10
	2010	10	8	91
Alsea Bay	2008	6	6	97
	2009	7	7	82
	2010	6	6	48
Alsea Surf	2008	12	7	33
	2009	6	2	5
	2010	10	2	2

Table 3.3: Parameters used in proportional back-calculation equations of juvenile size in two surf zones (Coos and Alsea Surf) and two estuaries (Coos and Alsea Bay) during three years. Parameters were estimated using simple linear regressions of fork length on otolith width.

Location/Year	Parameters		r^2	n
	a	b		
Coos 2008	1.008 (± 0.137 SE)	-2.277 (± 0.439 SE)	0.64	35
Alsea 2008	0.875 (± 0.093 SE)	-1.787 (± 0.297 SE)	0.63	54
Coos 2009	0.832 (± 0.155 SE)	-1.701 (± 0.496 SE)	0.51	33
Alsea 2009	0.988 (± 0.100 SE)	-2.159 (± 0.321 SE)	0.75	35
Coos 2010	0.992 (± 0.088 SE)	-2.191 (± 0.285 SE)	0.65	28
Alsea 2010	0.692 (± 0.109 SE)	-1.193 (± 0.350 SE)	0.63	72

Table 3.4: Annual mean (SD) (a) catch (ind. 100m⁻²), (b) stomach fullness (% of body weight) and (c) growth rate (mm day⁻¹) of juveniles collected in two estuaries (Coos and Alsea Bay) and two surf zones (Coos and Alsea Surf) during three years. Also included in parenthesis is the number of days from which data were collected. Number of fish per day ranged from 2 to 15. * = analysis not possible due to low number of juveniles collected

	Coos Bay	Coos Surf	Alsea Bay	Alsea Surf
	Mean ± SD catch (ind. 100m ⁻²)			
a) 2008	14.9 ± 19.2	3.2 ± 5.8	49.2 ± 24.9	0.09 ± 0.14
2009	10.6 ± 10.0	0.3 ± 0.4	61.9 ± 24.9	0.14 ± 0.56
2010	31.5 ± 24.9	2.8 ± 2.5	37.6 ± 23.7	0.06 ± 0.38
	Mean ± SD stomach fullness (% of body weight)(#days)			
b) 2008	2.0 ± 1.0 (3)	5.1 ± 3.1 (2)	2.0 ± 1.9 (6)	1.5 ± 0.7 (4)
2009	2.3 ± 0.8 (4)	1.8 ± 0.8 (3)	1.9 ± 1.2 (6)	1.8 ± 0.6 (2)
2010	1.8 ± 1.6 (5)	1.3 ± 1.0 (9)	1.3 ± 1.2 (3)	*
	Mean ± SD growth rates (mm day ⁻¹)(#days)			
c) 2008	0.42 ± 0.09 (3)	0.48 ± 0.09 (2)	0.40 ± 0.09 (5)	0.39 ± 0.09 (4)
2009	0.38 ± 0.12 (4)	0.29 ± 0.04 (3)	0.51 ± 0.09 (6)	0.36 ± 0.00 (2)
2010	0.53 ± 0.13 (5)	0.49 ± 0.13 (6)	0.34 ± 0.06 (3)	*

Table 3.5. Prey taxa observed in stomachs of juvenile Chinook salmon collected in two estuaries and two surf zones on the Oregon coast. Life history stage (Stage), group, number of sites at each habitat in which the taxa was observed (Sites) and percent frequency (Freq.) are also presented

Taxa	Stage	Group	Estuarine		Surf zone	
			Sites	Freq.	Sites	Freq.
<i>Allorchestes angusta</i>	Adult	Amphipoda	0	0	1	0.72
<i>Ampithoe lacertosa</i>	Adult	Amphipoda	0	0	1	2.17
<i>Atylus tridens</i>	Adult	Amphipoda	2	30.07	2	30.43
<i>Caprellidea</i> spp.	Adult	Amphipoda	1	0.33	2	26.09
<i>Corophium</i> spp.	Adult	Amphipoda	2	55.23	0	0
<i>Dogielinotus loquax</i>	Adult	Amphipoda	2	6.21	2	28.99
<i>Eogammarus covernicus</i>	Adult	Amphipoda	1	0.65	0	0
<i>Eohaustorius washingtonianus</i>	Adult	Amphipoda	2	1.31	1	1.45
<i>Eusiroidea</i> sp.	Adult	Amphipoda	2	2.94	1	2.9
Gammaridea	Adult	Amphipoda	2	4.25	2	11.59
<i>Jassa</i> spp.	Adult	Amphipoda	2	4.9	2	80.43
<i>Mandilophoxus</i> sp.	Adult	Amphipoda	0	0	1	0.72
<i>Megalorchestia pugettensis</i>	Adult	Amphipoda	2	0.65	1	5.8
<i>Pleustidae</i> sp.	Adult	Amphipoda	0	0	1	0.72
<i>Stenothoides burkanki</i>	Adult	Amphipoda	1	0.33	0	0
Spider	Adult	Araneae	0	0	1	1.45
Bivalve siphons	Adult	Bivalvia	1	0.33	0	0
Cephalopoda	Larvae	Cephalopoda	0	0	1	2.17
Copepoda	Adult	Copepoda	1	0.33	0	0
Crustacea	Larvae	Crustacea	1	0.33	1	0.72
Crustacea	Adult	Crustacea	2	6.54	1	1.45
Cumacea spp.	Adult	Cumacea	2	7.19	2	1.45
Brachyura	Zoea	Decapoda	2	0.65	0	0
<i>Cancer magister</i>	Megalopa	Decapoda	2	13.73	2	4.35
<i>Cancer magister</i>	Juvenile	Decapoda	1	0.33	1	0.72
<i>Cancer oregonensis/productus</i>	Megalopa	Decapoda	2	14.71	1	7.97
<i>Cancer</i> spp.	Zoea	Decapoda	1	0.33	0	0
Crangonidae	Megalopa	Decapoda	1	0.33	1	0.72
Crangonidae	Juvenile	Decapoda	0	0	1	0.72
<i>Euphausia pacifica</i>	Adult	Decapoda	1	0.33	1	2.17
<i>Fabia subsquatra</i>	Megalopa	Decapoda	1	0.33	0	0

<i>Lissocrangon stylirostris</i>	Adult	Decapoda	2	2.94	1	0.72
<i>Lophopanopeus bellus</i>	Megalopa	Decapoda	1	0.33	1	7.97
<i>Neotrypaea californiensis</i>	Zoea	Decapoda	1	0.33	0	0
<i>Pachycheles</i> spp.	Megalopa	Decapoda	1	0.65	1	1.45
Porcellanidae	Megalopa	Decapoda	1	0.33	1	0.72
Porcellanidae	Zoea	Decapoda	2	15.03	1	3.62
Gastropoda	Adult	Gastropoda	1	0.33	0	0
Insecta	Adult	Insecta	2	41.18	2	39.86
Insecta	Larva	Insecta	2	1.63	1	2.9
Insecta	Pupae	Insecta	2	1.63	0	0
<i>Excirrolana inornata</i>	Adult	Isopoda	1	0.65	0	0
<i>Excirrolana kincaidi</i>	Adult	Isopoda	2	3.59	2	10.87
<i>Gnorimosphaeroma oregonensis</i>	Adult	Isopoda	2	5.88	1	1.45
<i>Idotea</i> spp.	Adult	Isopoda	2	0.98	2	1.45
<i>Lycaeopsis themistoides</i>	Adult	Isopoda	0	0	1	35.51
<i>Munna</i> spp.	Adult	Isopoda	0	0	1	0.72
<i>Archaeomysis grebnitzkii</i>	Adult	Mysidacea	2	2.61	2	32.61
Mysidacea	Adult	Mysidacea	1	0.33	0	0
Oligochaeta	Adult	Oligochaeta	1	0.33	0	0
<i>Ammodytes hexapterus</i>	Juvenile	Osteichthyes	2	1.31	0	0
<i>Clinocottus embryum</i>	Larvae	Osteichthyes	0	0	1	1.45
<i>Engraulis mordax</i>	Juvenile	Osteichthyes	2	3.92	0	0
<i>Gasterosteus aculeatus</i>	Juvenile	Osteichthyes	1	0.33	0	0
<i>Leptocottus armatus</i>	Larvae	Osteichthyes	1	0.98	1	5.8
Osteichthyes	Juvenile	Osteichthyes	2	14.38	1	5.07
<i>Nereis</i> sp.	Adult	Polychaeta	1	2.61	0	0

Table 3.6. Percent Similarity Index (PSI) of juvenile Chinook salmon diet in two surf zones (Coos Surf and Alsea Surf) and two estuaries (Coos Bay and Alsea Bay) during 2008-2010. “*” indicates that no comparisons were made due to low sample sizes

Comparison	2008	2009	2010
Coos Bay vs. Coos Surf	5.16	16.77	11.39
Alsea Bay vs. Alsea Surf	14.89	23.96	*
Coos Surf vs. Alsea Surf	31.12	56.88	*
Coos Surf vs. Alsea Bay	12.66	19.21	17.52
Alsea Surf vs. Coos Bay	9.08	29.47	*
Coos Bay vs. Alsea Bay	74.90	51.83	54.07

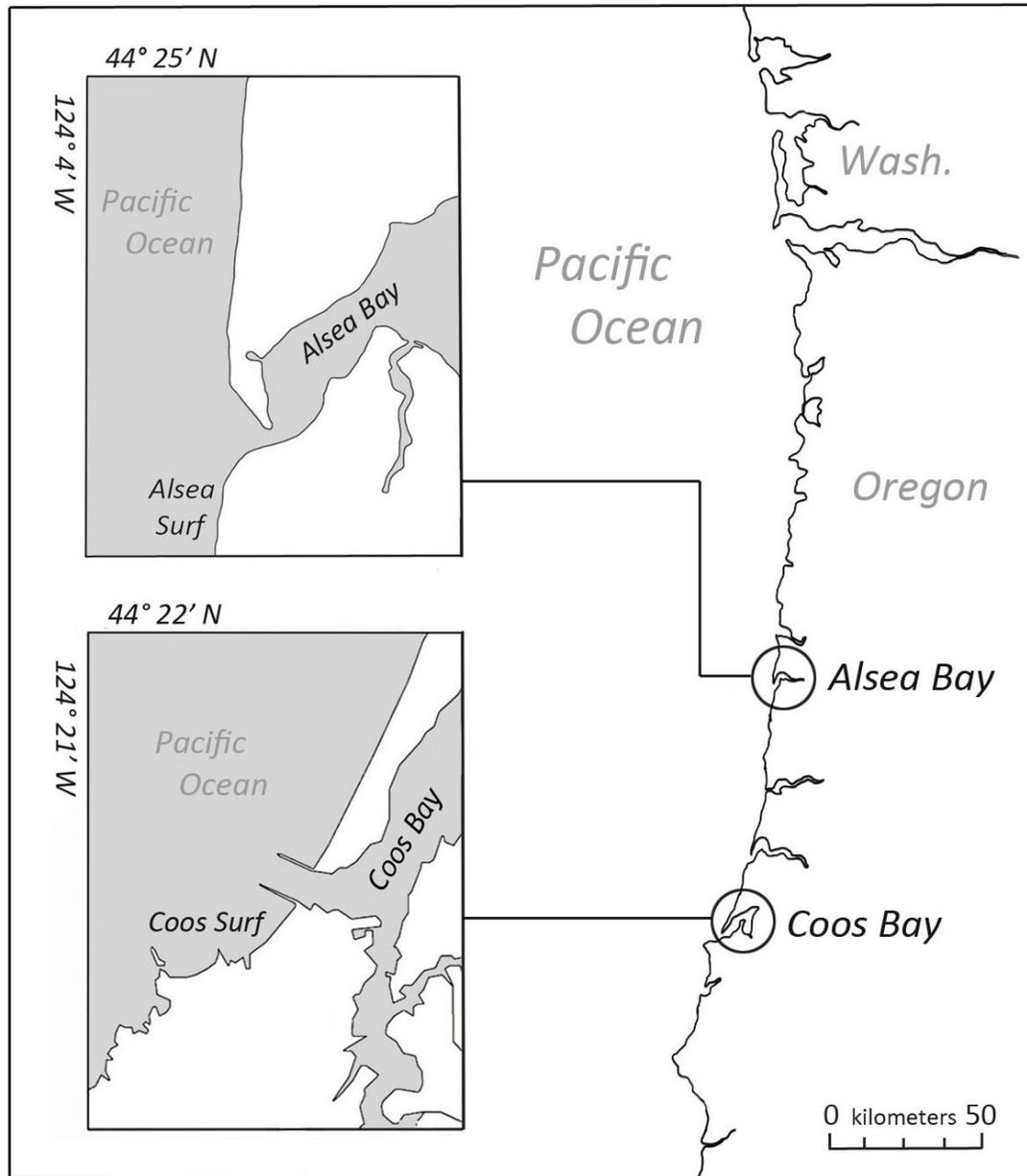


Fig. 3.1: Map with location of two estuaries (Coos Bay and Alsea Bay) and two surf zones (Coos and Alsea Surf) where juvenile Chinook salmon were collected during 2008 – 2010

