Salish Sea Marine Survival Project (4):

Successful juvenile life history strategies in returning adult Chinook from five Puget Sound populations (4.1)

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Age and growth of Chinook salmon in selected Puget Sound and coastal Washington watersheds (4.2)

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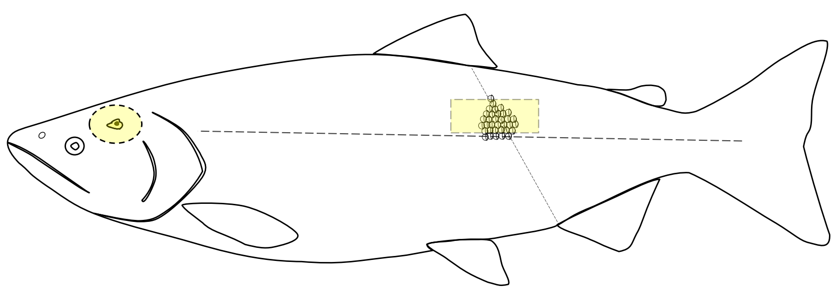

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Executive Summary

This report provides results for two research topics funded under the Salish Sea Marine Survival Project to examine early marine survival in Chinook salmon as it relates to life history expression and growth. The first, an otolith microchemistry project examining juvenile life history strategies of surviving adults and the second investigating the relationship between early marine growth (inferred from fish scales), marine survival, and ocean conditions.

Otolith Project — In this study, we used otolith chemistry to reconstruct the juvenile life history of Chinook salmon returning to 5 Puget Sound populations. This report provides definitive evidence that small fry sized (35-60mm) Chinook salmon survive early migration from their natal habitat and comprise as much as 35% of the returning adults. Survival/success of juvenile Chinook fry (fish <60mm) was greater in the two populations we sampled in Northern Puget Sound (Nooksack and Skagit Rivers) while the success of the fry life history was low (<5 %) in adult populations examined from the Cedar River, Green River and Puyallup River (mid and South Puget Sound). This work shows compelling evidence that the smallest migrants (sometimes viewed as excess production) survive and contribute to adult returns. We discuss the differences in life history expression we observed and propose how the lack of the fry life history in mid and southern Puget Sound may be related to early marine survival. Of special note is apparent correlation between estuary/delta habitat condition, pathogen and contaminate exposure and life history success at the very beginning of the marine migration. Though this research was conducted on many individual adult Chinook (n~450) our inference to specific geographic locations (n=5) and return years (n=1) is low. Therefore caution is advised when making any corollary inference. This work does show compelling evidence that life history expression and survival of the fry life history is severely limited in 3 of the most developed and contaminated estuaries within Puget Sound. These findings are relevant to life history theory, habitat restoration, survival, and stock recovery efforts.

Scale Project —In this study, we used scale analysis of returning adults to examine the relationship between early marine growth and survival for 3 Puget Sound and 2 coastal populations of Chinook salmon. In total, we examined scales from 2,604 individuals over 7 outmigration years characterized by relatively poor, average, and good survival from 1976 to 2008. We observed a positive relationship between growth during the first year at sea and survival for adults returning to the Skagit, Green/Duwamish, and Puyallup Rivers. In addition, growth of age 3 fish from north and mid Puget Sound was a useful predictor of cohort survival (age 3 to 5). Conversely, we observed no evidence of a relationship between growth and survival for fish returning to the Quillayute River but, on average, fish returning to northern costal Washington grew 14% (SD = 9%) more during the first year at sea than Puget Sound populations. These results support previous research that factors influencing early marine growth (i.e. prey abundance and quality) are important to the survival of Puget Sound Chinook salmon. In addition, early marine growth may be a useful biological indicator for pre-season forecasting of Chinook salmon populations in Puget Sound.

Successful juvenile life history strategies in returning adult Chinook salmon from five Puget Sound populations

Introduction

Chinook salmon populations within Puget Sound have declined precipitously over the last two decades, leading to the listing as Threatened under the Endangered Species act. Concurrently, populations in the Columbia River and coastal Washington have rebounded from low returns during the 90's to record returns in some cases (US SST *draft* 2014). This has lead researchers to hypothesis that factors unique to Puget Sound may be limiting recovery. The goal of the Salish Sea Marine Survival Project is to identify the most significant factors limiting marine survival of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss)*. This research supports that goal by measuring juvenile life history parameters (size at estuary/ocean entry) by using otolith chemistry of adult Chinook salmon returning to three geographic regions within Puget Sound (southern, middle, and northern). We will evaluate the hypothesis that the diversity of juvenile salmon life histories determined from returning adults differs among regions of Puget Sound and is related to variation in marine survival among populations.

The survival of hatchery Chinook and coho salmon (*O. kisutch*) within Puget Sound has been linked to geographic location (Hobday and Boehlert 2001, Beetz 2009, Zimmerman et al 2013), estuarine contaminant levels (Meador 2014), ocean conditions and interspecific interactions (Ruggerone and Goetz 2004), and early marine growth (Beamish et al. 2004, Duffy and Beauchamp 2011). However, relatively little is known about the early marine survival of natural salmon stocks within Puget Sound, which may be expected to exhibit more life history variation than hatchery conspecifics.

Life history, "the strategies an organism exhibits during critical periods that effect reproductive success" (Stearns 1992), and its diversity has been shown to correlate with salmonid population resiliency and overall abundance- Key factors for fisheries management and stock recovery (Watters et al 2002, Hill et al. 2003, Einum et al 2003, Hilborn et al. 2003, Beechie et al 2006, Schindler et al. 2010, Moore et al. 2014). Aspects of juvenile Chinook life histories were documented and described early in the 20th century (Gilbert 1912) where two primary types were termed; ocean and stream type. Where ocean type migrated to the sea within their first year of life and dominated in summer and fall returning adult populations. While stream type spent a year in their natal freshwater streams before making their seaward migration and dominated in spring returning adult populations (Gilbert 1912, Taylor 1990). While such classifications are helpful in understanding broad patterns and descriptions they also have been shown to be overly simplistic and often missing key components of population structure (Riemers 1971, Healey 1980, Taylor 1990, Beckman and Dickhoff 1998, Miller et al 2010, Zimmerman et al 2015). To that end, juvenile Chinook have been observed migrating soon after emergence as fry, later as parr in early spring through fall and the following winter/spring as yearlings. Variation in outmigration timing has been observed both within and between populations (Taylor 1990, Beckman and Dickhoff 1998, Copeland and Venditti 2009, Teel et al 2014, Schroeder et al 2016). In some large systems with diverse adult run timings, juvenile Chinook can be found migrating at any time of the year, though peak migrations may still be found within specific months (Taylor 1990, Teel et al 2014, Schroeder et al 2016). Within the greater Salish Sea (Puget Sound), a similar trend has been observed, where peak count numbers are often observed early in the year (soon after emergence ~45mm) followed by another peak during early summer. Fish leaving in the late summer and following spring are also observed but usually in reduced numbers or in specific locations (Kinsel et al. 2008, Topping et al. 2013, Burger et al 2016). For example, the presence of yearling migrants in snow melt dominated streams in the Cascade Mountains (Beechie et al. 2006, Zimmerman et al. 2015).

Calcified fish tissue and bones are well suited for studies of age, life history, residency, and growth due to three factors: 1) periodicity of newly deposited calcified tissue—days to weeks (Panella 1971, Boyce 1985); 2) relationship between fish size and structure size (scales, otoliths) (Bilton 1975, Campana and Neilson 1985, Volk et al. 2010); 3) correspondence between water chemistry and the microchemistry of certain calcified structures (Kalish 1990, Fowler et al. 1995, Zimmerman 2005). Moreover, the formation of daily growth increments and annuli (otoliths), and the chemical signal in these structures are not subject to change once deposited (with some exceptions). Therefore these structures can provide an archival record of size, growth, and the environmental chemistry an individual fish encounters during its life cycle (see review by Campana 1999). A critical life history transition made by juvenile anadromous salmonids occurs when they move from freshwater rearing areas into brackish or marine waters. Fortuitously, the concentration of strontium (Sr), a close chemical analog of calcium (Ca), increases dramatically from freshwater to seawater. As such, several researchers have used the difference in abundance of Sr to delineate when salmonids enter and start to rear in brackish/marine waters (Kennedy et al. 2002, Volk et al. 2010, Miller et al 2010, Campbell 2010, Claiborne et al. 2014). Transects of anadromous salmonid otoliths, for instance, are characterized by low Sr:Ca ratios for periods of freshwater rearing and increased Sr:Ca during periods of brackish and marine-water residency (Kalish 1990, Friedland et al. 1998, Zimmerman 2003).

In this study we use otolith microchemistry to reconstruct juvenile life history pathways of individuals that returned to spawn in 5 river basins within Puget Sound. We will test the hypothesis that life history strategies vary between basin in relation to survival, geographic location, habitat, and stock.

Methods

Adult otolith collection

Adult otoliths collections came from unmarked (no adipose clip, Coded Wire Tag, or thermal mark) from 5 river basins within Puget Sound. Two collections came from North Puget Sound (Nooksack and Skagit River), two from mid Puget Sound (Cedar ad Green River) and one from south Puget Sound (Puyallup River). Two Spring Chinook stocks (Nooksack, Puyallup) one Summer stock (Skagit) and 3 fall stocks (Cedar, Green, Puyallup) were included in the analysis (Figure 1). Otoliths were collected during spawning surveys in the summer/fall of 2015. The one exception was the collection of Spring Chinook from the Puyallup River, which came from unmarked fish from the White River (tributary) used for brood stock (White River hatchery). Where sample sizes were large (~ >100) otolith samples were randomly selected amongst the entire collection to account for run timing, age and sex (Table 1).

Otolith Preparation & Chemistry

Otolith chemistry was analyzed to reconstruct the juvenile life histories of adult Chinook sampled on the spawning grounds during return year 2015. Age estimates were determined using scale analysis and individual samples were assigned to brood year (Table 1). Adult sagittal otoliths were prepared for chemical analysis by thin sectioning in the sagittal plane, where otolith material was removed from both the distal and proximal surfaces until primordia were clearly visible (Volk et al. 2010, Campbell et al. 2015, Claiborne and Campbell 2016). All otolith chemistry was conducted at the Keck Collaboratory for Plasma Mass Spectrometry at Oregon State University. We used Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS) to collect otolith chemical data. Specifically, instrumentation consisted of a Thermo X series II ICPMS coupled with a Photon Machines G2 193-nm excimer laser. Ablated material was transported from the laser to the mass spectrometer using Helium as the carrier gas. The LA-ICPMS operating conditions were as follows: 13 L/min cooling gas, 0.95 L/min auxiliary gas, 0.75 L/min Helium. The laser beam diameter was set at 30 microns, scanned at 5 microns/second at a pulse rate of 8 Hz. Laser transects were analyzed from the otolith core to the otolith edge in the dorsal/posterior quadrant (Figure 2). The point of estuary/ocean entrance for each otolith was determined as the point of Strontium (Sr) inflection, defined here as the point of rapid Sr increase from a baseline freshwater signal (Figure 3). All reported Sr values are ratios of Calcium (Ca) and reported in mmol/mol. We used a fish size/otolith size relationship from the Green River (y=0.1468x-0.5545, n=211, Ruggerone and Volk 2004) and otolith radius at Sr inflection (Figure 3) to back-calculate fish size at estuary/ocean entrance. We used estimates of size at estuary/ocean entry to infer broad life history characteristics defined as: fry (<60mm), parr (>60mm) and yearlings (presence of a scale or otolith annulus).

Results

Estimated size of juvenile Chinook at estuary/ocean entrance in returning adults

To examine the successful juvenile life history of returning adult Chinook salmon in the Salish Sea we examined 451 unmarked adult Chinook otoliths from 5 river basins. Overall, we found returning adult Chinook to exhibit a wide range of juvenile sizes at outmigration (35-160mm). Broadly speaking we found a distinct difference with a higher proportion of smaller fish (<60mm) surviving and returning as adults in the Nooksack and Skagit populations compared to those in Mid and South Puget Sound. Fry were found in all populations examined (albeit in low frequency) except the Cedar River (Table 2). The highest proportion of fry were found in the summer Skagit (0.36) and spring Nooksack populations (0.24) where these small fish made up approximately a third of the total population we sampled. Yearlings were found in all populations but the Puyallup (fall stock), and made up approximately one third of the sample in the Nooksack River (Figure 4-6). On average, fish from Northern Puget Sound were significantly smaller at estuary/ocean entrance than those from Mid and South Puget Sound (Figure 7, Table 3). For subyearling migrants only, the Skagit River summer population had the smallest mean size at estuary/ocean entry (mean ± SD = 64.6 ± 14.9 mm), while the largest mean size at estuary/ocean entrance came from the Cedar (mean ± SD = 86.7 ± 6.8 mm) (figure 6). The only populations that were not statistical different from one another was the Nooksack and the Skagit; and the Green and the Puyallup (Table 3, Dunns's Test, p=<0.001).

Size at outmigration by adult run time and age

We hypothesized that stocks from summer and spring Chinook would have a larger size at estuary/ocean entrance given their tendency to produce yearling migrants and due to the fact that their spawning location is generally farther upriver then fall stocks. However, results from this study suggest that the summer and spring populations we examined were on average the smallest sized fish at estuary/ocean entry (for survivors). We speculate that this has more to do with the habitat available to small fish in these systems but it is interesting none the less that spring and summer populations in Puget Sound may readily exhibited small fry life histories that are often associated with fall stocks.

Age analysis of the 451 adult Chinook otoliths found the primary brood year of the samples examined to come from parents in return year 2011 (outmigration year 2012). The age composition varied between populations (from 2 year olds to 5 year olds) but fish returning at age 4 made up greater than 50% of the population in all systems (Table 1). Our selection of unmarked/untagged fish likely biases this age composition towards the natural origin population.

Discussion

The results of this research show clear evidence that fry sized (35-60mm) juvenile Chinook survive to contribute to several populations in Puget Sound. These results suggest their contribution is not limited to an "alternate" life history strategy, but rather a potentially significant and sizable portion of the population. We observed, in return year 2015, up 36% of the returning adults sampled on the spawning grounds came from these small fry sized fish. Conversely, some populations had no evidence (or low <3%) of their spawning population coming from a fry life history. In general, higher proportions of the fry life history were observed in Northern Puget Sound watersheds and populations, then mid and Southern Puget Sound.

The initial focus of this research was twofold; 1.) Evaluate juvenile life history contribution to adult returns and 2.) Examine potential life history differences between geographic regions within Puget Sound. We hypothesized that juvenile life history success (as measured in adults) would inform early marine survival. For example, if larger juvenile migrants were found in higher proportion in specific geographic regions, while juvenile outmigration numbers were similar, we would take that as evidence that small fry sized fish did not survive.

When examining life history contributions to a population two key factors must be considered; 1) The number of organisms that are available to exhibit a given life history, and 2) The subsequent survival rate of that life history to the adult stage. Observation from field studies in Puget Sound have shown the proportion of fry and parr leaving a basin is variable between years and has been shown to vary greatly (>90% fry to < 20% fry) and has been shown to be correlated with both river discharge and spawner density (Zimmerman et al 2015). Juvenile salmonid trapping is conducted on all 5 of the rivers that we used in this study and both fry and parr migrants have been documented in all cases (Kinsel et al. 2008, Topping et al. 2013, Burger et al 2016, E. Brown *personal communication*, Beamer et al. 2016). For example, the Skagit River which showed the highest proportion of successful fry migrants to the returning adult population (36%) also exhibited a high proportion of juvenile fry migrants (~ 80% of the fish estimated at the trap) during the outmigration years that would contribute to the adult return used in this study (Kinsel 2015). The Green River trap estimates for fry during this time period were substantial but lower than the Skagit (47-73% for outmigration years 2011-2014) (Topping et al 2014). However, unlike the Skagit population,< 1% of the Green river adults returned after exhibiting the fry migrant life history suggesting survival of the fry migrants was near zero despite making up between 47-73% of the out-migrants from the Green River.

Our results in Mid and South Puget Sound (<3% fry life history in returning adults) coupled with the presence of both fry and parr life histories in their outmigrating juveniles suggests a mortality bottleneck in the Cedar, Green and Puyallup basins, not observed (at least too the same degree) in the northern (Nooksack and Skagit) basins. These results support the idea that increased differential size selected mortality is occurring among populations somewhere after ocean/estuary entrance. Factors that may play a role in this mortality effect could include the degree of estuary degradation, contamination, pathogen and predatory exposure, growth and genetic disposition for specific life histories. For these factors to contribute to our results (reduced survival of fry in Mid and South Puget Sound populations) they would need to differentially affect survival (based on size) or the proportion of the population exhibiting a given life history strategy (genetic control).

In estuaries and river deltas small fry sized fish have been found to reside for extended periods of time, 30-90 days on average (Beamer and Larson 2004, Volk et al. 2010, Campbell 2010), and found to utilize shallow and deep water habitat differentially based on size (Roegner et al. 2016). In addition, evidence suggests the degree of residency in a given habitat is a function of size. Where residency times of the smallest fish (~ 40 mm) were found to reside for 50-90 days (depending on year of outmigration), while larger 110mm fish on average spent less than 9 days in brackish waters of the Columbia River estuary (Campbell 2010). As a whole there seems to be a preponderance for small fish to utilize shallow water habitat like the type of habitat found in the lower reaches of rivers and streams and their estuaries/deltas. If habitat loss or contamination has degraded shallow water estuarine habitat it stands to reason that the fry life history would be the most effected.

Though all systems we examined in this study have sizable human impacts; from fisheries to habitat degradation, hatchery domestication and pollutants, the Cedar, Green and the Puyallup without question are the most heavily altered and developed (Simenstad et al. 2005, Beechie et al. 2017). A project monitoring habitat status and trends in Puget Sound reported < 5 % of the estuary/delta habitat remained in a natural state for the Puyallup and

Green basins. While the Skagit and Nooksack still had ~ 50 % of their estuary/delta in a natural state (Beechie et al. 2017). The importance of estuary habitat to Chinook salmon has long been recognized (Reimers 1973, Healey 1980, Beamer and Larson 2004, Bottom et al. 2005). Utilization of estuarine habitat by juvenile Chinook has been documented on the Oregon Coast (Reimers 1973, Volk et al 2010) Columbia River (Campbell 2010, McNatt et al. 2016), Puget Sound and the Strait of Georgia (Healey 1980, Beamer and Larson 2004, Ruggerone and Volk 2004). However, little is known about how these life histories survive and contribute to spawning Chinook populations in Washington state. Analysis of coded wire tagged returns from estuaries coast-wide found suggestive evidence that systems with less altered estuaries (Magnusson and Hilborn 2003) and fewer contaminants (Meador 2014) had higher survival rates of hatchery fish. The results presented in this research coupled with the available habitat data (Beechie et al. 2017) support the hypothesis that survival (especially amongst the smaller migrants) is impacted by habitat availability and condition (Fig 8). We found < 3 % of adults returning to the Green and Puyallup to exhibit the fry migrant life history while approximately 95 percent of their estuary habitat has been eliminated (Beechie et al. 2017). The converse was true from the Skagit and Nooksack estuaries where ~ 50 % of the estuary remained in a natural state (Beechie et al. 2017) and 36 and 24 % of the adult population we examined returned from small fry sized fish respectively.