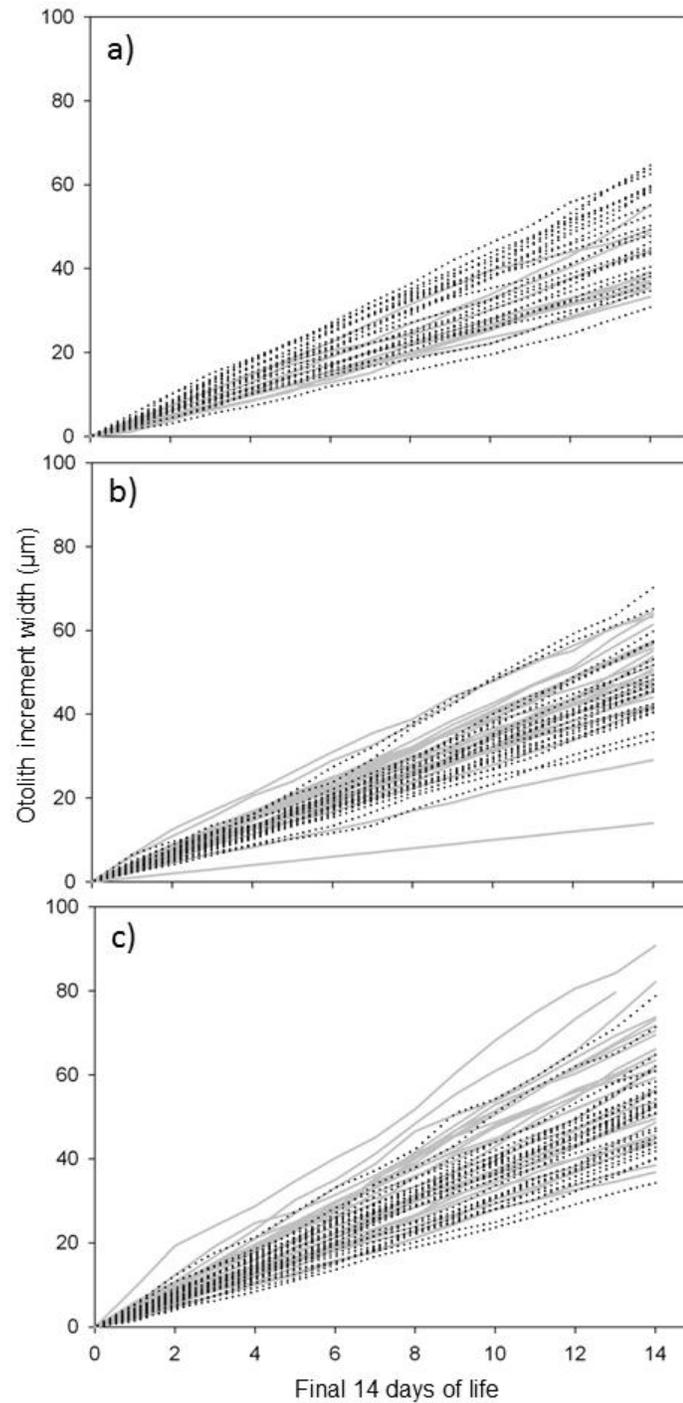


Fig. 3.2. Individual otolith growth trajectories for subyearling Chinook salmon collected at (a) Coos Bay and Surf 2008, (b) Alsea Bay and Surf 2008, (c) Coos Bay and Surf 2010. Dashed line = surf zone data, continuous line = estuarine data

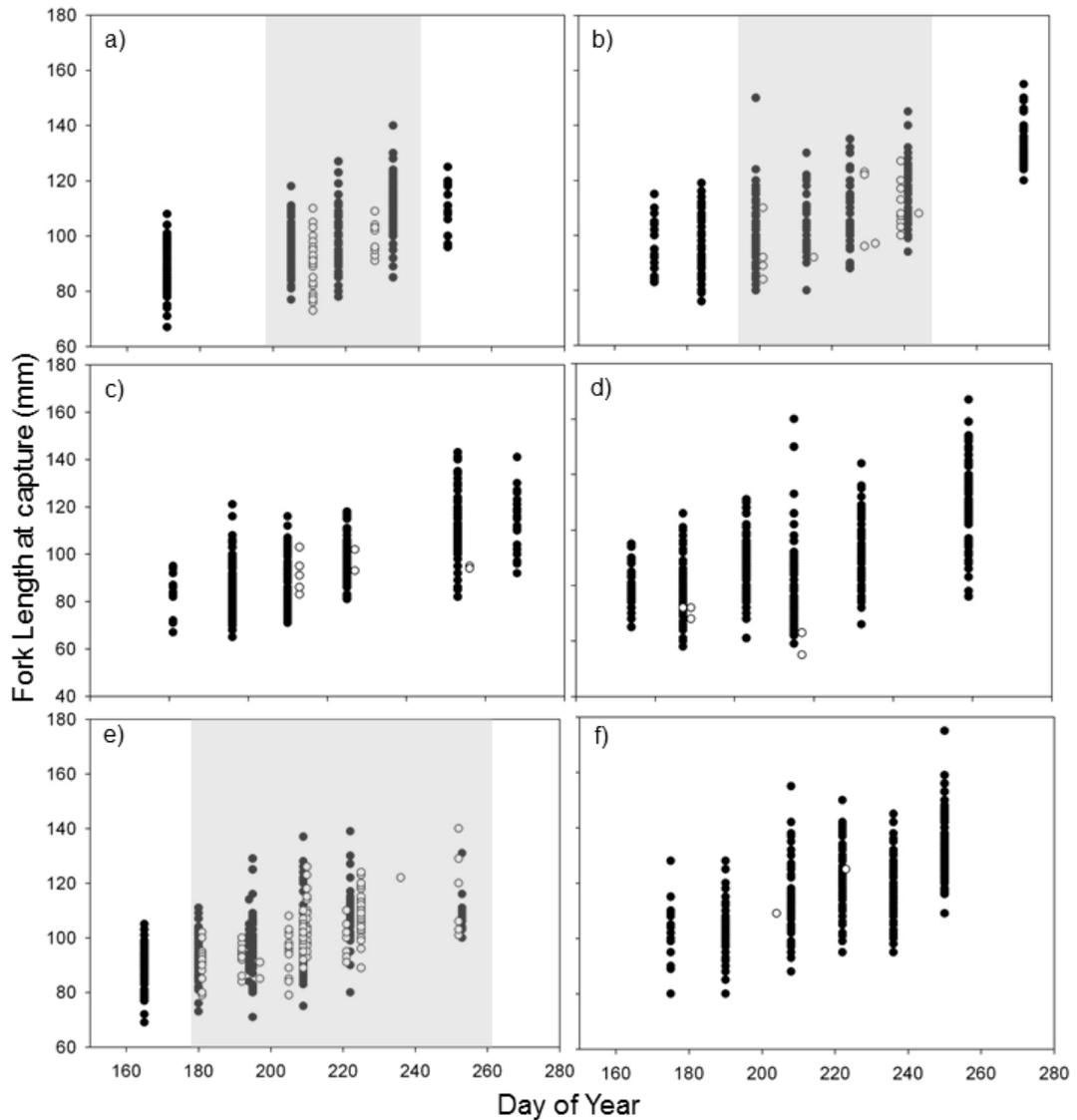


Fig. 3.3: Relationship between fork length at capture (mm) and day juveniles were collected at Coos Bay (closed circles) and Surf (open circles) during 2008 (a), 2009 (c) and 2010 (e) and Alsea Bay (closed circles) and Surf (open circles) during 2008 (b), 2009 (d) and 2010 (f). Grey areas show data used to statistically compare surf zone and estuarine juvenile size at capture. When necessary, surf zone data were offset to allow better visual inspection.

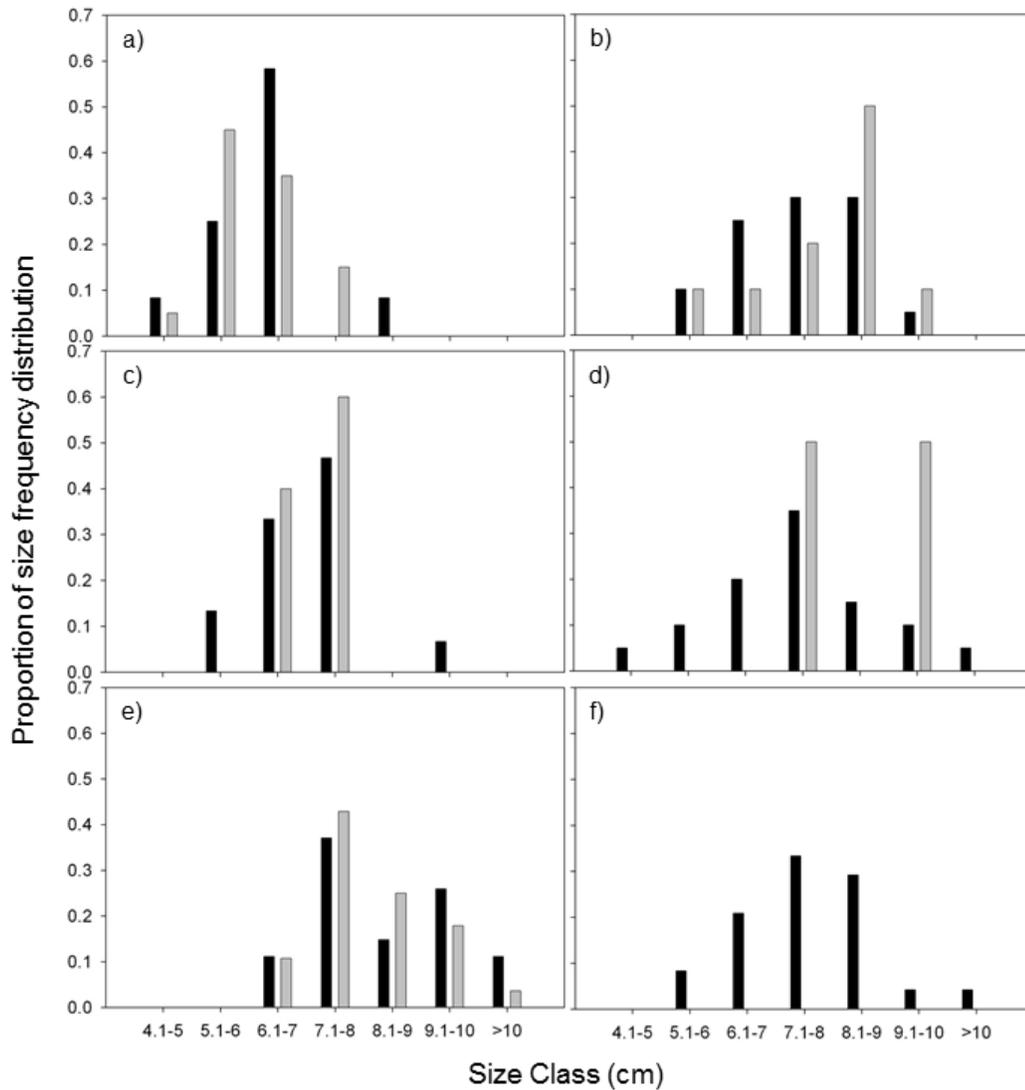


Fig. 3.4: Comparison of size at marine entry (cm) frequency distribution of juveniles collected in surf zone (gray bars) and estuaries (black bars). Samples collected at (a) Coos Bay and Surf during 2008 (Number of fish included in analysis: CB = 12 and CS = 22 fish), (b) Alsea Bay and Surf during 2008 (AB = 23 and AS = 21 fish), (c) Coos Bay and Surf during 2009 (CB = 16 and CS = 4 fish), (d) Alsea Bay and Surf during 2009 (AB = 21 and AS = 2 fish), (e) Coos Bay and Surf during 2010 (CB = 28 and CS = 28 days) and (f) Alsea Bay during 2010 (AB = 23 days).

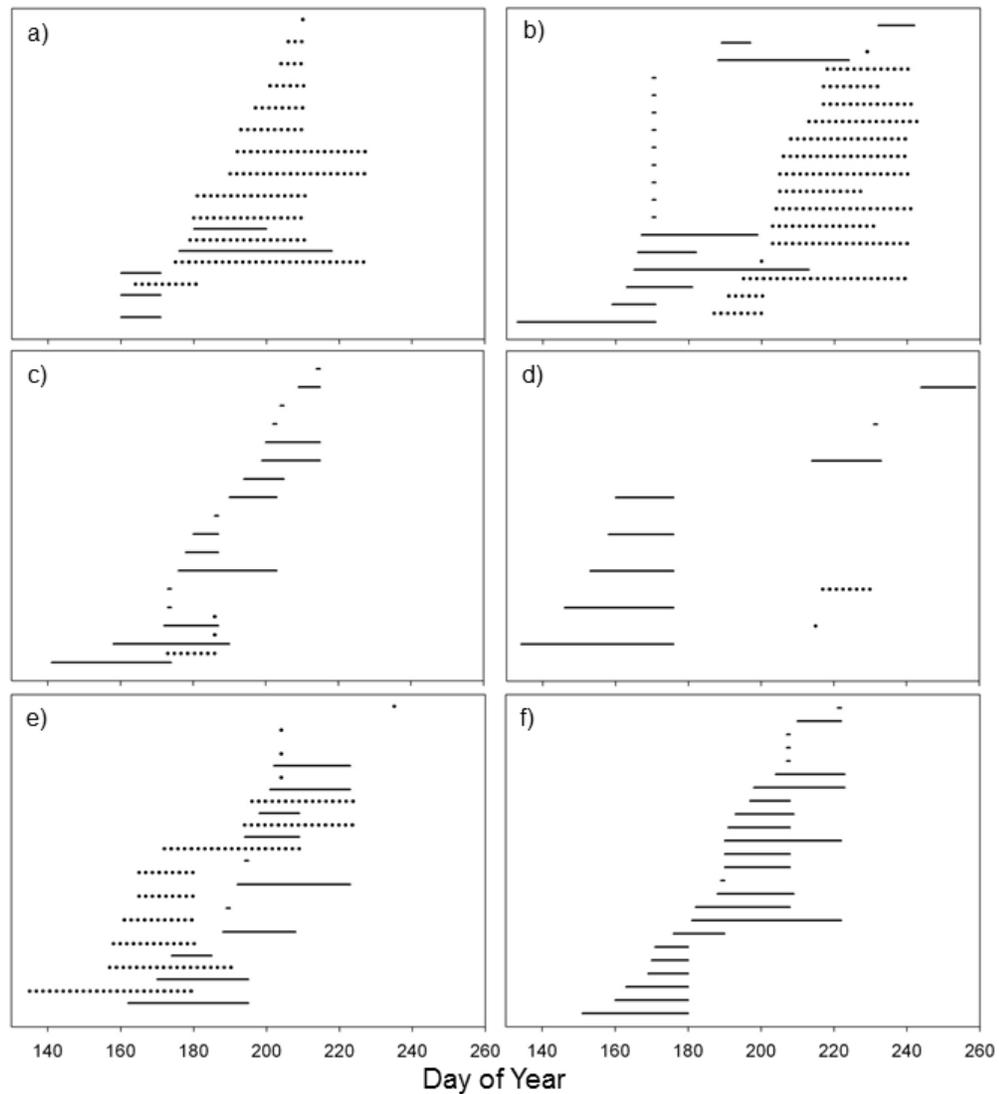


Fig. 3.5. Day of entrance into marine waters and capture for juvenile Chinook salmon collected at two estuaries and surf zones during 2008-2010. Line starts when fish entered marine water and length signifies residence in marine water until juvenile was collected. Filled lines = individual collected in estuary, dashed line = individual collected in surf zone. (a) Coos Bay and Surf 2008, (b) Alsea Bay and Surf 2008, (c) Coos Bay and Surf 2009, (d) Alsea Bay and Surf 2009, (e) Coos Bay and Surf 2010, (f) Alsea Bay 2010.