Research examining the role of contaminants and contaminated estuaries has been shown to effect growth (Meador et al. 2006) and survival (Arkoosh et al. 1998, Meador 2014) of hatchery juvenile Chinook. It is worth noting that in addition to greatly degraded estuarine habitat, the Green and Puyallup watersheds also have the greatest levels of contaminants such as polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB's) (Meador 2014). Though we are unaware of studies examining the effect of PAH's and PCB's on survival of large and small fish there is some suggestive evidence from other contaminants (the fire retardant PHOS-CHEK LC-95A, Dietrich et al 2014) and pathogens (Arkoosh and Diettrich 2015). For example a fire retardant was found to have negative impacts on survival and growth related to smolting and release age (and presumable size) (Dietrich et al. 2014). In addition, experimental trials of juvenile sablefish *Anoplopoma fimbria* and the pathogen family of *Vibrionaceae* show evidence that smaller size fish at infection have reduced growth and greater incidences of mortality when exposed to four species of *Vibrionaceae* (Arkoosh and Dietrich 2015).

As migrants move from estuaries and deltas to nearshore and offshore habitats, size selective mortality may occur as suggested by a critical size hypothesis (Beamish and Mahnken 2001, Duffy and Beauchamp 2011). The critical size hypothesis suggests that fish must obtain a certain size entering their first ocean winter to survive. Our results could be explained by such a process. However our findings would suggest that such a process (critical size) is not universal but rather variable and dependent on other factors, such as basin of origin/geographic location (this study) and outmigration year (Ruggerone and Goetz 2004, Woodson et al. 2013, Gamble 2016). We feel the research described here is a valuable piece in understanding size selective mortality effects as it is the first to examine this phenomenon to returning adult Chinook salmon in Puget Sound. The relevance of this adult study (and inference to juvenile life history/size) is that it does not require assumptions about fish leaving the study area. However it is severely limited when making any kind of inference to where this mortality may be occurring (estuary, nearshore, offshore, etc). A combination of study design's sampling juveniles on the seaward migration followed by returning adults is needed to test this hypothesis further.

While research of hatchery Chinook has shown clear evidence of prolonged residency in Mid and South Puget Sound (O'Neill and West 2009, Chamberlin et al. 2011), and that residency appears to be related to the release location (Chamberlin and Quinn 2014), there is no evidence at this point that increased Puget Sound residency is related to smaller size at entry into saline waters in hatchery or wild Chinook. If residency was correlated with juvenile life history then it may explain a decrease in the survival of the fry life history through marine mammal, avian and piscivorous fish predation (Beauchamp and Duffy 2011, Pearson et al 2015, Chasco et al. 2017,) that has been suggested for parts of Puget Sound.

Management implications and further research recommendation

The results of this research show clear evidence that small, fry sized (35-60mm) juvenile Chinook survive to contribute to returning adult populations in parts of Puget Sound. These results suggest their contribution is not limited to an "alternate" life history strategy, but rather a potentially significant and sizable portion of the population. We observed, in return year 2015, up to 36% of the returning adults sampled on the spawning grounds came from these small fry sized fish. In addition we found river basins with ~50% of the natural estuary intact were much more likely to exhibit a fry life history in their returning adults. This has potentially major implications for habitat restoration and recovery efforts. This work supports the idea that increased habitat capacity for a given life stage will benefit population abundance.

This research shows compelling evidence that juvenile Chinook life history success is not equal among the populations we examined in Puget Sound. There is anecdotal evidence that this may be due to geographic region and the subsequent habitat condition small fry sized fish encounter on their migration. To further answer this question we recommend expanding this research in the following ways:

1.) Add samples from the Nisqually and Snohomish Rivers. The Nisqually is a restored estuary similar to the Nooksack and Skagit systems. The Snohomish has some functioning estuary habitat while also having elevated contaminants (intermediate to that of the Duwamish and the Puyallup).

2.) Continue analysis on return year 2016 and 2017 to compare return brood year vs outmigration brood year (what proportion of juveniles left vs what proportion of the fry and parr life histories returned as adults).

3.) Add populations from the Washington coast (Quillayute), Hood Canal (Skokomish), and the Strait of Juan de Fuca (Elwha) to examine the role of habitat condition and life history expression.

4.) Examine juvenile samples quantifying residency in Puget Sound estuaries in relation to toxins (PCB, PAH), and pathogen levels in order to test the hypothesis that fish with higher residency have reduced survival.

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Tables

Table 1. Juvenile outmigration years for the otoliths examined in this study (return year 2015). Number of samples examined for chemical analysis (n) and number used for age analysis (parenthesis).

	Outmigration Year				
	2014	2013	2012	2011	n
Nooksack	0.00	0.07	0.86	0.07	67(59)
Skagit	0.01	0.09	0.74	0.15	94(86)
Cedar	0.02	0.09	0.87	0.02	55(53)
Green	0.00	0.34	0.56	0.10	124(107)
Puyallup (fall)	0.00	0.12	0.75	0.12	86(65)
Puyallup (spring)	0.07	0.43	0.43	0.07	22(14)

Table 2. The proportion of subyearling Chinook that migrated to the estuary/ocean <,> 60mm (yearlings and Puyallup spring Chinook removed).

BC (fl-mm)	Nooksack	Skagit	Cedar	Green	Puyallup
n	46	94	55	124	86
<60mm	0.24	0.36	0.00	0.01	0.03
>60mm	0.76	0.64	1.00	0.99	0.97

Table 3. Shows the median difference (Median Diff), z statistic (Z) and p-value (p) from Dunn's multiple comparison procedures comparing size (fl) at juvenile outmigration in adult Chinook sampled on the spawning grounds from five Puget Sound Chinook populations. Puyallup/White River Spring Chinook was not included due to small sample size.

Population	Median Diff (mm)	Z	p
Nooksack vs Skagit	4.3	0.64	1.00
Nooksack vs Cedar	-16.7	6.91	<0.01
Nooksack vs Green	-11.1	5.33	<0.01
Nooksack vs Puyallup	-9	-3.63	<0.01
Skagit vs Cedar	-21	9.22	<0.01
Skagit vs Green	-15.4	8.04	<0.01
Skagit vs Puyallup	-13.3	5.51	<0.01
Cedar vs Green	5.6	2.91	0.02
Cedar vs Puyallup	7.7	4.33	<0.01
Green vs Puyallup	2.1	1.98	0.24

Figures

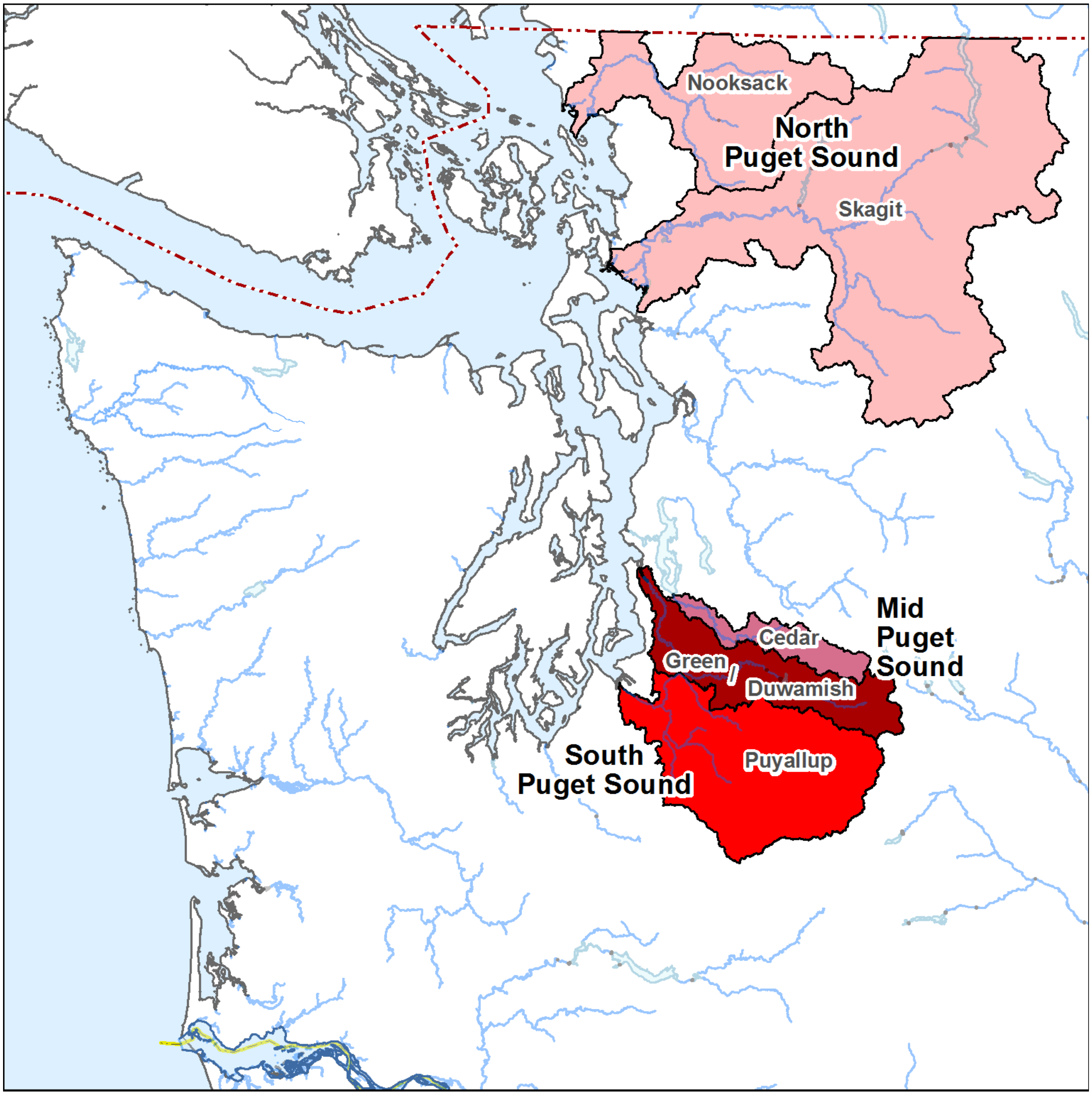

Figure 1. Map of the geographic areas and river basins where Chinook salmon otolith used in this study were sampled. Otolith samples were taken from unmarked individuals on the spawning grounds.

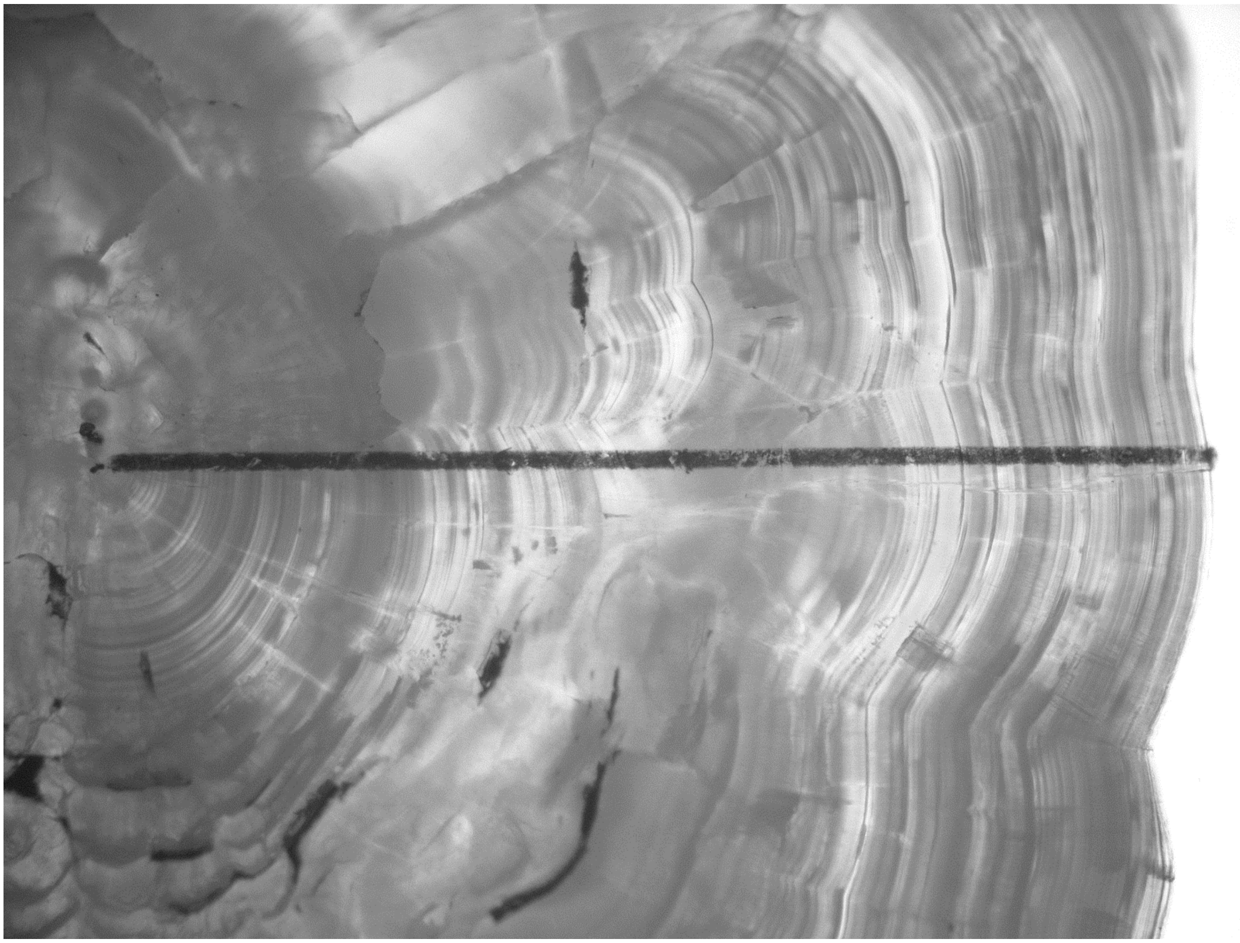

Figure 2. Adult Chinook otolith sagittal thin section of a Green River adult Chinook. Laser transect from otolith core (left) to otolith edge (right). Note dark laser scar, filled with wax pen post ablation for contrast.

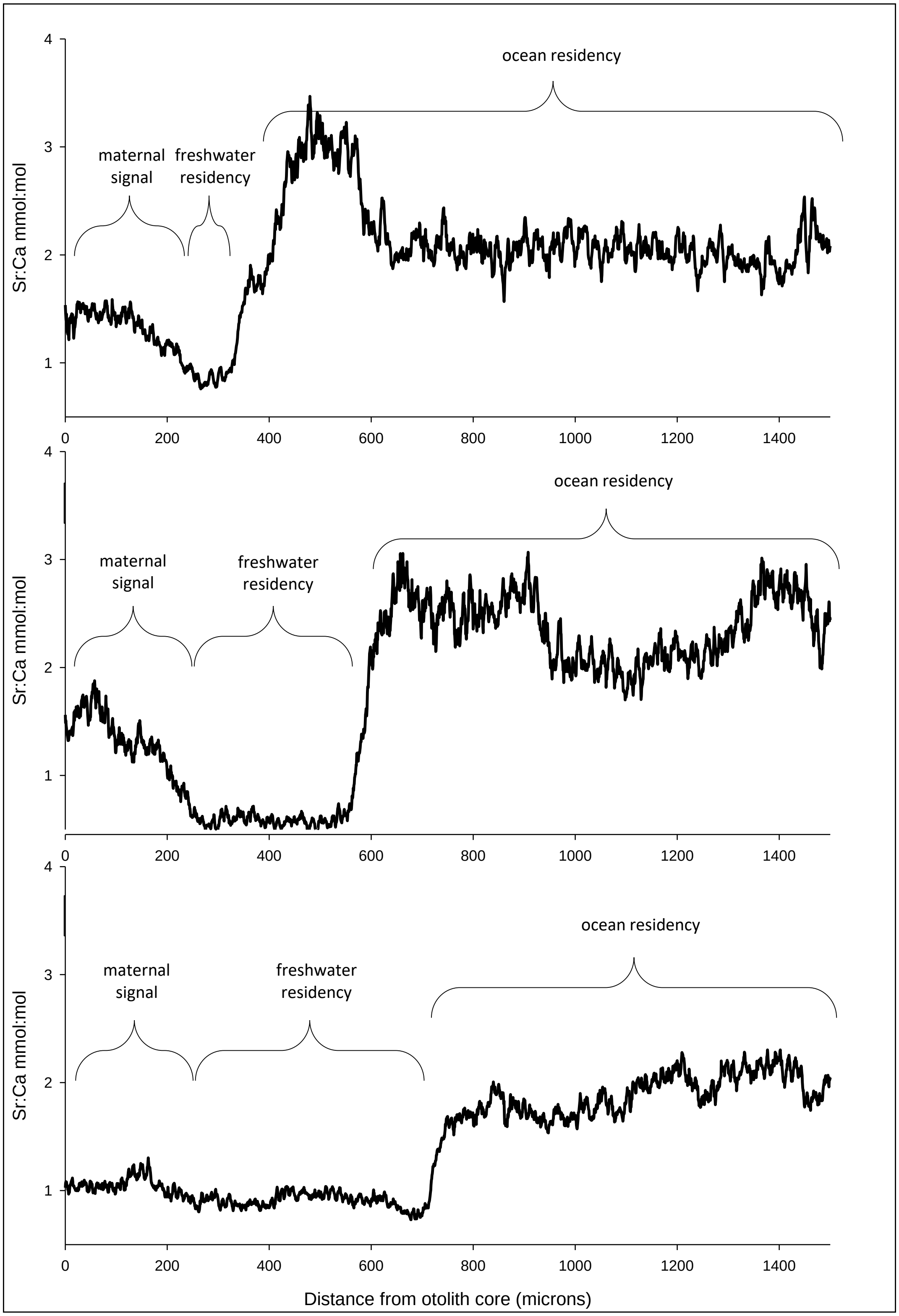

Figure 3. Sr:Ca life history profiles. Laser transects from the core to the otolith edge covering the maternal, freshwater and ocean otolith growth. The top panel shows a typical fry life history pattern (Skagit), the middle shows a parr life history pattern (Green) and the bottom panel shows a yearling life history pattern (Nooksack).