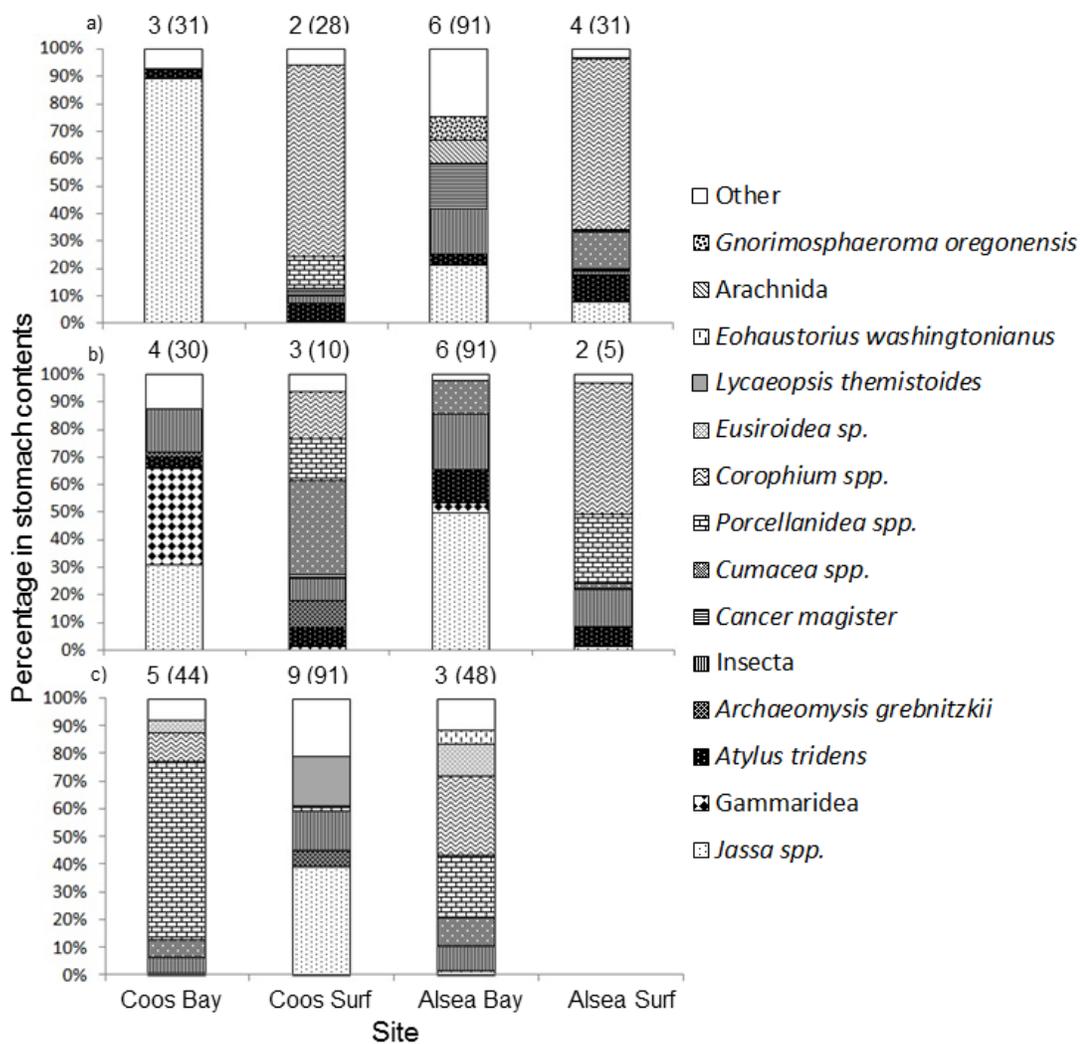


Fig. 3.6. Numerical percentage of juvenile Chinook salmon main prey items collected in two estuaries (Coos Bay and Alsea Bay) and two surf zones (Coos Surf and Alsea Surf) during 2008 (a), 2009 (b) and 2010 (c). Also detailed is the number of days and number of juveniles (in parenthesis) included in analyses. Low sample sizes did not allow analysis of diet composition at Alsea Surf during 2010.

CHAPTER 4

JUVENILE CHINOOK SALMON GROWTH IN SURF ZONES AND ESTUARIES AND POTENTIAL IMPACTS OF CLIMATE CHANGE

Jose R. Marin Jarrin

ABSTRACT

Early marine residence is considered a critical period for juvenile salmonids. During this important period, the majority of juvenile Chinook salmon age-0 reside in estuaries for several months but a small number (<10%) also use sandy beach surf zones. Despite the importance of this period, the factors influencing juvenile Chinook salmon to use surf zones or variation in growth in this habitat are still unclear. We correlated juvenile catch from two surf zones with growth rates and catches in estuaries and growth rates in surf zones; examined factors that affect variation in growth in both surf zones and estuaries; and determined how growth in these habitats may vary due to climate change. We collected juvenile Chinook salmon during three years at two surf zones and their adjacent estuaries and examined growth variation using otolith, bioenergetics and sensitivity analyses. Catches were positively related to surf zone growth at one beach. Under current conditions, consumption rates accounted for more of the variation in growth (>50%) than prey energetic content (>10%) and temperature (>5%) in both surf zones and estuaries. Based on predictions of future increases in water temperature due to climate change, growth rates would decrease by 9 to 40% in surf zones and estuaries

if diet composition and consumption rates remain similar to present conditions. Our results suggest good growth conditions in surf zones can influence surf zone use, and that in surf zones and estuaries, variation in present day growth rates is most strongly influenced by variation in consumption rates. However, our predicted increases in water temperature in both habitats may decrease overall juvenile growth and potentially survival. To compensate for the decline in growth, juveniles may increase their consumption rates or consume more energetically rich prey, if available. Better understanding of the impact of climate change on juvenile salmon growth will require predictions on alterations to the abundance and composition of prey fields in coastal habitats.

INTRODUCTION

Anadromous species use a suite, or portfolio, of freshwater, coastal, and marine habitats during their ontogenetic migrations (McDowall 1988; Bertness et al. 2001). Overall population persistence may be increased if members of a population exploit different habitats across years so that, if there is a catastrophic event all individuals from the cohort are not eliminated (Healey and Prince 1995; Hilborn et al. 2003; Secor 2007; Fodrie et al. 2009; Schindler et al. 2010; Fulford et al. 2011; Dantas et al. 2012; Schein et al. 2012). Populations that use multiple habitats have been termed spatially split cohorts (Robinson and Wilson 1994) and have been observed in all vertebrate classes (for review see Skúlason and Smith 1995). The choice of habitat for anadromous fish, especially during their juvenile stage, is

considered a compromise between growth potential and predation pressure (Healey 1991; Quinn 2005; Taylor et al. 2007; Scharf et al. 2009; Woodland and Secor 2011). However, due to the narrow seasonal window during which juvenile transition from freshwater to marine habitat occurs, anadromous juveniles may increase their feeding rates to increase their growth, thus exposing themselves to higher predation risk (Healey 1991; Sandercock 1991; Werner and Gilliam 1984; Grand and Dill 1997).

Among the portfolio of habitats anadromous fish may use when they first enter the ocean are sandy beach surf zones (Strydom and d'Hotman 2005; Able et al. 2011; Marin Jarrin and Shanks 2011). Surf zones are defined as semi-enclosed environments that extend from the shoreline to the outer most breaking wave. These environments are inhabited by a fish community mostly composed of larvae and juveniles (reviewed in McLachlan and Brown 2006). Possible reasons for surf zone residence include an abundant supply of potential prey and shelter from predators in turbid shallow waters, factors that characterize most juvenile fish nursery habitats (Beck et al. 2001; Dahlgren et al. 2006; McLachlan and Brown 2006). Factors found to positively influence fish abundance and species richness specifically in sandy beach surf zones include the presence of nearby (or adjacent) estuaries or river mouths, structure within surf zones, greater abundance of detached macrophytes, and water temperatures appropriate for relatively high growth rates (Allen and Pondella II 2006; McLachlan and Brown 2006).

Chinook salmon (*Oncorhynchus tshawytscha*) is an anadromous fish species that spawns in most rivers of western North America north of San Francisco, California (Healey 1991). The majority of juveniles initiate their migration to the ocean during their first or second year of life, during which they are termed subyearlings or yearlings, respectively (Healey 1983). On the west coast of continental USA, most Chinook salmon migrate to the ocean as subyearlings (Rich 1920; Reimers 1973; Nicholas and Hankin 1988). For subyearling Chinook salmon, estuaries are considered a nursery habitat due to the high potential for growth, refuge from predation and ability to acclimate to oceanic waters (reviewed in Simenstad et al. 1982; Healey 1991; Bottom et al. 2005). Juveniles arrive in estuaries during the spring, summer and fall and may remain for up to six months before continuing their migration to deeper oceanic waters (reviewed in Simenstad et al. 1982; Healey 1991; Bottom et al. 2005). Due to high rates of mortality, this early period of marine residence is considered a critical time during which the number of juveniles surviving to adulthood can be determined (reviewed in Healey 1991; Pearcy 1992; Quinn 2005). During this critical marine period, water temperature and diet are hypothesized to be the main influences of growth and subsequent survival (Brett 1979; Wootton 1998; Trudel et al. 2002; Beauchamp and Duffy 2011), with larger faster growing juveniles often surviving at a higher rate than smaller slower growing fish (Beamish and Mahnken 2001; Reed et al. 2010; Tomaro et al. 2012).

During the summer season, a small number of subyearling Chinook salmon (<10%) also use sandy beach surf zones (Marin Jarrin et al. 2009, In review). The

factors influencing surf zone use by juvenile Chinook salmon are at present unclear; however, two hypotheses have been developed to explain their presence in surf zones. Reimers (1973) collected large numbers of subyearling Chinook salmon at sandy beaches adjacent to the Sixes River estuary in Oregon USA and hypothesized that juveniles had moved from the estuary to the surf zone when large increases in population abundance decreased the abundance of prey and therefore influenced growth conditions in the estuary during the summer. Marin Jarrin et al. (2009) collected juveniles at another Oregon beach adjacent to Coos Bay during summer and hypothesized that relatively high growth rates provided by the high prey abundance and/or low predation pressure may have attracted juveniles to surf zones. The latter hypothesis has been proposed to explain surf zone use by juvenile fish around the world (McLachlan and Brown 2006). To address these two hypotheses, we explored if growth rates in estuaries or adjacent sandy beach surf zones influence surf zone use by juvenile Chinook salmon.

Salmon populations in western North Pacific are hypothesized to be severely impacted by the near future predicted changes in climate (IPCC 2007). In coastal habitats of western North America, modeling studies predicted an increase in fresh water temperature, annual precipitation, sea surface height and wave height, and a decrease in water pH (Wootton et al. 2008; Mantua et al. 2009; Mote and Salathé 2009; Ruggiero et al. 2010). In this region, coastal upwelling reduces water temperature of nearshore environments during the summer season (Hickey and Banas 2003). Regional predictions for how climate change will affect coastal

upwelling are inconclusive (Bakun et al. 2010). Some researchers predict local upwelling winds will either not change (Mote and Mantua 2002; Mote and Salathé 2009) or increase in strength and variability in the near future (Di Lorenzo et al. 2005; Bakun et al. 2010; García-Reyes and Largier 2010). However, Di Lorenzo et al. (2005) also predicted that increasing upwelling wind strength would be counteracted by surface heating, which would lead to warmer sea surface temperature, a deeper thermocline and higher stratification. Due to contradicting predictions on how upwelling wind strength would vary and because none of the studies that predict an increase in wind strength provide estimates on how much water temperature would decrease in the near future, in the present study we assumed that upwelling winds will not vary significantly in the next 50 years. However, future analysis will include scenarios in which upwelling wind strength increases and sea surface temperature decreases.

In the present study, we (1) tested the two hypotheses detailed above for surf zone use by relating surf zone catch to estuarine catch and specific growth rates in estuaries and the adjacent surf zones; (2) determined which factors accounted for the majority of growth variation in surf zones and estuaries under present day conditions; and (3) estimated how predicted changes in climate could modify present day estuarine and surf zone water temperature and therefore affect growth in both habitats.

MATERIALS AND METHODS

We collected juveniles during three years at two Oregon (USA) estuaries and adjacent surf zones, and estimated catches and specific growth rates using otolith analysis. We then modeled growth rates during present day conditions using *in situ* measurements of prey energetic content and temperature, and conducted a sensitivity analysis to determine which variables (energetic content of prey, consumption rates, or water temperature) accounted for variability in growth. Finally, we estimated how growth rates may change in the near future in both habitats using a bioenergetics model and regional predictions for future changes in water physical characteristics.

Study region

Juveniles were collected at two estuaries (Coos and Alsea Bay) and two adjacent surf zones (Coos and Alsea Surf) in Oregon, USA (Fig. 4.1). Coos and Alsea Bay are drowned river mouth estuaries with very little freshwater inflow during the summer (Emmett et al. 2000). Coos and Alsea Bay differ in their sizes, depth, classification and the origin of juvenile Chinook salmon within them (Table 4.1). Coos and Alsea Surf are dissipative (shallower slope) sandy beaches (McLachlan 1980; Short and Wright 1983) that experience moderate wave height in the summer (average wave height: 1-2 m) when sand accretion may transform them into intermediate beaches (Komar et al. 1976). Coos Surf is located immediately to the south of the Coos Bay mouth and is approximately 3 km long while Alsea Surf is the beach located immediately to the south of the mouth of Alsea Bay and is approximately 10 km long.

Sampling methods

Juveniles were collected between June 1 and September 30 of 2008-2010. In estuaries, juvenile Chinook salmon were collected by Oregon Department of Fish and Wildlife personnel using a 38 m x 4 m x 1.3 cm beach seine with a lead and cork line and a 2.5 m x 2.5 m x 1 cm bag in the center, which was extended from shore in a loop. In surf zones, juveniles were collected using a smaller beach seine (15 m x 1.5 m x 1.0 cm) as detailed in Marin Jarrin and Shanks (2011). Briefly, three people carried the net into the water to a depth of 1.5 m where it was opened parallel to the shoreline in a V-shape and towed back on shore. During 2008, to increase our sample sizes, juveniles were also collected at the beach immediately to the north of Alsea Bay mouth, which is also 10 km long and has similar physical characteristics as Alsea Surf (Marin Jarrin, unpublished data).

Juvenile Chinook salmon are present in surf zones and estuaries during all tides throughout the day during the summer (Reimers 1973; Healey 1980; Marin Jarrin 2007; Marin Jarrin et al. 2009, In review); therefore sampling was conducted approximately once a day every two weeks during lower low spring tide in both habitats for safety reasons (Table 4.2). Each day three to six tows were taken and up to 30 juvenile Chinook salmon were euthanized with MS-222 (tricaine methanesulfonate, Argent Chemical Laboratories, $150 \text{ mg}\cdot\text{l}^{-1}$) buffered with baking soda (sodium bicarbonate, $300 \text{ mg}\cdot\text{l}^{-1}$) and then transported back to the laboratory on ice for further analysis. During 2010 we also collected surf zone potential prey using

a hyperbenthic sledge, as detailed in Marin Jarrin and Shanks (2011), to determine the energetic content of prey.

Environmental data collection

To study how water temperature influences growth variability and estimate future water temperature we developed mixing models using data on fresh, estuarine, surf zone and sea surface water temperature, estuarine tidal range, and coastal wave height. The most informative mixing model was selected using stepwise, computer assisted, multiple linear regressions and tested assumptions as described below (Ramsey and Schafer 2002). We obtained estuarine and fresh water temperature data for Coos Bay and Winchester Arm (within Coos watershed) from the National Estuarine Research Reserve sampling stations (NERRS: <http://cdmo.baruch.sc.edu/get/export.cfm>). During 2010, water temperature at Alsea Bay, and Coos and Alsea Surf was measured every 30 minutes by placing HOBO® digital temperature loggers (model UA-002-64) on the Alsea Bay bridge (44° 26' 30 N, 124° 03' 00 W), and on buoys located in the surf zone of Coos and Alsea Surf and on the Coos Bay south jetty. Coastal sea surface temperature and wave height data were obtained from the National Oceanic and Atmospheric Administration Buoy Station 46229 located 30 km west of Reedsport, Oregon (43°46'10" N 124°33'2" W). Tidal range data for Coos and Alsea Bay data was obtained from NOAA tides and currents (<http://tidesandcurrents.noaa.gov/geo.shtml?location=9432780>). We developed predictive relationships for both estuaries and surf zones to use when data at Alsea

Bay, and Coos and Alsea Surf were not available (2008 and 2009) and to predict future changes in estuarine and surf zone water temperature (Table 4.3).

Juvenile size, catch and prey analysis

In the lab, juveniles were measured (fork length, FL, mm) and weighed (g), and we extracted stomachs and otoliths. Juvenile catch was estimated by determining the area sampled by each net (individuals 100m^{-2}). In estuaries the area sampled was calculated by assuming the length of the net was the perimeter of a circle, and in surf zones by using the distance from the shoreline to the point at which the beach seine was opened and the width of the mouth of the seine when opened in a V-shape.

We determined diet composition and estimated the energetic content of prey to use as input variables in the bioenergetics model. We determined diet composition by identifying and counting stomach contents to the lowest taxonomic level possible. We then averaged fish data to calculate an overall diet composition per day. We also identified potential prey samples collected during 2010 to the lowest taxonomic level possible and then determined the energetic content of prey using a bomb calorimeter (PARR Oxygen Bomb Calorimeter Model 1341) following manufacturer protocols. Samples used to determine prey energetic content were wet weighed, dried at 70°C for 24 hours, reweighed and pulverized prior to combustion. After combustion, dry weight energy data (Joules g^{-1} dry weight) was transformed to wet weight (Joules g^{-1} wet weight) using wet-to-dry weight ratios estimated from lab analysis. Percentage of prey that was indigestible was also recorded (Table 4.4). Energetic content of prey

that were not collected with the sledge were obtained from the literature (Davis 1993; Groot et al. 1995; Gray 2005).

Juvenile specific growth rates

We used otolith microstructure to estimate juvenile specific growth rates in surf zones and estuaries. We employed specific growth rates to account for difference in fish sizes. Otoliths were extracted and processed as detailed in Miller (2007). Otoliths were prepared for analysis by grinding both sides using wet-or-dry paper and lapping film to expose the dorsal-ventral growth axis. Microstructure was analyzed using ImagePro Plus[®] software. Otoliths were photographed at 40 and 400x to visualize and measure otolith and increment widths, respectively. We estimated individual growth rates by estimating juvenile size using a proportional back-calculation method (Francis 1990), which allowed us to account for individual variation in fish size. We developed separate regression models for each estuary/surf zone site during each year (Table 4.5) as described below:

$$\log_{10}(FL_C) = a + b * \log_{10}(OW_C)$$

(1)

where FL_C = fork length (mm) at capture and OW_C = otolith width (μm) at capture.

We then back-calculated fork length as described below

$$\log_{10}(FL_{BC}) = \frac{\log_{10}(FL_C)}{\log_{10}(FL_{EC})} * [a + b * \log_{10}(OW_{BC})]$$

(2)

where FL_{BC} = fork length (mm) at a back-calculated size, FL_{EC} = estimated fork length at capture (mm, estimated using equation 1), OW_{BC} = otolith width (μm) at a back-calculated size (for more detail see Francis 1990).

We measured increment widths for the last 14 days of the fish's life to estimate their growth rates. We chose the last 14 days since we collected juveniles every 14 days and because there were no difference in average increment widths between the last 14 and 10, 7 or 3 days (paired t-test, $p > 0.05$). Widths of the last 14 increments were measured twice at least a week apart and the difference in measurements recorded to estimate error (<5%). We then back-calculated size 14 days before capture using Equation 2 and calculated recent growth rates with the following:

$$\text{Growth rates (mm)} = \frac{\text{Fork length at capture} - \text{Fork length 14 days earlier}}{14}$$

(3)

We transformed growth in length to growth in weight using the relationship between FL and weight ($n = 248$, $r^2 = 0.95$, $p < 0.01$) obtained with local measurements:

$$\text{Mass (g)} = 0.0082 * \text{Length (cm)}^{3.1598}$$

(4)

Finally, we calculated specific growth rates as % of body weight day^{-1} :

$$\text{Specific growth rate} = \frac{\text{Growth rate (g day}^{-1}\text{)} * 100\%}{\text{Fish mass (g)}}$$

(5)

Relation of surf zone catch with growth rates and estuarine catch

To test the hypotheses that surf zone use is influenced by estuarine or surf zone growth conditions we correlated surf zone catch to estuarine specific growth rates and catches and surf zone specific growth rates using simple linear regression analysis separately at each beach. We only used days when juveniles were collected in surf zones, and when estuarine collections occurred within a week (Table 4.6). Data were $\log_{10}(x+1)$ transformed in order to meet parametric assumptions, which were tested using normal probability (quantile–quantile) plots, and boxplots of residuals versus fitted values (Sokal and Rohlf 1981). The relative influence of each observation was determined using Cook’s distance (Ramsey and Schafer 2002).

Variables influencing juvenile growth rates

To evaluate how consumption rates, mean energetic content of prey, and temperature account for variability in growth, we modeled specific growth rates in surf zones and estuaries throughout the summer and conducted a vary “one-at-a-time” sensitivity analysis (Beauchamp et al. 1989). This analysis allows us to account for the variability in a response variable (i.e. specific growth rate) from each member of a group of interacting input variables (i.e. consumption rates, energetic content of prey or temperature). This analysis was conducted separately at Coos and

Alsea habitats. To model growth rates we used the Wisconsin Bioenergetics model and the Chinook salmon species parameters (Stewart and Ibarra 1991; Hanson 1997). The Wisconsin bioenergetics model is based on the premise that the energy obtained through consumption is equal to the energy used in metabolism, waste products and growth. In this particular model, metabolism includes respiration and specific dynamic action, while waste includes excretion and egestion products. The model is constructed with four sub-models: consumption, respiration, egestion/excretion and predator energy density. The consumption sub-model is a function of the physiological maximum prey consumed, proportion of the physiological maximum prey consumed, and water temperature (Thornton and Lessem 1978). The respiration sub-model is a function of fish weight, water temperature and activity, where the activity function is based on swimming speed (Stewart et al. 1983). The egestion/excretion sub-model (Stewart et al. 1983) is based on the proportion of maximum food consumed, water temperature and indigestibility of prey. The excretion portion of the sub-model also incorporates the energy obtained through consumption that is lost through egestion. Finally, the predator energy density is a linear function of body mass (Stewart and Ibarra 1991). This sub-model assumes the relationship between energy and body mass is different if the fish is above or below 4,000g.

The Wisconsin bioenergetics model has been evaluated and successfully used in multiple habitats such as streams, lakes, estuaries and oceans to estimate growth and consumption rates in Chinook salmon (Brodeur et al. 1992; Sommer et al. 2001;

Madenjian et al. 2004; Gray 2005; Koehler et al. 2006; MacFarlane 2010) but to our knowledge has never been used in sandy beach surf zones. To validate the bioenergetics model in surf zones we sampled juveniles every 3 hours during a 27-hour period during the summer of 2010 at Coos South and estimated consumption rates using the MAXIMS fish feeding model (Jarre-Teichmann et al. 1993). We then used these consumption values in the model to estimate growth rates, which were within 2% of our otolith-derived values.

To determine how each variable accounted for variability in growth we first modeled daily consumption rates using daily average observations or estimates of temperature ($^{\circ}\text{C}$), diet composition (%), prey energetic content (Joules g^{-1} wet weight), percentage of each prey taxa that is indigestible (%), growth (g day^{-1}) and fish weight (g) as inputs for the model (Table 4.6). Therefore, model time step was set at 1 day. Besides consumption rates, the model also calculates the proportion of maximum consumption rates (p-value). Chinook salmon energy content is a variable that can be entered by the user or estimated by the model. We used model estimates because initial analysis found these to better fit field estimates of consumption rates (see discussion). We then modified the Bioenergetics model to provide growth rates as the output variable using water temperature, fish weight, mean energetic content of prey and consumption rates as input variables (i.e. energy used for growth is equal to energy obtained through consumption minus energy expended in metabolism and waste) and then followed the same procedure as above. Each input variable was averaged for each habitat/site, and used to calculate a specific growth rate reference

value. We then modified each input variable, except fish weight, by increasing and decreasing the mean by one standard deviation, rerunning the bioenergetics model and noting the percentage change in growth rates. We used a standard value for the percentage of prey that is indigestible (18%), which is the mean value for all prey items encountered in this study (Table 4.4).

Future change in surf zone and estuarine water temperature and juvenile growth rates

To study how climate change may affect growth rates in surf zones and estuaries we used the mixing model developed for the previous objective and modeled growth rates in the next 50 years. We evaluated how predicted changes in climate may influence estuarine and surf zone water temperature by using the predictive relationships detailed above for summer 2010 data (n = 60 days, Table 4.3) as a baseline and developed two future scenarios. We only used summer 2010 data because this was the year water temperature was measured directly at all sites. In the future scenarios, we assumed no change in coastal upwelling (Mote and Mantua 2002; Mote and Salathé 2009). In the first future scenario, we increased summer fresh water temperature, sea surface temperature and wave height by 1.5°C, 1.2 °C and 0.75 m, respectively during the 60 days we had measurements. In the second scenario, we increased the same variables by 5.8°C, 1.2°C and 0.75 m, respectively (Mantua et al. 2009; Mote and Salathé 2009; Ruggiero et al. 2010). We then entered these predicted future water temperature data (mean \pm 1 standard

deviation of 60 days) in the bioenergetics model and estimated how specific growth rates would change if other variables remain at present conditions (i.e. juvenile salmon weight, mean energetic content of prey, % of prey that is indigestible and consumption rates). We used average values from our 2008-2010 collections for present day conditions (Table 4.6) to obtain a realistic mean estimate for these factors at both habitats/sites. Finally, to study the effect changes in growth rates would have on fish size at the end of this critical period, we estimated the size that a juvenile Chinook salmon (5g) would attain after 60 summer days under present and future scenarios. We used 5g as an initial weight because a previous analysis found these to be average values for surf zone and estuarine caught juveniles when they first entered brackish/ocean waters (Marin Jarrin, unpublished data). For our present scenario we used an average value (1.4% of body weight day^{-1}) as specific growth rate for all sites.

RESULTS

Relation of surf zone catch and growth rates

Surf zone catches averaged 3 ± 6 ind. 100m^{-2} (7 ± 8 ind. 100m^{-2} at Coos Surf and 0.6 ± 0.4 ind. 100m^{-2} at Alsea Surf), while in estuaries they averaged 71 ± 62 ind. 100m^{-2} (34 ± 32 ind. 100m^{-2} at Coos Bay and 130 ± 60 ind. 100m^{-2} at Alsea Bay) (Table 4.6). Specific growth rates were similar when compared between surf zones (1.4 ± 0.3 and $1.4 \pm 0.4\%$ body weight day^{-1} in Coos and Alsea Surf, respectively) and estuaries (1.5 ± 0.4 and $1.4 \pm 0.3\%$ body weight day^{-1} in Coos and

Alsea Bay, respectively) (Table 4.6). At Coos Surf, juvenile catches were positively related to surf zone specific growth rates ($F_{1,7} = 23.69$, $p = 0.002$, $r^2 = 0.77$, Fig. 4.2) but were not related to estuarine specific growth rates or catches ($F_{1,7} = 1.82$ and 2.49 , respectively, $p > 0.05$). At Alsea surf, juvenile catches were not related to surf zone specific growth rates ($F_{1,4} = 1.59$, $p = 0.28$), estuarine specific growth rates ($F_{1,4} = 0.01$, $p = 0.92$) or estuarine catches ($F_{1,4} = 0.02$, $p = 0.90$).