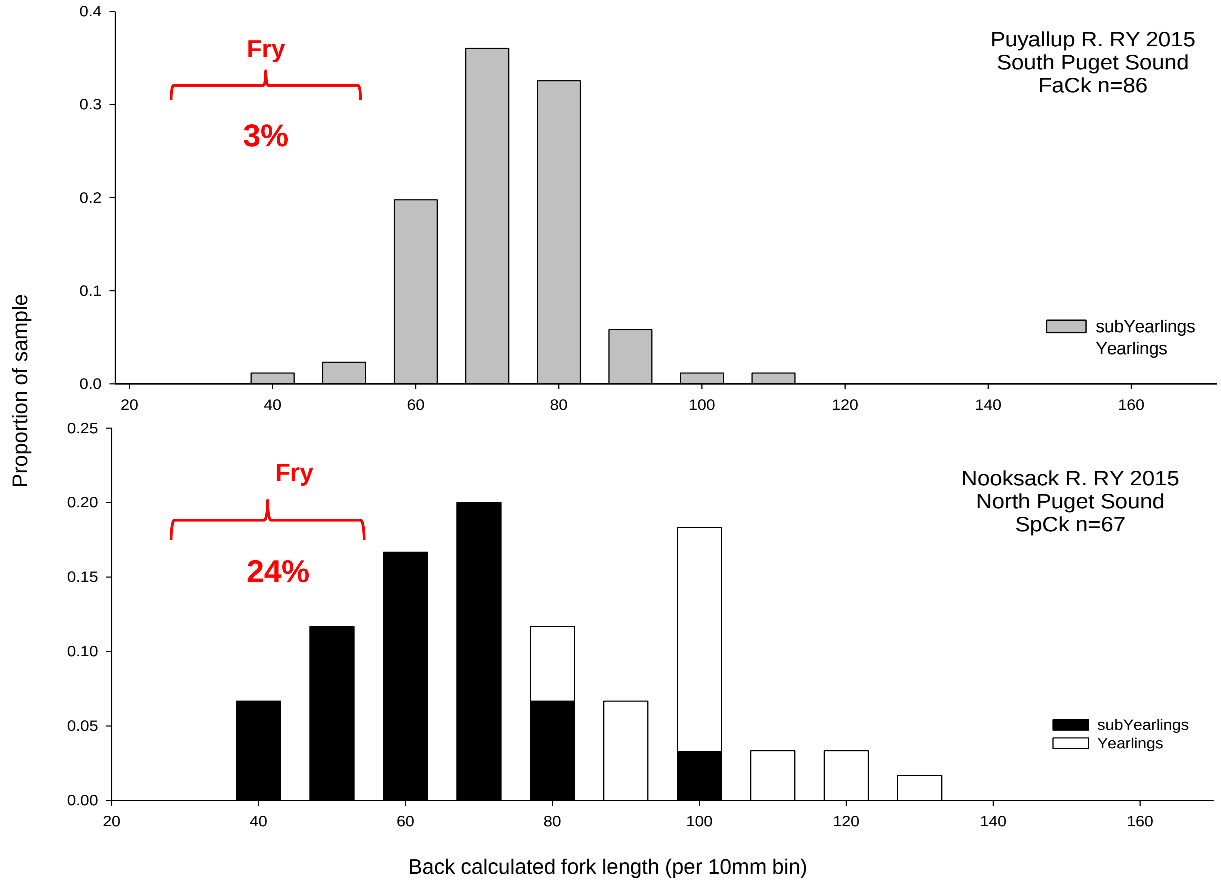

Figure 4. Length frequency histogram of back calculated size (Fl-mm) at estuary/ocean entrance of retuning adult Chinook salmon from the Cedar River (gray bars) and Nooksack River (black bars). Yearlings from each population in clear bars.

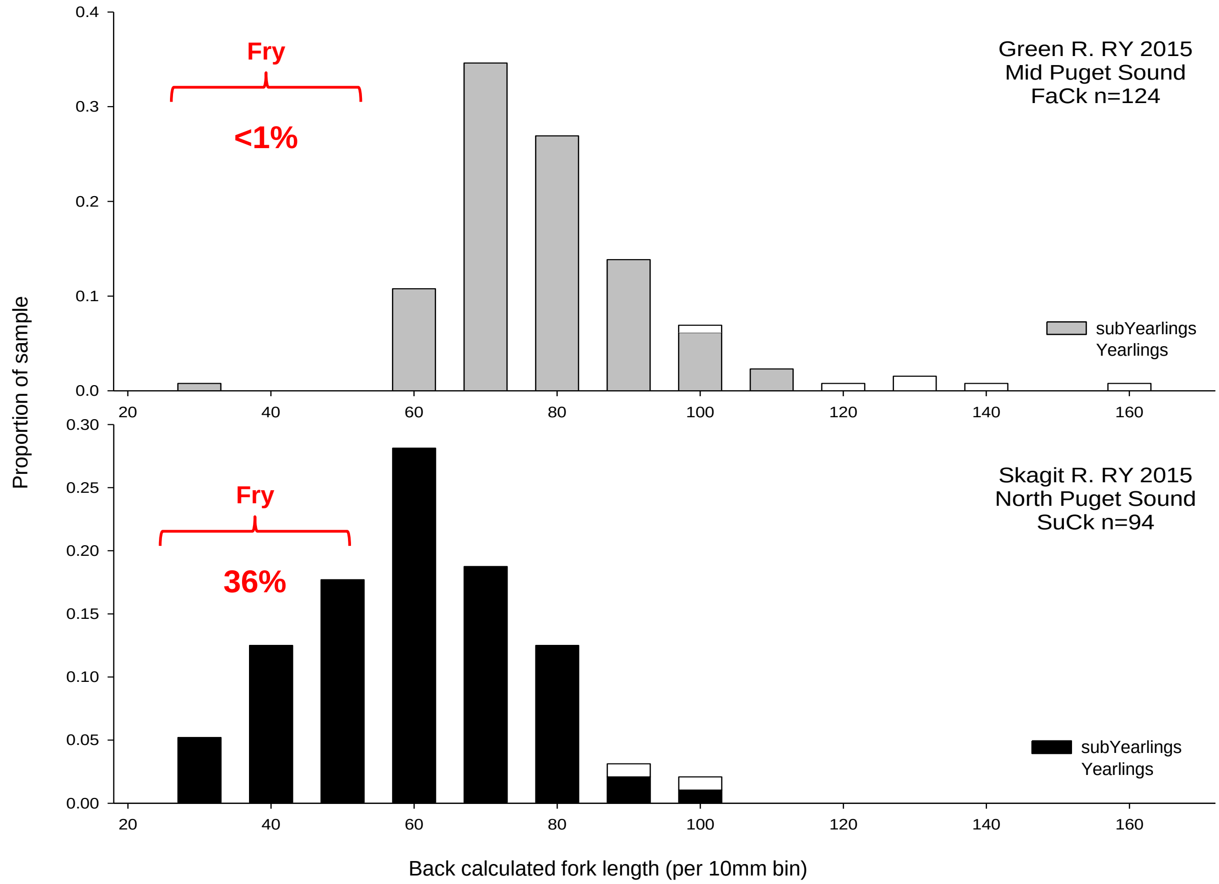

Figure 5. Length frequency histogram of back calculated size (Fl-mm) at estuary/ocean entrance of retuning adult Chinook salmon from the Green River (gray bars) and Skagit River (black bars). Yearlings from each population in clear bars.