Variables influencing juvenile growth

Overall, daily water temperature ranged from 11 to 14°C in estuaries (Coos Bay = 12.3 ± 1.2 and Alsea Bay = 12.2 ± 1.1 °C) and from 9 to 12°C in surf zones (Coos Surf = 9.9 ± 0.7 and Alsea Surf = 10.8 ± 0.7 °C). Juvenile mass averaged 13.6 ± 6.8 g (10.7 ± 4.5 in Coos habitats and 16.8 ± 7.7 g in Alsea habitats). In estuaries, juveniles fed on 49 taxa, the most abundant of which was *Corophium* spp. (60% of total diet items, Table 4.7). The main prey groups were amphipods (70% of taxa), crustacean zoea and megalopae (15%), cumaceans (5.3%) and insects (3.3%). Surf zone juveniles fed on 57 taxa, the most abundant of which was a gammarid amphipod, *Jassa* spp. (42% of total diet items). The main prey groups were amphipods (70% of taxa), dipteran insects (14%), mysids (6%), crab megalopae (5%), isopods (1%), and larval and juvenile fish (1%). Energetic content of prey varied from 2374 to 4811 Joules g⁻¹ wet weight and averaged 3607 ± 456 Joules g⁻¹ in estuaries and 4267 ± 385 Joules g⁻¹ in surf zones (Table 4.6). Consumption rates varied from 0.5 to 2.2 g day⁻¹, and averaged 1.31 ± 0.42 g day⁻¹ in estuaries and 0.87

$\pm 0.40 \text{ g day}^{-1}$ in surf zones. The proportion of maximum consumption (p-value) ranged from 0.40 to 0.98 and averaged 0.62 ± 0.15 . Consumption rates and p-values were strongly, positively related ($n = 29$, $r^2 = 0.86$, $p < 0.01$, Table 4.6).

We found that under current conditions, variation of ± 1 SD in consumption rates produced the largest change in surf zone specific growth rates (mean = 59%), followed by mean energetic content of prey (8%) and temperature (4%) (Table 4.8). Similarly, under current conditions, largest changes in estuarine specific growth rates occurred with variation of consumption rates (54%), followed by mean energetic content of prey (20%) and temperature (8%).

Change in surf zone and estuarine water temperature and juvenile growth rates

Estuarine and surf zone water temperatures would increase by 1.3 to 2.0°C under future scenario 1, and by 3.5 to 4.5°C under future scenario 2 (Fig. 4.3). Water temperature increases were slightly higher in the Coos habitats compared to the Alsea habitats (mean: $0.50 \pm 0.40^\circ\text{C}$ SD). Including these values in our bioenergetics model produced an average decrease in specific growth rates of 9% in surf zones and 14% in estuaries under scenario 1, and 28% in surf zones and 39% in estuaries under scenario 2 (Fig. 4.4). Finally, using these declines in specific growth rates, juveniles that entered brackish/ocean waters at 5 g would be slightly heavier in surf zones than in estuaries after 60 days under scenario 1 (mean: $8.8 \pm 0.2\text{g}$ vs. $8.6 \pm 0.3\text{g}$ SD, respectively) and scenario 2 ($8.0 \pm 0.3\text{g}$ vs. $7.8 \pm 0.3\text{g}$). However, juveniles from

both habitats and scenarios would be smaller than fish under present day conditions, i.e. 9.2 g (Fig. 4.4).

DISCUSSION

Our results from the surf zone adjacent to Coos Bay provide support for the hypothesis that when growth rates are relatively high, more juvenile Chinook salmon use sandy beach surf zones (Marin Jarrin et al. 2009). The possibility to use surf zones may arise as juvenile Chinook salmon arrive at estuaries. On average, surf zone caught Chinook salmon used in the present study entered marine waters at a later time than estuarine caught juveniles (Marin Jarrin, unpublished data), potentially because earlier arrivals had established residence in estuaries thus forcing later arrivals to move to surf zones. This territorial behavior during migration of first arrivals outcompeting later arrivals for the preferred habitat is common in Atlantic salmon (*Salmo salar*) in freshwater environments, to the point where only a few days may decide which fish occupies a preferred territory (Metcalf and Thorpe 1992; Kvingedal and Einum 2011). Therefore, if many size appropriate juvenile Chinook salmon move out of the estuary they may choose to use sandy beaches in higher numbers when surf zone growth rates are high.

Variables influencing juvenile salmon migration and movement remains one of the most poorly understood factors of their biology. However, several studies have suggested that variables influencing growth are related to juvenile salmon movement. MacFarlane and Norton (2002) suggested that low prey quality and

abundance and/or suboptimum water temperatures in the estuary could have influenced juvenile Chinook salmon to quickly migrate through the San Francisco estuary. In Puget Sound, higher potential growth due to higher prey availability has also been suggested to influence juvenile movement from the nearshore to deeper waters as juvenile Chinook salmon increase in size (Duffy et al. 2010). Our results indicate that at Coos Surf, high growth rates are related to higher juvenile Chinook salmon abundances.

We observed no evidence that juvenile Chinook salmon habitat use at Alsea Surf was related to catches or growth rates in estuaries or surf zones. The fact that we did not observe similar relationships at Alsea Surf as we did at Coos Surf may be due to low catches and number of days during which we collected juveniles at Alsea Surf. Alternatively, the lack of relationship at Alsea Surf might be due to the physical and human development differences between Coos and Alsea bays (Table 4.1). In particular (1) the lower levels of human development (i.e. jetties, rip rap, channels) could provide appropriate habitat for a larger number of subyearling Chinook salmon at Alsea Bay than at Coos Bay; (2) the lack of jetties at the Alsea Bay mouth that may allow juveniles to use surf zones during short time period foraging trips and quickly return to the estuary, and therefore be less available for collections; (3) the lack of hatchery releases at Alsea Bay, as hatchery juveniles have been known to use fresh water and estuarine habitats for shorter periods of time during migration than juveniles of natural origin (Dawley et al. 1986; Zhang and Beamish 2000; Chittenden et al. 2010), or (4) the fact that juveniles were on average

larger at Alsea than at Coos Bay, and larger juveniles may migrate faster and not seek shallow habitats when they exit the estuary (Dawley et al. 1978, 1986; Kjelson et al. 1982).

Consumption rates accounted for more of the variation in juvenile Chinook salmon growth than prey or temperature in surf zones and estuaries under present day conditions. This result suggests that prey availability or foraging conditions strongly influence growth rates; however, which is more influential on variation in consumption rates and therefore growth rates remains unclear. There was a strong positive relationship between consumption rates and proportion of maximum consumption, which is considered a measure of relative food availability (Beauchamp et al. 2007). We also observed a positive relationship between juvenile Chinook salmon stomach fullness (another measure of consumption rates) and the abundance of their main prey item (*Jassa* spp.) in the prey field (Marin Jarrin, unpublished data). However, wave height, which is a factor that may influence surf zones by affecting water velocity, turbulence and visibility, and thus influencing foraging conditions (Fausch 1984; Vogel and Beauchamp et al. 1999), was not related to modeled consumption rates. These observations combined indicate prey availability is a main influence of consumption and therefore growth rates in surf zones and estuaries. Similar conclusions have been reached in juvenile salmonid studies conducted in rivers (Sommer et al. 2001; Limm and Marchetti 2009), estuaries (Reimers 1973; Neilson et al. 1985) and the coastal ocean (Beauchamp et al. 2007; Beauchamp and Duffy 2011). Sommer et al. (2001) and Limm and

Marchetti (2009) compared growth rates in two habitats within the Sacramento River (California, USA) and found that the area with higher prey availability had higher juvenile growth rates. However, the second study did not disentangle the effects of prey availability and water temperature on growth rates. Reimers (1973) and Neilson et al. (1985) studied juvenile Chinook salmon in the Sixes River estuary (Oregon, USA) and observed a decrease in prey availability during the middle of the summer that was accompanied by a decrease in growth rates and increases in water temperature. Finally, Beauchamp et al. (2007) and Beauchamp and Duffy (2011) examined growth rates of salmonids between years with high and low survival rates and found that differences in consumption rates of their main prey item best explained the differences in growth and survival.

Several previous studies have suggested water temperature is the most influential variable on juvenile salmonid growth (Brett 1979; Geist et al. 2006; Crozier et al. 2010). Our analysis indicates that given our observed range, water temperature accounted for a small proportion of variation in growth rates, which may be because these surf zones and lower estuaries are strongly influenced by recently upwelled cold nutrient rich oceanic waters during the summer season (Emmett et al. 2000; Hickey and Banas 2003; Marin Jarrin and Shanks 2011). This oceanic influence may have maintained average daily water temperatures between 10 and 14°C in our study period (Marin Jarrin and Shanks 2011, <http://cdmo.baruch.sc.edu/get/export.cfm>), values which are considered within the optimum range for juvenile salmonid growth when consumption rates are above 50% of what is

physiologically possible (Brett 1979). Therefore in our study, consumption rates were more influential than water temperature on juvenile Chinook salmon growth rates in surf zones and estuaries potentially because water temperature remained within the range for optimum growth.

Our results indicate that growth rates for juveniles in both surf zones and estuaries would decrease in the next 50 years under predicted climate change scenarios. These results also suggest that future growth reduction may be slightly greater in estuaries than in surf zones, which may increase juvenile use of sandy beaches during the summer season. Given that juvenile salmon size and growth during early marine residence can influence survival to adulthood (Beamish and Mahnken 2001; Reed et al. 2010; Tomaro et al. 2012), reductions in growth rates during early marine residence could negatively impact survival. Because juveniles do not appear to be feeding at their maximum rate, they could compensate for this decrease in growth conditions by increasing their consumption or switching to prey with higher energetic content. Other studies have also suggested juvenile salmon growth will be reduced in the near future due to climate change. Crozier et al. (2008) found that in the Snake River USA, increases in summer water temperature and decreases in precipitation may increase mortality and therefore reduce the size of the various populations of Chinook salmon, potentially due to reduction in fish growth rates, predator avoidance and speed of developmental processes. In the coastal ocean, Trudel et al. (2002) found prey quality to be a main factor influencing juvenile coho salmon growth rates and suggested that predicted increases in sea

surface temperature in the Pacific Ocean could facilitate changes in the prey field. Parson et al. (2009) summarized potential impacts of climate change on the communities of western North America and predicted that rising water temperatures in rivers and estuaries would reduce growth rates and potentially survival to adulthood. Like these previous analysis, our study should be considered preliminary, as we were not able to include all potential changes in both habitats such as variation in upwelling wind strength. In coastal habitats during summer coastal upwelling provides cold waters that are rich in nutrients and fuel primary production (Hickey and Banas 2003). Recent studies have predicted that in the future upwelling wind strength will: (1) not change (Mote and Mantua 2002; Mote and Salathé 2009), (2) increase and therefore decrease coastal ocean water temperature (Bakun et al. 2010; García-Reyes and Largier 2010), and (3) increase but this will be counteracted by surface heating, which would lead to warmer sea surface temperature, a deeper thermocline and higher stratification (Di Lorenzo et al. 2005). In the present study we assumed that upwelling strength will not change and sea surface temperature will increase in the near future, but a future study will incorporate scenarios in which sea surface temperature decreases to include all potential outcomes.

Our bioenergetics approach is based on the assumption that the bioenergetics model accurately estimates conditions in highly dynamic environments such as estuaries and surf zones. To evaluate this assumption we looked at several lines of evidence: (a) The Wisconsin bioenergetics model has been previously evaluated and successfully used with multiple fish species (for review see Ney 1990; Madenjian et

al. 2004; Hartman and Kitchell 2008), and validated in the present study, (b) In our study, our average p-values are within the range considered common for juvenile fish in the wild and were always below maximum consumption, which suggests we did not overestimate growth rates in estuaries and surf zones. These results were obtained using the model estimates of predator energetic content that were found to fit the model better than user estimates, and are based on a positive relationship between fish weight and energetic content (Stewart and Ibarra 1991; Hanson 1997).

We also assumed that low sample sizes in surf zones did not bias our findings. Although larger sample sizes would be ideal, the fact that we only used days with juvenile collections, that our growth and consumption estimates are consistent with the literature (Koehler et al. 2006; Beauchamp et al. 2007; MacFarlane 2010) and that our results were not driven by data from days with smallest catches, as suggested by our low Cook's distance values (< 1), gives us confidence that our conclusions are an accurate assessment of growth and consumption in surf zones and estuaries.

Habitat quality as perceived by fish may vary spatially and temporally (Gibson 1994; Post and Johannes 1997; Kraus and Secor 2004). These variations may occur due to different or changing abiotic (sediment or water physical characteristics, water depth, habitat structure) and biotic factors (fish size, prey availability and quality, predation pressure, competition) (Post and Johannes 1997; Giannico and Healey 1999; Callihan et al. 2008; Raedemaeker et al. 2012).

Variation in the perceived quality of habitats may influence fish to move to alternative habitats and therefore to the formation of spatially split cohorts (Robinson and Wilson 1994; Skúlason and Smith 1995; Secor 2007; Kvingedal and Einum 2011). Spatially split cohorts have been mostly observed in fish, but also occurs in amphibians, reptiles, birds and mammals (for review see Skúlason and Smith 1995) and is hypothesized to increase population resilience by reducing the probability of a catastrophic event eliminating the whole cohort (Secor 2007). In the case of subyearling Chinook salmon, using estuaries and surf zones may allow them to take advantage of different prey fields while staying in habitats hypothesized to have relatively low predation pressure (Simenstad et al. 1982; Bottom et al. 2005; McLachlan and Brown 2006).

Our findings indicate that juvenile Chinook salmon surf zone use can be influenced by surf zone growth conditions, as demonstrated by the positive relationship between catch and specific growth rates at Coos Surf. At Alsea Surf this influence may have not been detectable due to the conditions in the estuary that could allow juveniles to leave at a larger size thus not requiring the shallow surf zone. In surf zones and estuaries, observed growth variation was most influenced by consumption rates under present day conditions, potentially because current water temperatures in these habitats remained at optimal levels for growth during summer. Predicted changes in climate in coastal western North America will likely modify juvenile growth conditions in the next 50 years, which could result in more juveniles using surf zones and potentially reduce overall survival. Additional insights into the

potential impacts of climate change on juvenile salmon will require estimates of changes in the composition, energetic quality and abundance of prey communities inhabiting coastal environments.

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Table 4.1: Estuary size, mean water depth at lower low tide (depth), type and classification based on human development, and juvenile origin and annual mean number of juveniles of hatchery-origin (\pm SD) released in watershed. - = no juveniles of hatchery-origin released.

Characteristics	Coos Bay	Alsea Bay
¹ Size (km ²)	54	10
^{2,3} Depth (m)	4	< 3
⁴ Type	Drowned river mouth	
⁵ Classification	Draft Developmental (jetty and channels)	Conservation (minor development)
⁶ Juvenile Origin	Hatchery & Natural	Natural
⁶ Hatchery production	2,006,043 \pm 460,675	-

¹Oregon Coastal Atlas web-page: www.coastalatlas.net/:

²NOAA 1985

³ Robert Buckman, Oregon Department of Fish and Wildlife

⁴Emmett et al. 2000

⁵Cortright et al. 1987

⁶Regional Mark Processing Center web-page: www.rmhc.org

Table 4.2: Location, year, number of sampling days (Sampled), number of days in which juveniles were collected (Collected), and sample sizes used for analysis of diet composition and specific growth rates (Growth) in two estuaries (Coos and Alsea Bay) and two surf zones (Coos and Alsea Surf). * = analysis not possible due to low number of juveniles collected.

Location	Year	Sampled	Collected	Diet	Growth
Coos Bay	2008	5	4	31	11
	2009	6	4	30	19
	2010	6	5	44	31
Coos Surf	2008	6	2	28	24
	2009	6	3	10	7
	2010	10	5	91	34
Alsea Bay	2008	6	5	91	29
	2009	7	4	80	30
	2010	6	6	48	30
Alsea Surf	2008	6	4	31	23
	2009	6	2	5	4
	2010	10	2	*	*

Table 4.3. Predictive relationships developed for water temperatures in two estuaries and surf zones on the Oregon coast. Variables included are fresh water temperature (FWT), Coos Bay water temperature (CBT), Coos and Alsea Bay tidal range (CB- and AB-TR, respectively), sea surface temperature (SST), and wave height (WH). +1 and -1 = data lagged one day before or after, ^2 = square term. All temperature values are in °C and wave height in m. All models are significant at $p < 0.0001$.

Location	Model	r^2	n
Coos Bay	FWT + FWT (-1) - CB-TR + SST (+1) + SST (-1) + WH (+1)	0.84	60
Coos Surf	CBT + SST (+1) - SST (+1)^2 - WH + WH^2	0.82	61
Alsea Bay	FWT + AB-TR (+1) + SST (+1) + SST (-1) + WH (+1)	0.68	60
Alsea Surf	CBT^2 - SST (+1) + SST^2 - WH + WH^2	0.62	61

Table 4.4: Values of energetic content of prey taxa (Energy, Joules g⁻¹ wet weight) and percentage of taxa that are indigestible (% indigestible) estimated and used in bioenergetics model of juvenile Chinook salmon collected in two estuaries (Coos and Alsea Bay) and two surf zones (Coos and Alsea Surf) during 2008-2010. Taxa life stage (Stage) and Group are also presented. * = values taken from literature (Davis 1993; Groot et al. 1995; Gray 2005).

Taxa	Stage	Group	Energy	% Indigestible
Caprellidea sp.	Adult	Amphipoda	4438.03	18.07
<i>Corophium</i> spp.*	Adult	Amphipoda	3090.00	26.00
<i>Eohaustorius washingtonianus</i>	Adult	Amphipoda	5270.29	20.00
<i>Eogammarus covernicus</i> *	Adult	Amphipoda	3100.00	26.00
Eusiroidea sp.	Adult	Amphipoda	4438.03	17.56
Gammaridea spp.	Adult	Amphipoda	5270.29	20.00
<i>Jassa</i> spp.	Adult	Amphipoda	4438.03	17.56
<i>Mandilophoxus</i> sp.	Adult	Amphipoda	5270.29	20.00
<i>Megalorchestia pugettensis</i>	Adult	Amphipoda	5270.29	20.00
Pleustidae sp.	Adult	Amphipoda	4438.03	17.56
<i>Dogielinotus loquax</i>	Adult	Amphipoda	5270.29	20.00
<i>Lycaeopsis themistoides</i>	Adult	Amphipoda	4510.32	8.00
<i>Allorchestes angusta</i>	Adult	Amphipoda	4438.03	17.56
<i>Ampithoe lacertosa</i>	Adult	Amphipoda	4438.03	17.56
<i>Atylus tridens</i>	Adult	Amphipoda	3605.77	15.12
<i>Stenolhoides burkanki</i>	Adult	Amphipoda	5270.29	20.00
Squidlets*	Larvae	Cephalopoda	3968.98	7.75
Copepoda sp.*	Adult	Copepoda	2623.37	9.00
Crustacea*	Larvae	Crustacea	3976.00	18.07
Unidentified crustaceans	Larvae	Crustacea	4792.41	18.07
Cumacea *	Adult	Cumacea	3370.00	18.07
Brachyura sp.*	Zoea	Decapoda	3976.00	18.07
<i>Cancer magister</i>	Megalopa	Decapoda	4224.71	18.50
<i>Cancer orogenensis/productus</i>	Megalopa	Decapoda	4224.71	18.50
<i>Cancer</i> sp.*	Zoea	Decapoda	3976.00	18.07
Crangonidae sp.	Juvenile	Decapoda	3953.41	18.98

<i>Euphausia pacifica</i> *	Adult	Decapoda	3110.00	0.10
<i>Fabia subsquatra</i> *	Zoea	Decapoda	3976.00	18.07
<i>Neotrypaea californiensis</i> *	Zoea	Decapoda	3976.00	18.07
<i>Emerita analoga</i>	Adult	Decapoda	5702.63	32.10
<i>Pachycheles</i> sp.	Megalopa	Decapoda	4224.71	18.50
Porcellanidae sp.*	Zoea	Decapoda	3976.00	18.07
<i>Lophopanopeus bellus</i>	Megalopa	Decapoda	4224.71	18.50
Insecta	Adult	Insecta	3510.91	3.33
Insecta*	Larvae	Insecta	2580.00	8.33
Insecta*	Pupae	Insecta	3232.00	17.70
<i>Excirrolana inornata</i> *	Adult	Isopoda	2460.00	50.00
<i>Excirrolana kincaidi</i>	Adult	Isopoda	6864.51	20.00
<i>Gnorimosphaeroma oregonensis</i> *	Adult	Isopoda	2460.00	50.00
<i>Idotea</i> sp.*	Adult	Isopoda	2460.00	50.00
<i>Munna</i> sp.*	Adult	Isopoda	2460.00	50.00
<i>Gnorimosphaeroma oregonensis</i> *	Adult	Isopoda	2460.00	50.00
<i>Archaeomysis grebnitzkii</i>	Adult	Mysidacea	4207.62	11.83
<i>Holmesimysis sculpta</i>	Adult	Mysidacea	4207.62	11.83
Unidentified mysidacea	Adult	Mysidacea	4207.62	11.83
Worm*	Adult	Oligochaeta	1980.00	2.00
<i>Gasterosteus aculeatus</i>	Juvenile	Osteichthyes	3420.00	4.00
<i>Clinocottus embryum</i>	Larvae	Osteichthyes	3420.00	4.00
Fish*	Egg	Osteichthyes	3976.00	0.00
<i>Engraulis mordax</i>	Juvenile	Osteichthyes	3675.85	11.19
<i>Ammodytes hexapterus</i>	Juvenile	Osteichthyes	4432.12	12.59
<i>Leptocottus armatus</i>	Larvae	Osteichthyes	3420.00	4.00
Unidentified fish	Juvenile	Osteichthyes	4104.27	13.67
Polychaeta sp.*	Adult	Polychaeta	1980.00	2.00

Table 4.5: Parameters used for proportional-back calculation of juvenile size in two estuaries (Coos and Alsea Bay) and two surf zones (Coos and Alsea Surf) during three years. Parameters were estimated using simple linear regressions of fork length on otolith width. Location = Estuary and surf zone at which juveniles were collected. All models $p < 0.01$.

Location/Year	Parameters		r^2	n
	a	b		
Coos 2008	1.008 (± 0.137 SE)	-2.277 (± 0.439 SE)	0.64	35
Alsea 2008	0.875 (± 0.093 SE)	-1.787 (± 0.297 SE)	0.63	54
Coos 2009	0.832 (± 0.155 SE)	-1.701 (± 0.496 SE)	0.51	33
Alsea 2009	0.988 (± 0.100 SE)	-2.159 (± 0.321 SE)	0.75	35
Coos 2010	0.992 (± 0.088 SE)	-2.191 (± 0.285 SE)	0.65	28
Alsea 2010	0.692 (± 0.109 SE)	-1.193 (± 0.350 SE)	0.63	72

Table 4.6: Site, year, day of year, values of temperature ($^{\circ}\text{C}$), juvenile weight (g), catch (ind. 100m^{-2}), mean energetic content of prey (Prey, Joules g^{-1}), specific growth rates (Growth, % body weight day^{-1}), consumption rates (g day^{-1}), and proportion of maximum consumption (p-value) for juvenile Chinook salmon collected in two estuaries and two adjacent surf zones.

Site	Year	Day of year	Temperature	Weight	Catch	Prey	Growth	Consumption	p-value
			$^{\circ}\text{C}$	g	ind. 100m^{-2}	Joules g^{-1}	% body weight day^{-1}	g day^{-1}	proportion
Coos Bay	2008	205	10.47	12.55	58.00	3526.93	2.17	0.97	0.63
Coos Bay	2008	218	13.14	10.83	13.00	3985.92	1.29	0.91	0.56
Coos Bay	2009	190	14.18	8.56	26.20	3607.82	1.22	0.79	0.56
Coos Bay	2009	205	11.82	11.48	19.33	3989.88	1.08	0.79	0.48
Coos Bay	2009	233	12.18	17.62	16.80	3050.02	1.50	2.21	0.98
Coos Bay	2010	180	13.85	9.70	36.20	4068.69	2.49	1.24	0.82
Coos Bay	2010	209	11.56	12.00	28.25	3879.12	1.78	1.18	0.71
Coos Bay	2010	222	11.92	14.90	45.50	4154.77	1.36	1.16	0.58
Coos Bay	2010	252	10.74	15.86	6.50	2373.99	1.26	1.79	0.91
Coos Surf	2008	211	11.20	6.86	26.67	4455.85	1.85	0.67	0.54
Coos Surf	2008	228	10.26	11.47	2.11	4377.76	1.57	0.85	0.56
Coos Surf	2009	192	10.13	8.89	1.51	4586.64	1.08	0.49	0.40
Coos Surf	2009	207	9.36	11.27	0.14	4577.03	0.96	0.62	0.44
Coos Surf	2009	233	9.62	10.19	0.49	4811.42	0.88	0.53	0.36
Coos Surf	2010	181	10.96	8.70	10.68	4274.43	1.72	0.66	0.52
Coos Surf	2010	210	8.68	13.48	10.04	4253.81	1.49	0.97	0.65
Coos Surf	2010	225	10.11	15.74	8.11	4491.88	1.42	1.14	0.60
Coos Surf	2010	252	10.40	19.33	7.11	4198.80	1.33	1.50	0.67
Alsea Bay	2008	199	10.95	11.93	149.00	3829.13	1.51	1.10	0.67
Alsea Bay	2008	213	12.14	12.94	238.50	3567.17	1.12	1.15	0.64

Alsea Bay	2008	226	11.81	15.08	128.75	3342.59	1.51	1.68	0.84
Alsea Bay	2008	241	12.52	19.46	92.50	3281.22	1.20	2.03	0.83
Alsea Bay	2009	187	13.00	11.09	78.75	3820.39	1.66	1.05	0.64
Alsea Bay	2009	215	14.13	11.84	89.50	3358.86	1.62	1.26	0.72
Alsea Surf	2008	200	11.30	13.80	1.41	4281.65	1.28	1.07	0.58
Alsea Surf	2008	215	10.76	7.44	0.35	4415.11	1.28	0.54	0.47
Alsea Surf	2008	232	10.98	10.47	0.51	4104.79	1.28	0.80	0.54
Alsea Surf	2008	244	11.24	14.97	0.83	4402.82	1.28	1.05	0.54
Alsea Surf	2009	187	9.90	9.17	0.50	4484.69	1.34	0.58	0.47
Alsea Surf	2009	215	11.64	6.05	0.24	3980.39	2.17	0.50	0.52

Table 4.7. Prey taxa observed in stomachs of juvenile Chinook salmon collected in two estuaries and two surf zones on the Oregon coast. Life history stage (Stage), group, number of sites at each habitat in which the taxa was observed (Sites) and percent frequency (Freq.) are also presented.