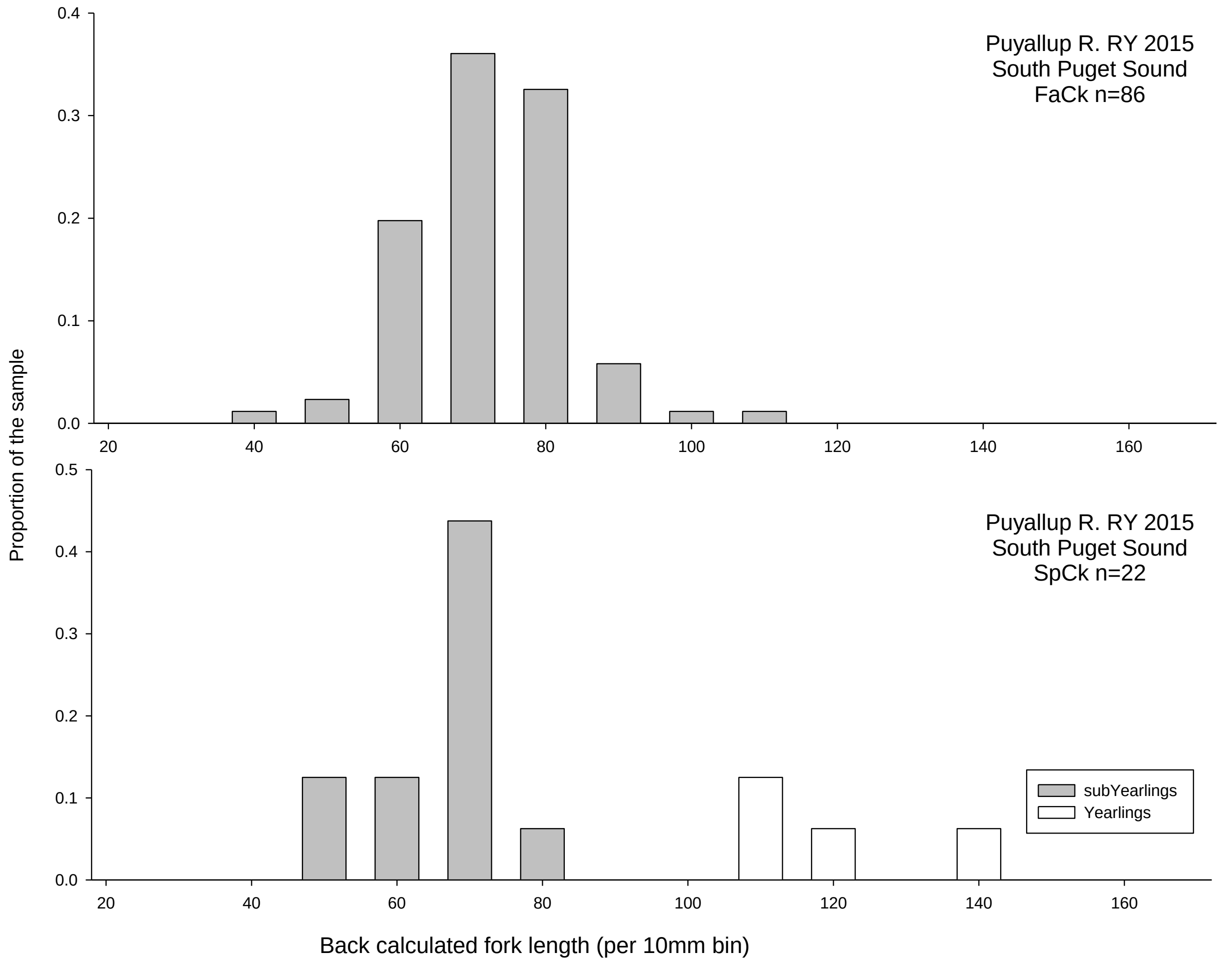

Figure 6. Length frequency histogram of back calculated size (Fl-mm) at estuary/ocean entrance of retuning adult fall (top panel) and spring (bottom panel) Chinook salmon from the Puyallup River (gray bars). Yearlings from each population in clear bars.

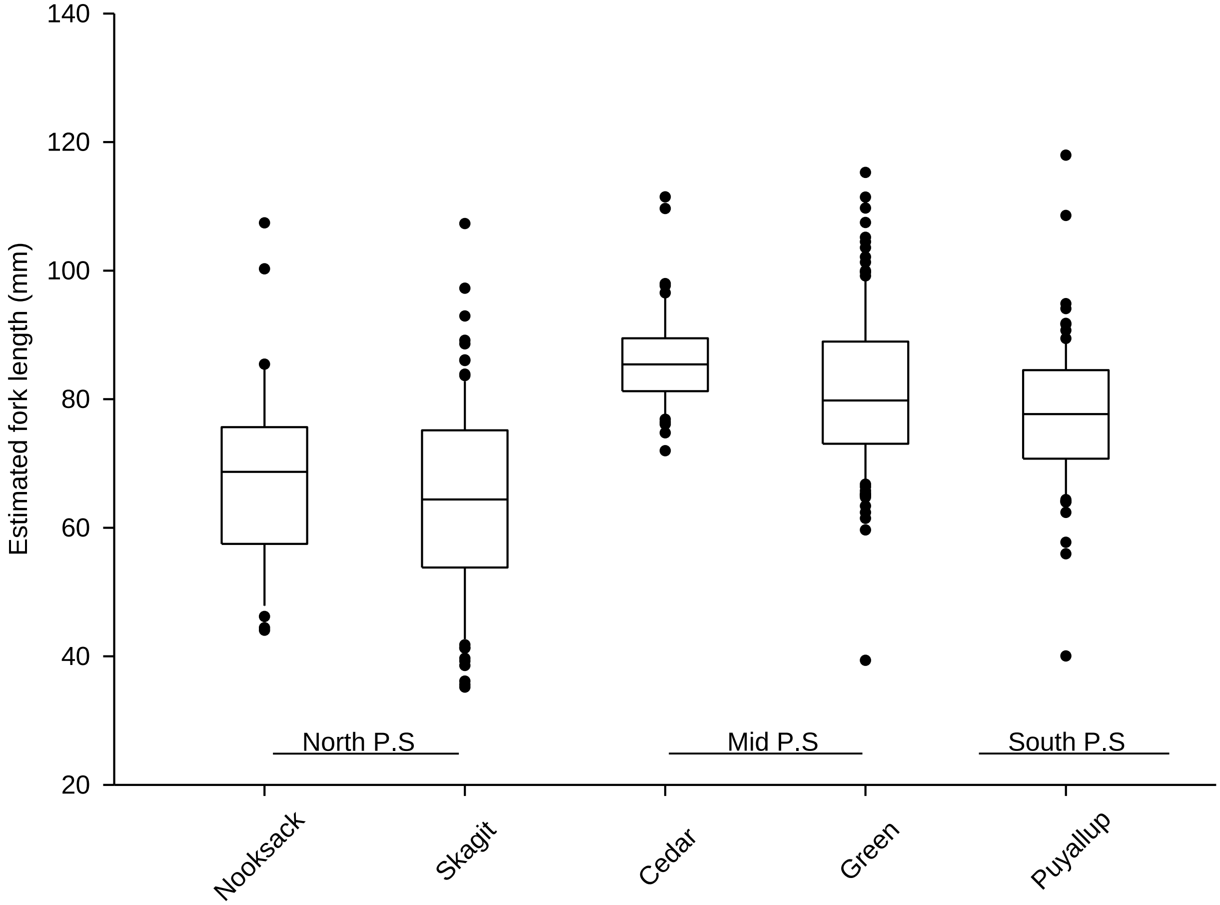

Figure 7. Estimated size (fl-mm) at estuary/ocean entrance of adult Chinook salmon recovered from the spawning grounds from five select Puget Sound populations. Note: populations are arranged from north to south. Graphic includes unmarked subyearling migrants only.

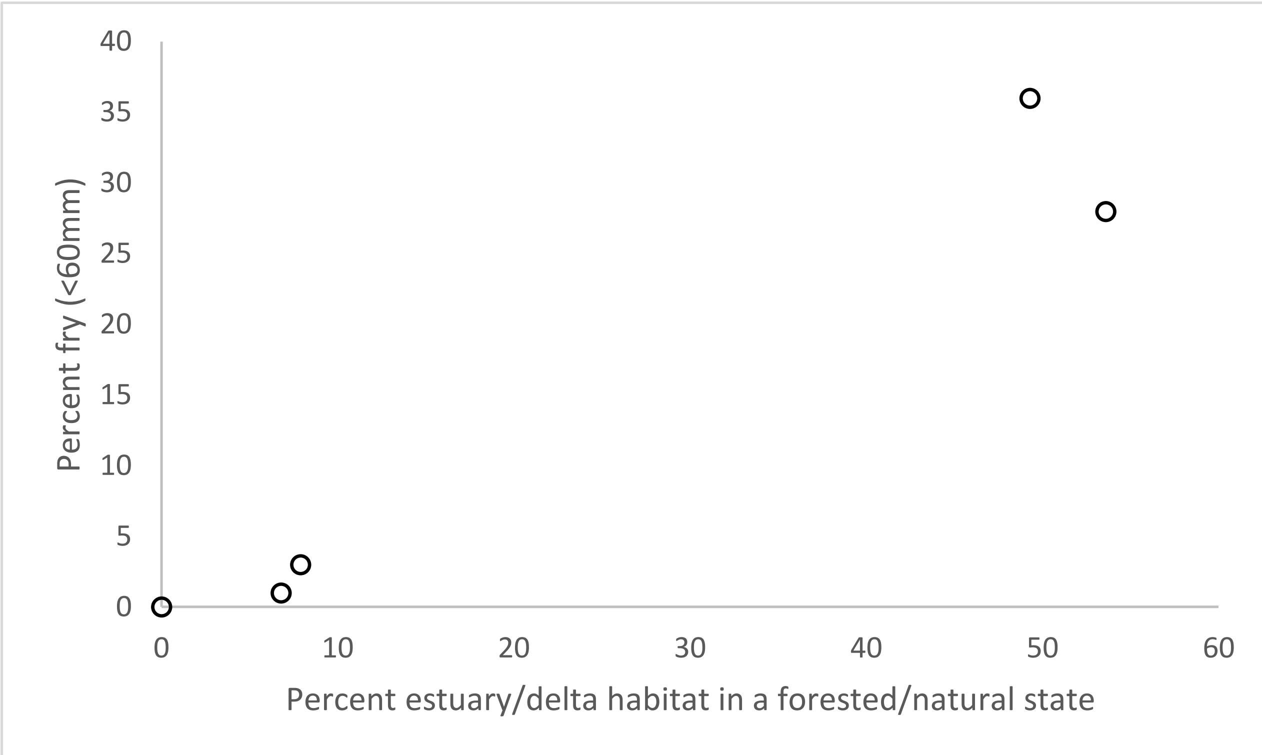

Figure 8. Relationship between the percent estuary/delta habitat and the percent fry life history estimated for returning adult Chinook salmon from 5 populations in Puget Sound estimated habitat data from Beechie et al. (2017
).

Age and growth of Chinook salmon in selected Puget Sound and coastal Washington watersheds

Introduction

Marine survival of Pacific salmon (*Oncorhynchus* spp.) is influenced by a variety of anthropogenic, environmental, and biotic factors. Studies have shown that early marine growth is an important factor related to adult survival for several species (Holtby et al. 1990, Beamish et al. 2004, Ruggerone et al 2007, Cross et al. 2009, Tomaro et al. 2012). For Puget Sound Chinook salmon *(Oncorhynchus tshawytscha*), early marine growth of hatchery fish has been observed to be positively related to adult survival, highlighting the importance that local conditions and bottom-up processes have on survival (Duffy and Beauchamp 2011). For example, prey composition has been observed to vary inter annually in Puget Sound (Duffy et al. 2010) and prey availability may be the primary factor limiting early marine growth in some years (Gamble 2016). While the specific mechanisms and timing of mortality are not clear, it is hypothesized that increased growth may reduce the duration of periods associated with high mortality in early life stages of fish (i.e. stage duration hypotheses, Houde 1987), and increase survival through periods of starvation (Sogard 1997, Beamish and Mahnken 2001).

Fish scales have long been used to estimate age, growth and other life history parameters (Dall 1911, Gilbert 1913). For relatively short lived (2-8 years) semelparous Pacific salmon, scales are well suited for studies of age and growth because somatic growth is related to scale growth (Bilton 1975, Fukuwaka and Kaeriyama 1997, Fukuwaka 1998). As such, the relationship between fish size and scale size has been used to back calculate size at specific locations on the scale, such as annuli and ocean entry (Henderson and Cass 1991, Bond et al. 2008, Claiborne et al. 2011).

The primary objective of this study was to evaluate the relationship between early marine growth and survival. Using back calculated growth estimates at ocean entrance and at the end of ocean age 1 and 2; we examined 7 years of data covering some of the lowest and highest hatchery survival rates on record (0.2-9.5%). We examined populations of Chinook salmon in Puget Sound and coastal Washington to test the hypothesis that there were geographic differences in growth and survival over the last three decades.

Methods

Study Design.— Spatially, analysis focused on differences between large geographic regions: Puget Sound (southern, middle, northern), north Washington coast (small estuaries), and south Washington coast (large estuaries) (Figure 1). Temporally, analysis focused on poor, mixed and good survival years across time (late 1970’s through 2008). We selected populations to represent large scale geographic regions where historical scale collections existed from terminal gill net fisheries (Figure 1). Secondary populations were used to augment low sample numbers or when samples were unavailable (Figure 1; Tables 1 & 2). North Washington coast (NWC) was represented by summer Chinook salmon returning to the Quillayute River. South Washington coast (SWC) was represented by fall returning fish to Grays Harbor and Willapa Bay. North Puget Sound (NPS) was represented by summer and fall returning fish to the Nooksack (fall) and Skagit Rivers (summer). Mid Puget Sound (MPS) was represented by fall returning adults to the Green/Duwamish River and south Puget Sound (SPS) was represented by fall returning Chinook salmon in the Puyallup River. Samples were collected July-October from terminal gill net fisheries in each river system (Figure 1). For each region and outmigration year, up to 15 preferred area (Scarnecchia 1979) and non-regenerated scale samples, per age class (age-3_1 to age-5_1) and sex, were selected to be digitized (Tables 1 & 2)

Scale Analysis.— Acetate impressions of scales were digitized using a compound microscope (Leica DM 1000; 25X and 50X) with a mounted camera (Leica DC 30). Image Pro version 6.2 was used to measure each scale in microns (µm) from the focus to ocean entry, from ocean entry to end of the first marine annuli, and the distance between any subsequent annuli and the scale edge (Figure 2). Measurements from Image Pro were exported to excel where scale size at ocean entry (focus to ocean entry), scale growth during the first ocean year (ocean entry to ocean annuli-1), scale radius at end of the first year at sea (scale focus to ocean annuli-1) and scale growth during the second marine year (ocean annuli-1 to ocean annuli-2) were calculated for each fish (Figure 2).

Data analysis.—Marine growth may vary between male and female Chinook salmon (Ruggerone et al. 2007). However, we observed no effect of sex on early marine scale growth after accounting for age for any population examined (Two-way ANOVA $p > 0.05$). In this study we aimed to select scales from fish that were unmarked (No adipose clip or Coded Wire Tagged) biasing the collection towards natural origin fish. However, unmarked hatchery fish were prevalent during the years used in this study and undoubtedly contribute to the collection as a whole. For example, on average 95.42 ± 8.07% (mean±SD) of hatchery fish from Puget Sound and coastal Washington were released unmarked each year between 1976 and1999, compared to 5.63 ± 4.73% (mean±SD) from 1999-2008. In addition, in some outmigration years and for some populations, only marked fish were available (1 & 2). Therefore, we combined unmarked and marked fish to increase sample sizes when there was no difference between scale growth during the first marine year (t-test $p > 0.05$).

Size at the end of the first marine year has been observed to be negatively related to age at return in Chinook salmon (Claiborne et al. 2011). Similarly, we observed that early marine growth was negatively related to age at return for NPS, MPS, and SWC (Two-way ANOVA $p < 0.05$). Therefore, to standardize growth by age we estimated annual growth estimates for each population using the method seen in Ruggerone et al. 2009 (1).

$$(1)\ AG_i = [(SG_3 * N_3) + (SG_4 * N_4) + (SG_5 * N_5)] / [N_3 + N_4 + N_5]$$

where AG_i = is the annual mean scale growth in ocean year-1, or -2, SG_3, SG_4, SG_5, = the standardized mean scale size at ocean anulli-1, annulli-2 for age-3, age-4, and age-5 respectively.

N_3, N_4, N_5 = the number of age-3, age-4, and age-5 fish respectively. Standardized mean scale size is the number of standard deviations above or below the mean for all outmigration years.

An objective of this study was to evaluate how marine growth of coastal and Puget Sound populations was related over high, low and moderate survival years. Therefore, we used Pearson's Correlation Coefficients to examine the relationship of marine scale growth among populations. To evaluate differences in marine growth between coastal and Puget Sound populations we used the Kruskal-Wallis Rank Sum Test followed by pairwise comparisons using the Dunn Test and Bonferroni adjusted p-values. For this analysis we aggregated scale measurements across outmigration years (1992, 1998, 1999, 2002, 2005, and 2008) and age classes where scale measurements were the dependent variable and geographic region was the independent variable. To test the hypothesis that marine growth and size at ocean entry are related to survival we used Pearson's Correlation Coefficients to relate annual mean scale growth to standardized estimates of survival. Survival estimates from Ruff et al. (In review) were used for each outmigration year and population or nearest population with complete estimates. Survival estimates for Samish fall fingerlings were used for NPS, Green River fall fingerlings for MPS, South Puget Sound and Puyallup River fall fingerlings for SPS, Queets River fall fingerlings for NWC. Complete survival data was not available for fish from Willapa Bay and Grays Harbor. Standardized survival was calculated as the number of standard deviations above or below the mean for all outmigration years in this study. To investigate the utility of predicting survival using early marine growth, we used mean scale growth of age-3_1 fish during the first year at sea to predict estimates of survival using simple linear regression.

Results

Regional Comparisons of Marine Growth.—We digitized and measured a total of 2604 scales from 5 geographic regions and 7 outmigration years (Tables 1 & 2). Over the entire study period, coastal populations had a 14% greater size at ocean entry than Chinook salmon returning to Puget Sound (Figure 3, Table 3). This may indicate early emergence timing for coastal populations, higher freshwater growth rates, or later seaward migration timing. Scale growth during the first ocean year was significantly greater for Quillayute River fish than those retuning to SWC or to Puget Sound (Figure 3, Table 3). This resulted in coastal Chinook salmon reaching a significantly greater scale size at the end of their first year at sea compared to fish returning to Puget Sound (Figure 3, Table 3). Within Puget Sound, fish returning to NPS had significantly smaller scale size at ocean entry than MPS and SPS (Figure 3, Table 3). Overall, Chinook salmon returning to SPS had significantly lower scale growth during the first marine year and the smallest median scale radius at the end of the first year at sea (Figure 3, Table 3). Over the entire study, scale growth during the second year at sea was relatively similar between coastal and Puget Sound populations (Figure 3, Table 3). Finally, we investigated the relationship between early marine growth and published metrics of ocean condition (i.e. Pacific Decadal Oscillation, Upwelling Index) but observed no relationship for any of the populations examined.

Marine Growth and Survival.— Growth during the first year at sea was positively and significantly related to survival for NPS ($r = 0.75$, $n=7$, $p = 0.05$), MPS ($r = 0.89$, $n=7$, $p = 0.01$), and SPS ($r = 0.76$, $n=7$, $p = 0.05$) populations (Figure 4). We found no evidence of a growth/survival relationship during the first year at sea for Quillayute River Chinook salmon (Figure 5) or during the second year at sea for any population ($p > 0.05$). Figure 4 shows that outmigration year 1976 was associated with the highest annual mean growth during the first year at sea for MPS and SPS populations and the highest survival estimates on record for those populations. Growth during the first year at sea for north and mid Puget Sound populations was positively and significantly related (Figure 4, $r = 0.78$, $n=7$, $p = 0.04$). Growth during the first year at sea of south Puget Sound Chinook was not significantly related to growth of either mid ($r = 0.58$, $n=7$, $p = 0.17$) or north ($r = 0.66$, $n=7$, $p = 0.12$) Puget Sound populations, suggesting differential survival of stocks within Puget Sound. Growth during the second year at sea was positively correlated among all Puget Sound populations (mid versus north, $r = 0.83$, $n=7$, $p = 0.02$; mid versus south, $r = 0.79$, $n=7$, $p = 0.03$; north versus south, $r = 0.88$, $n=7$, $p = 0.01$). Growth of coastal and Puget Sound populations was not significantly related ($p > 0.05$) during the first or second year at sea.

An objective of this study was to evaluate the utility of using scale growth of younger fish returning from a cohort to predict survival of the entire cohort (age-3_1 to 5_1). Growth of age 3_1 fish was positively and significantly related to survival for both north and mid Puget Sound populations (Figure 6) indicating scale growth estimates in the first year at sea may benefit forecasting models. The relationship between marine growth and survival was weaker and non-significant for fish from the Puyallup River (Figure 6).