Taxa	Stage	Group	Estuarine		Surf zone	
			Sit.	Freq.	Sit.	Freq.
<i>Allorchestes angusta</i>	Adult	Amphipoda	0	0	1	0.72
<i>Ampithoe lacertosa</i>	Adult	Amphipoda	0	0	1	2.17
<i>Atylus tridens</i>	Adult	Amphipoda	2	30.07	2	30.43
<i>Caprellidea</i> spp.	Adult	Amphipoda	1	0.33	2	26.09
<i>Corophium</i> spp.	Adult	Amphipoda	2	55.23	0	0
<i>Dogielinotus loquax</i>	Adult	Amphipoda	2	6.21	2	28.99
<i>Eogammarus covernicus</i>	Adult	Amphipoda	1	0.65	0	0
<i>Eohaustorius washingtonianus</i>	Adult	Amphipoda	2	1.31	1	1.45
<i>Eusiroidea</i> sp.	Adult	Amphipoda	2	2.94	1	2.9
Gammaridea	Adult	Amphipoda	2	4.25	2	11.59
<i>Jassa</i> spp.	Adult	Amphipoda	2	4.9	2	80.43
<i>Mandilophoxus</i> sp.	Adult	Amphipoda	0	0	1	0.72
<i>Megalorchestia pugettensis</i>	Adult	Amphipoda	2	0.65	1	5.8
<i>Pleustidae</i> sp.	Adult	Amphipoda	0	0	1	0.72
<i>Stenothoides burkanki</i>	Adult	Amphipoda	1	0.33	0	0
Spider	Adult	Araneae	0	0	1	1.45
Bivalve siphons	Adult	Bivalvia	1	0.33	0	0
Cephalopoda	Larvae	Cephalopoda	0	0	1	2.17
Copepoda	Adult	Copepoda	1	0.33	0	0
Crustacea	Larvae	Crustacea	1	0.33	1	0.72
Crustacea	Adult	Crustacea	2	6.54	1	1.45
<i>Cumacea</i> spp.	Adult	Cumacea	2	7.19	2	1.45
Brachyura	Zoea	Decapoda	2	0.65	0	0
<i>Cancer magister</i>	Megalopa	Decapoda	2	13.73	2	4.35
<i>Cancer magister</i>	Juvenile	Decapoda	1	0.33	1	0.72
<i>Cancer oregonensis/productus</i>	Megalopa	Decapoda	2	14.71	1	7.97
<i>Cancer</i> spp.	Zoea	Decapoda	1	0.33	0	0
Crangonidae	Megalopa	Decapoda	1	0.33	1	0.72
Crangonidae	Juvenile	Decapoda	0	0	1	0.72
<i>Euphausia pacifica</i>	Adult	Decapoda	1	0.33	1	2.17
<i>Fabia subsquatra</i>	Megalopa	Decapoda	1	0.33	0	0

<i>Lissocrangon stylirostris</i>	Adult	Decapoda	2	2.94	1	0.72
<i>Lophopanopeus bellus</i>	Megalopa	Decapoda	1	0.33	1	7.97
<i>Neotrypaea californiensis</i>	Zoea	Decapoda	1	0.33	0	0
<i>Pachycheles</i> spp.	Megalopa	Decapoda	1	0.65	1	1.45
Porcellanidae	Megalopa	Decapoda	1	0.33	1	0.72
Porcellanidae	Zoea	Decapoda	2	15.03	1	3.62
Gastropoda	Adult	Gastropoda	1	0.33	0	0
Insecta	Adult	Insecta	2	41.18	2	39.86
Insecta	Larva	Insecta	2	1.63	1	2.9
Insecta	Pupae	Insecta	2	1.63	0	0
<i>Excirolana inornata</i>	Adult	Isopoda	1	0.65	0	0
<i>Excirolana kincaidi</i>	Adult	Isopoda	2	3.59	2	10.87
<i>Gnorimosphaeroma oregonensis</i>	Adult	Isopoda	2	5.88	1	1.45
<i>Idotea</i> spp.	Adult	Isopoda	2	0.98	2	1.45
<i>Lycaeopsis themistoides</i>	Adult	Isopoda	0	0	1	35.51
<i>Munna</i> spp.	Adult	Isopoda	0	0	1	0.72
<i>Archaeomysis grebnitzkii</i>	Adult	Mysidacea	2	2.61	2	32.61
Mysidacea	Adult	Mysidacea	1	0.33	0	0
Oligochaeta	Adult	Oligochaeta	1	0.33	0	0
<i>Ammodytes hexapterus</i>	Juvenile	Osteichthyes	2	1.31	0	0
<i>Clinocottus embryum</i>	Larvae	Osteichthyes	0	0	1	1.45
<i>Engraulis mordax</i>	Juvenile	Osteichthyes	2	3.92	0	0
<i>Gasterosteus aculeatus</i>	Juvenile	Osteichthyes	1	0.33	0	0
<i>Leptocottus armatus</i>	Larvae	Osteichthyes	1	0.98	1	5.8
Osteichthyes	Juvenile	Osteichthyes	2	14.38	1	5.07
<i>Nereis</i> sp.	Adult	Polychaeta	1	2.61	0	0

Table 4.8: Percentage change in specific growth rate (% body weight day⁻¹) estimates of juvenile Chinook salmon collected in two estuaries and surf zones during 2008-2010 after vary-one-at-a-time sensitivity analysis. Estimates obtained with Wisconsin bioenergetics model using species specific parameters and modifying input variables $\pm 1SD$. In parenthesis = average value of SD. Input variables = water temperature ($^{\circ}C$), Mean prey energy density (Prey energy, Joules g⁻¹), consumption rate (g day⁻¹).

Site	Mean specific growth rate	Water temperature		Mean prey energy		Consumption	
		+1SD (0.84)	-1SD (0.84)	+1SD (332)	-1SD (332)	+1SD (0.34)	-1SD (0.34)
Coos Bay	1.49	-9.00	7.54	27.42	-27.40	59.64	-66.57
Coos Surf	1.47	-4.62	4.03	7.21	-7.21	60.01	-63.57
Alsea Bay	1.44	-7.84	6.87	12.14	-12.09	43.93	-46.89
Alsea Surf	1.44	-4.28	3.98	8.14	-8.11	56.82	-56.99

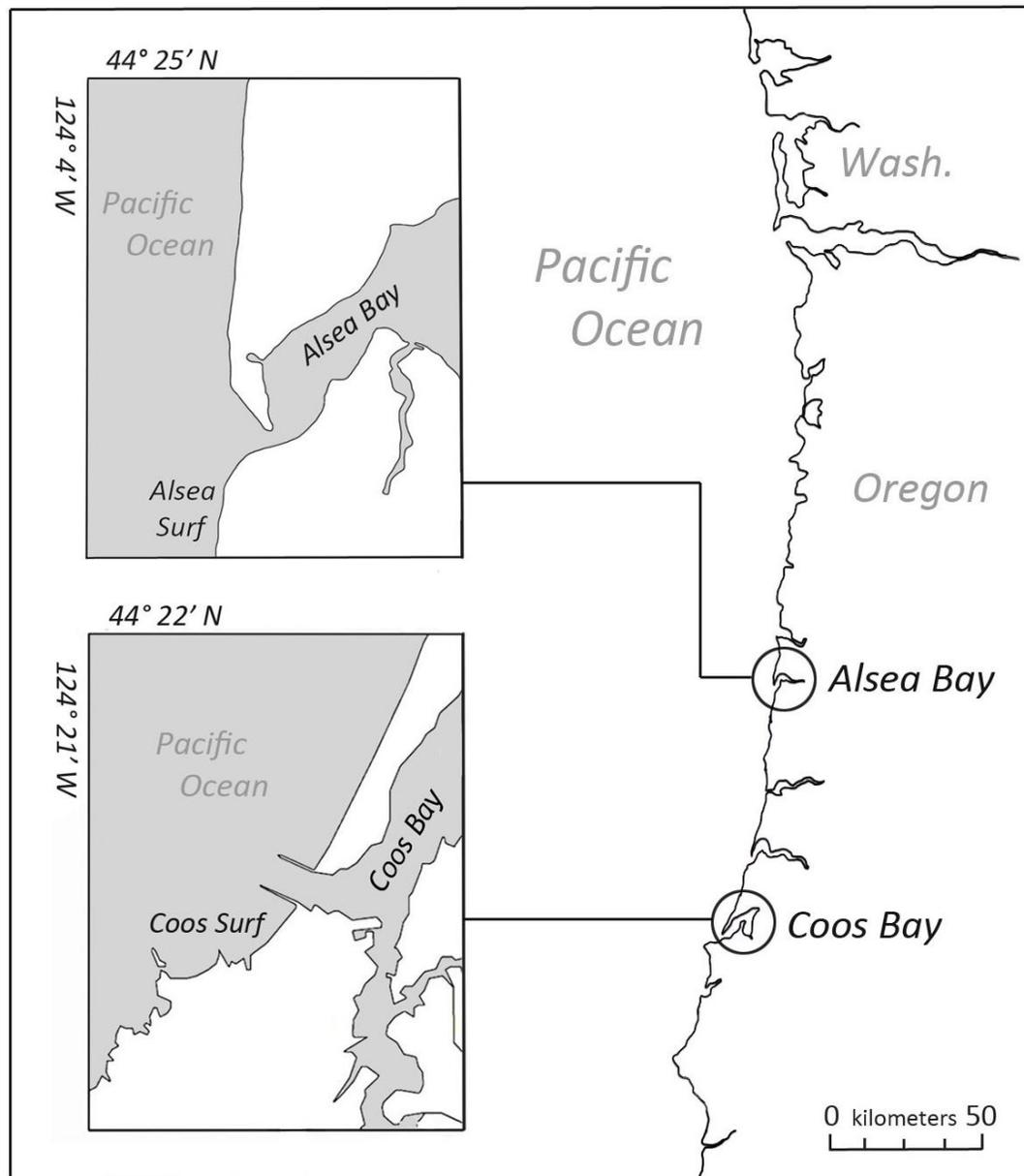


Fig. 4.1: Map with location of two estuaries (Coos Bay and Alsea Bay) and two surf zones (Coos and Alsea Surf) where juvenile Chinook salmon were collected during 2008 – 2010.

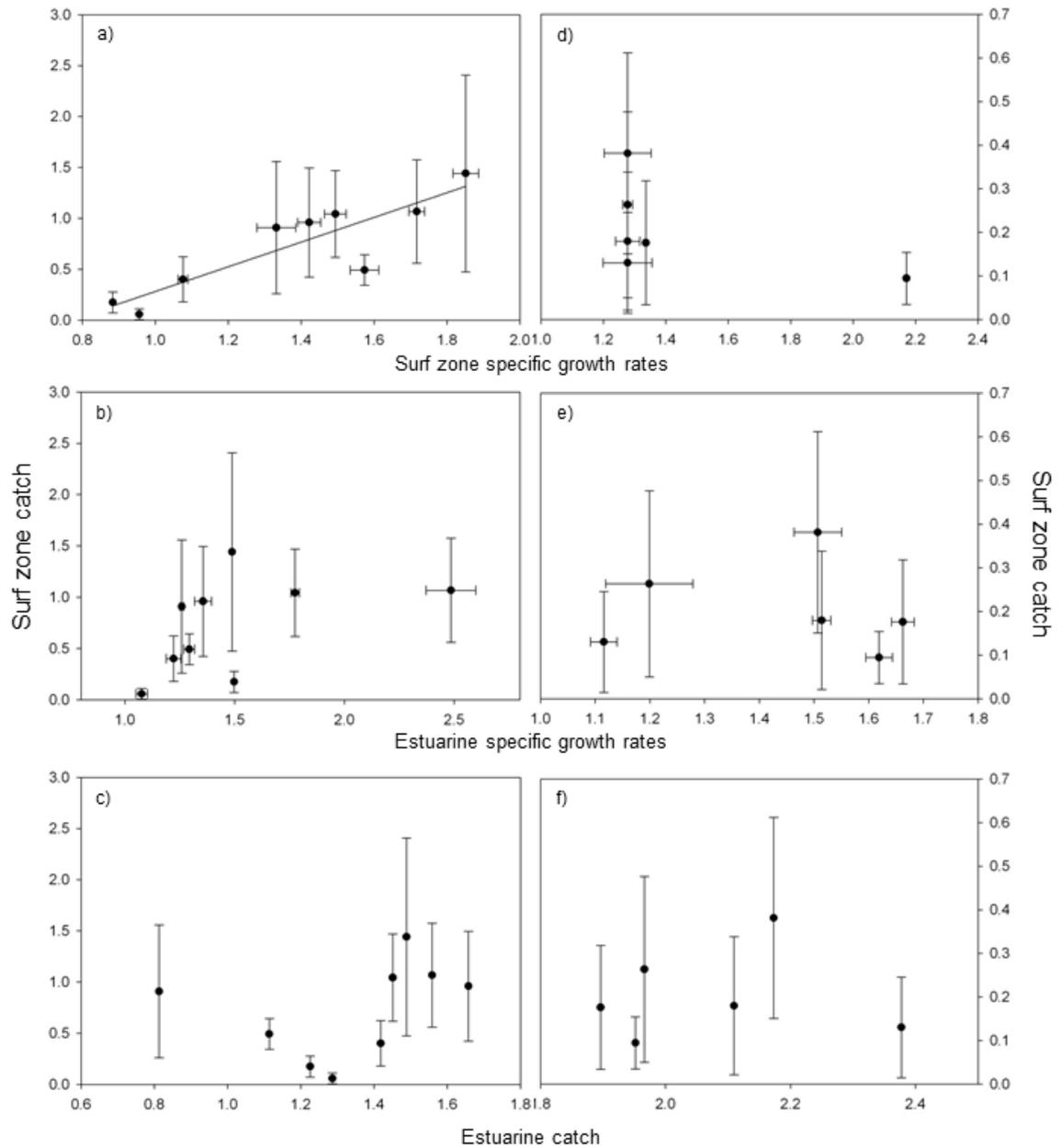


Fig. 4.2. Relationship between estimates of surf zone specific growth rate (% body weight day⁻¹), estuarine specific growth rates and estuarine catch (log₁₀, ind. 100 m⁻²) with juvenile Chinook salmon catches (log₁₀, ind. 100 m⁻²) at Coos Surf (a, b, c, respectively) and Alsea Surf (d, e, f, respectively). Data obtained during 2008-2010. Bars = standard error, which were not included in estuarine catches to improve visual inspection.

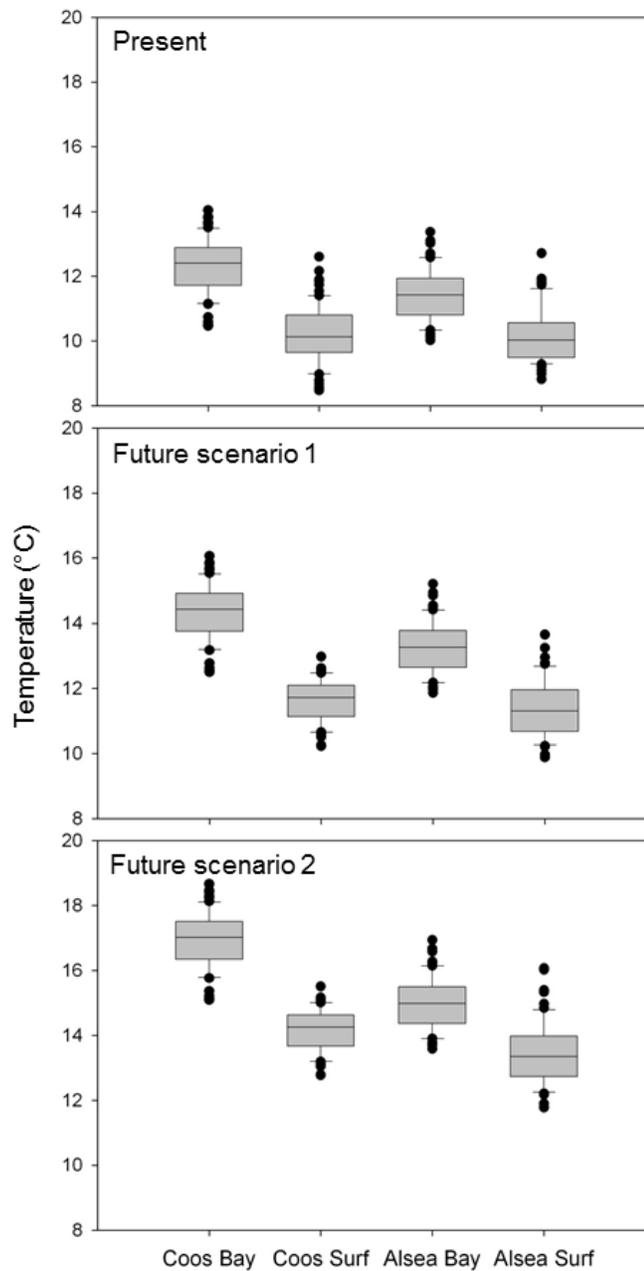


Fig. 4.3. Water temperature during the present (summer 2010) and predicted future scenarios (+50 years) at two estuaries and two surf zones. Temperature in future scenarios were estimated using predictive relationships described in Table 4.3 and increasing fresh water temperature by 1.5°C (scenario 1) or 5.8°C (scenario 2), sea surface temperature by 1.2 °C (both scenarios) and wave height by 0.75 m (both scenarios).

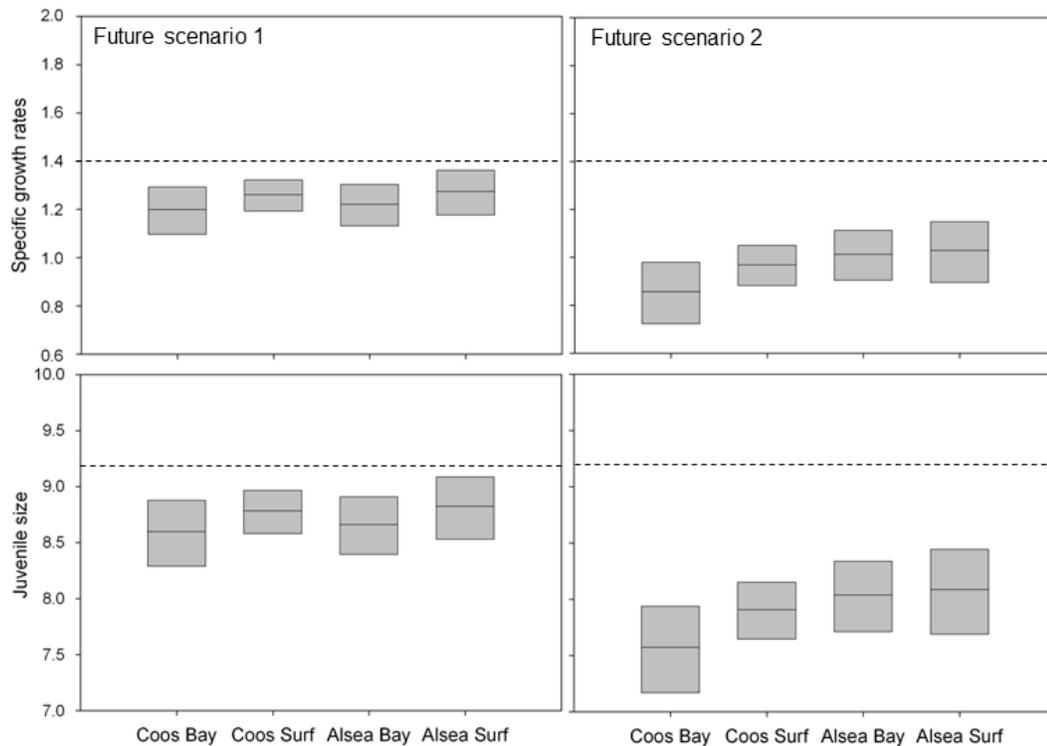


Fig. 4.4. Modeled future (+50 years, Scenario 1 and 2) specific growth rates (% body weight day⁻¹) and juvenile size at end of summer (g) at two estuaries and two surf zones on the Oregon coast. Dashed line represents average present day specific growth rates and juvenile size at the end of summer. Specific growth rates were estimated using the Wisconsin bioenergetics model using present day and predicted future water temperatures. Temperature in future scenarios were estimated using predictive relationships described in Table 4.3 and increasing fresh water temperature by 1.5°C (scenario 1) or 5.8°C (scenario 2), sea surface temperature by 1.2 °C (both scenarios) and wave height by 0.75 m (both scenarios). Juvenile size at the end of summer season (after 60 days) was estimated using estimated specific growth rates and assuming the size of the fish at the beginning of the season was 5 g at both habitats/sites.

CHAPTER 5: CONCLUSIONS

Numerous studies have highlighted early marine residence as the period during which the potential for mortality is highest for salmonids during their ocean life (*sensu* Healey 1991; Pearcy 1992; Quinn 2005). During this period, high mortality rates are thought to occur through an ‘integrated process’ (Houde 2008) that includes variable juvenile size, changes in water physical conditions, higher diversity and abundance of predators, and high spatial and temporal variability in prey field (Hare and Mantua 2000; Beamish and Mahnken 2001; Zabel and Achord 2004; Beauchamp et al. 2007; Emmett and Krutzikowsky 2008; Tomaro et al. 2012). The number of juveniles that survive this early ocean period has been found to be positively correlated to the number of fish that will survive to adulthood (Pearcy 1992; Beamish and Mahnken 2001; MacFarlane 2010).

Some juvenile Chinook salmon reside in sandy beach surf zones adjacent to estuaries when they first enter oceanic waters (Marin Jarrin et al. 2009). Sandy beach surf zones are a habitat for marine and diadromous species of fish throughout the world (Dominguez Granda et al. 2004; Strydom and d’Hotman 2005; Sato et al. 2008; Able et al. 2011; Marin Jarrin and Shanks 2011). Surf zones are defined as semi-enclosed environments that extend from the shoreline to the outer most breaker. These environments are inhabited by a fish community mostly composed of larvae and juveniles (reviewed in McLachlan and Brown 2006). Possible reasons for surf zone residence include an abundant supply of potential prey and, shelter from predators in the highly turbid shallow waters. However, despite the role of surf zones

for other diadromous fish and the importance of this early marine period for juvenile salmonids, little is known about the ecology of Chinook salmon in sandy beach surf zones.

The main objective of this study was to determine the role of sandy beach surf zones for early life history stages of Chinook salmon. My prior study conducted at one beach during 2006 and 2007 found that juvenile Chinook salmon were present in the surf zone only during the summer; therefore in Chapter 2, I determined the presence and distribution of juveniles at beaches of the western North American coast, and tested if timing, size, catch, stomach fullness and diet composition are similar among beaches and years, and between trough and flat areas. In Chapter 3, I further defined the relative importance of surf zones by comparing the role of surf zones and estuaries, a known nursery habitat. Finally, in Chapter 4, I studied the variables related to surf zone use examined the factors that influence growth in surf zones and estuaries, and explored how potential increases in coastal habitat water temperature could impact juvenile growth and size in surf zones and estuaries.

I found that a consistent small number of juveniles are present in surf zones mostly adjacent to estuaries that present trough areas, which are beach sections where sand moved by currents and waves produce a trench-like shape where they feed on a diverse invertebrate and vertebrate prey field. Surf zone fish were collected in significantly lower numbers than estuarine juveniles but presented similar migration patterns, consumed similar prey groups and exhibited similar stomach

fullness and growth rates. These results suggest that despite the small number of juvenile Chinook salmon that use surf zones, the role of this environment is to provide favorable foraging and growth conditions during the summer for subyearlings with similar ontogenetic migratory patterns as those present in estuaries. At one surf zone site, I observed a positive relationship between surf zone catches and surf zone specific growth rates but not with estuarine specific growth rates or catches. At the other surf zone site, which is adjacent to an estuary with relatively low human development, catch was not related to growth conditions in surf zone or estuary. My findings suggest growth rates in surf zones can influence surf zone use; however, that lower levels of human development in a watershed can reduce surf zone residence. In both habitats, consumption rates accounted for a higher proportion of the variability in growth than the energetic content of the prey or water temperature. Finally, the analysis of how the role of surf zones and estuaries would change if fresh water temperature, sea surface temperature and coastal wave height increased found that depending on the scenario, specific growth rates would decrease by 9 to 28% in surf zones and 14 to 39 % in adjacent estuaries. These explorations suggest that under current conditions, variation in consumption rates appears to be the main factor influencing juvenile growth in Oregon coastal habitats potentially because current water temperature is optimum for growth. However, predicted increases in water temperature may decrease overall juvenile growth and potentially survival, while increasing surf zone use.

This study provides novel information on surf zones, a poorly studied habitat, and estuaries, a known nursery habitat for Chinook salmon during a critical period. Given the extensive data collection and comparison with a nursery habitat, these results provide a robust evaluation of the role of surf zones for the early life history of Chinook salmon. However, the role of sandy beach surf zones may change in the near future if estuarine conditions deteriorate as predicted in current and previous studies (Mantua et al. 2009, Mote and Salathe 2009, Ruggiero et al. 2010). Additional insights into the potential impacts of climate change on juvenile salmon will require estimates of changes in the composition, energetic quality and abundance of prey communities inhabiting coastal environments.

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APPENDIX

Appendix Table 1. List of accompanying macrofauna collected using a beach seine. Scientific, life stage, group and number of sandy beach sites at which species were collected is also detailed.

Scientific name	Stage	Group	Sites
<i>Aequorea aequorea</i>	Adult	Cnidaria	1
<i>Chrysaora</i> sp.	Adult	Cnidaria	2
<i>Obelia</i> sp.	Adult	Cnidaria	1
<i>Polyorchis penicillatus</i>	Adult	Cnidaria	6
<i>Cancer magister</i>	Adult	Crustacea	9
<i>Cancer magister</i>	Juvenile	Crustacea	7
<i>Cancer magister</i>	Megalopa	Crustacea	7
<i>Cancer productus</i>	Juvenile	Crustacea	2
<i>Cancer</i> sp.	Megalopa	Crustacea	2
<i>Emerita analoga</i>	Adult	Crustacea	9
<i>Euphausia pacifica</i>	Adult	Crustacea	2
<i>Heptacarpus brevirostris</i>	Adult	Crustacea	1
<i>Lissocrangon stylirostris</i>	Adult	Crustacea	11
<i>Majoidea</i> sp.	Juvenile	Crustacea	2
Paguroidea	Adult	Crustacea	3
<i>Pleurobrachia</i> sp.	Adult	Ctenophora	6
<i>Idotea</i> sp.	Adult	Isopoda	6
<i>Olivella biplicata</i>	Adult	Mollusca	10
<i>Siliqua patula</i>	Juvenile	Mollusca	2
<i>Ammodytes hexapterus</i>	Juvenile	Osteichthyes	8
	Juvenile -		
<i>Amphistichus rhodoterus</i>	Adult	Osteichthyes	6
<i>Aulorhynchus flavidus</i>	Adult	Osteichthyes	3
<i>Blepsias cirrhosus</i>	Juvenile	Osteichthyes	1
<i>Clinocottus embryum</i>	Juvenile	Osteichthyes	1
	Juvenile -		
<i>Cymatogaster aggregata</i>	Adult	Osteichthyes	3
<i>Engraulis mordax</i>	Juvenile	Osteichthyes	4
<i>Engraulis mordax</i>	Larva	Osteichthyes	2
<i>Gasterosteus aculeatus</i>	Adult	Osteichthyes	5
<i>Hemilepidotus</i>	Juvenile	Osteichthyes	2

<i>hemilepidotus</i>			
<i>Hexagrammos</i>			
<i>decagrammus</i>	Juvenile	Osteichthyes	4
<i>Hyperprosopon</i>			
<i>ellipticum</i>	Juvenile	Osteichthyes	9
<i>Hypomesus pretiosus</i>	Juvenile	Osteichthyes	7
	Juvenile -		
<i>Leptocottus armatus</i>	Adult	Osteichthyes	9
<i>Leptocottus armatus</i>	Juvenile	Osteichthyes	3
<i>Oligocottus maculosus</i>	Juvenile	Osteichthyes	2
<i>Oligocottus rimensis</i>	Juvenile	Osteichthyes	1
<i>Oncorhynchus</i>			
<i>tshawytscha</i>	Juvenile	Osteichthyes	8
<i>Oncorhynchus kisutch</i>	Juvenile	Osteichthyes	1
<i>Parophrys vetulus</i>	Juvenile	Osteichthyes	11
<i>Parophrys vetulus</i>	Post-larva	Osteichthyes	0
<i>Pholis</i> spp.	Adult	Osteichthyes	1
<i>Platichthys stellatus</i>	Juvenile	Osteichthyes	8
<i>Scorpaenichthys</i>			
<i>marmoratus</i>	Juvenile	Osteichthyes	1
Sebastidae sp.	Juvenile	Osteichthyes	2
<i>Syngnathus</i>			
<i>leptorhynchus</i>	Juvenile	Osteichthyes	1
<i>Thaleichthys pacificus</i>	Juvenile	Osteichthyes	2
<i>Nephtys californiensis</i>	Adult	Polychaeta	0
<i>Nereis</i> sp.	Adult	Polychaeta	1