Discussion

In this study, we examined the relationship between early marine growth and survival for Puget Sound Chinook salmon. We observed a positive relationship between growth during the first year at sea and survival for each of the populations examined in Puget Sound. Conversely, we observed no evidence of a relationship between growth and survival for fish returning to the Quillayute River (NWC) or for any population during the second year at sea. These results support previous observations that factors influencing early marine growth such as temperature, prey abundance and composition are important to the survival of Puget Sound Chinook salmon (Duffy et al 2010, Duffy and Beauchamp 2011, Gamble 2016). In addition, these results also have implications for management. We observed that marine growth of the youngest returning fish may be a biological indicator of survival for an entire cohort.

Pre-season forecasting of salmon populations is required to allocate harvest quotas among user groups and fisheries. Accurate predictions of the number of returning adults may be particularly important when numbers are near or below escapement goals. Currently, several different approaches are used for forecasting adult returns (PFMC 2015) including moving average, and sibling and age-based models (Peterman 1982). However, few models incorporate biological and environmental predictors of salmon survival (Rupp et al. 2012, Burke et al. 2013, Zimmerman et al. 2013). In this study, growth of age 3_1 fish was positively and significantly related to survival for both north and mid Puget Sound populations indicating the utility of incorporating scale growth to predict survival of the entire cohort (age-3_1 to 5_1). Future efforts should explore this approach for other Puget Sound populations and predict survival of cohorts returning currently in the Green/Duwamish and Skagit Rivers.

Prey availability (Litz et al. 2017a), and temperature (Gamble 2016) have been shown to be important factors related to early marine growth in Chinook salmon. Using concurrent catches of Chinook salmon and their prey off Columbia River over two years, Litz et al. (2017a) observed that Chinook salmon condition and growth increased with increased availability of young of the year Northern anchovy (*Engraulis mordax*). Faster growing individuals during early life stages often have increased survival (see review by Sogard 1997). For example, in the laboratory, Chinook salmon with increased growth and energy reserves had increased swimming speed as compared to smaller fish with less lipid stores, suggesting that they may have a survival advantage during periods of starvation or low prey availability (Litz et al 2016b). Results from this study support previous conclusions that bottom up factors that affect growth are important to the survival of Puget Sound Chinook salmon (Duffy et al. 2010, Duffy and Beauchamp 2011, Gamble 2016). However, future studies should explore the relationship between local indices of temperature, primary productivity, and prey availability in Puget Sound in relation to our growth estimates.

The positive relationship between early marine growth and survival observed in this study and that of Duffy and Beauchamp (2011) and Tomaro et al. (2012) is not consistently observed across the range of Chinook salmon. Similar to our results from the Quillayute, Ruggerone et al. (2009) found no relationship between marine growth and adult abundance for Yukon River Chinook salmon. While Miller et al. (2013) found a negative relationship between early marine growth measured in juvenile otoliths and subsequent adult returns, indicating top-down factors such as size selective mortality, or competition, may be limiting survival. Together, results from these studies indicate that the factors influencing early marine survival vary between stocks, life-history types, and geographic areas.

Adults returning to the Puyallup River consistently had the lowest growth during the first year at sea, and attained the smallest size observed in this study. Puget Sound Chinook salmon exhibit both resident and coastal ocean migrations (Pressey 1953) and it is estimated that nearly one third of out-migrants reside in Puget Sound (O'Neill and West 2009). Chamberlin and Quinn (2014) observed higher residence in mid and south Puget Sound hatchery Chinook salmon, compared to those originating from northerly populations. In addition, residents have been observed to grow slower than ocean migrants (Lasater and Haw 1964) and we suspect that fish returning to the Puyallup River had a higher proportion of fish residing in Puget Sound for longer periods of time.

In conclusion we examined scales from adult Chinook salmon returning rivers in north, mid, and south Puget Sound and coastal Washington in 7 outmigration years from 1976 to 2008. We found a positive relationship between growth during the first year at sea and survival for adults returning to the Skagit, Green/Duwamish, and Puyallup Rivers but not for coastal populations. Furthermore, growth of age 3_1 fish from north and mid Puget Sound was a useful predictor of cohort survival (age 3_1 to 5_1). Our results support previous research that bottom up factors and processes influencing early marine growth are important to the survival of Puget Sound Chinook salmon. In addition, early marine growth may a useful biological indicator for pre-season forecasting of some Chinook salmon populations in Puget Sound.

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Tables

Table 1 shows Puget Sound Chinook salmon from different rivers and outmigration years used in this study. Samples for each outmigration year and area are shown by percent age-class (3_1, 4_1, 5_1), sex (Male, Female), mark status (CWT, Adipose clipped, No mark) and total number of samples in an outmigration year. Samples in parenthesis show the number of samples originating from the Nooksack River.

Outmigration Year	% Marked	% No Mark	n	% age-3_1	% age-4_1	% age-5_1	% M	% F
North Puget Sound Skagit & Nooksack Rivers								
1976	87	13	0 (71)	36	46	18	41	59
1992	0	100	60	45	52	3	50	50
1998	0	100	66	32	42	26	52	48
1999	0	100	52	31	56	13	60	40
2002	0	100	96	30	34	35	49	51
2005	0	100	96	35	35	29	49	51
2008	0	100	83	34	36	30	48	52
Mid Puget Sound Green/Duwamish River								
1976	35	65	49	14	57	29	43	57
1992	0	100	68	47	46	7	47	53
1998	0	100	61	46	46	8	51	49
1999	0	100	93	39	33	28	46	54
2002	32	68	66	39	50	11	56	44
2005	0	100	39	51	49	0	67	33
2008	14	86	50	32	54	14	52	48
South Puget Sound Puyallup River								
1976	0	100	15	0	100	0	73	27
1992	0	100	68	49	49	3	51	49
1998	0	100	53	39	54	7	56	44
1999	0	100	77	29	42	30	57	43
2002	27	73	60	48	52	0	50	50
2005	0	100	62	50	50	0	40	60
2008	0	100	13	0	100	0	54	46

Table 2 shows Coastal Washington Chinook salmon from the different rivers and outmigration years used in this study. Samples for each outmigration year and area are shown by percent age-class (3_1, 4_1, 5_1), sex (Male, Female), mark status (CWT, Adipose clipped, No mark) and total number of samples in an outmigration year. Samples in parenthesis show the number of samples originating from the Grays Harbor.

Outmigration Year	% Marked	% No Mark	% Unk$_{mark}$	n	% age-3_1	% age-4_1	% age-5_1	% M	% F	% Unk$_{sex}$
				North Washington Coast Quillayute River						
1985	0	100	-	42	17	67	17	50	50	-
1992	0	100	-	57	28	21	51	58	42	-
1998	0	100	-	98	26	37	38	54	46	-
1999	0	100	-	76	28	39	33	51	49	-
2002	0	100	-	84	18	43	39	52	48	-
2005	0	100	-	105	37	34	29	47	53	-
2008	0	100	-	106	34	34	32	48	52	-
				South Washington Coast Willapa Bay & Grays Harbor						
1985	0	100	0	90	33	33	33	51	49	0
1992	0	65	35	95	33	33	35	0	0	100
1998	0	34	66	99	30	35	34	18	16	66
1999	0	55	45	104	35	33	33	21	22	57
2002	0	39	61	110	35	33	32	12	10	78
2005	0	100	0	73 (7)	49	51	0	18	4	78
2008	1	100	0	113 (47)	45	24	31	2	4	95

Table 3 shows the median difference (Median Diff), z statistic (Z) and p-value (p) from Dunn's multiple comparison procedures comparing scale size at ocean entry (OE), scale growth during the first ocean year (OG1), scale radius at the end of the first ocean year (R OA1), and scale growth during the second ocean year (OG2) between geographic areas. South Puget Sound was not included due to incomplete data.

	OE			**OG1**			**R OA1**			**OG2**		
Area	**Median Diff (µm)**	**Z**	**p**	**Median Diff (µm)**	**Z**	**p**	**Median Diff (µm)**	**Z**	**p**	**Median Diff (µm)**	**Z**	**p**
MPS vs NWC	-82	14.71	<0.01	-63	-5.63	<0.01	-144	-10.36	<0.01	-56	-0.03	1.00
MPS vs NPS	27	3.73	<0.01	4	-0.76	1.00	-3	0.70	1.0	-16	1.85	0.19
MPS vs SWC	-55	-11.40	<0.01	21	-0.25	1.00	-45	-4.27	<0.01	-78	-.074	1.00
MPS vs SPS	-7	-2.5	0.06	72	5.92	<0.01	59	4.88	<0.01	-27	-0.60	1.00
NWC vs NPS	109	19.56	<0.01	67	5.11	<0.01	141	11.69	<0.01	41	2.05	0.12
NWC vs SWC	27	4.05	<0.01	84	6.08	<0.01	100	7.00	<0.01	-22	-0.77	1.00
NWC vs SPS	75	11.67	<0.01	170	11.90	<0.01	234	15.30	<0.01	-19	-0.62	1.00
NPS vs SWC	-82	-16.22	<0.01	17	0.58	1.00	-42	-5.30	<0.01	-62	-2.85	0.01
NPS vs SPS	-34	-6.29	<0.01	103	6.98	<0.01	92	4.43	<0.01	-59	-2.43	0.07
SWC vs SPS	48	8.42	<0.01	86	6.84	<0.01	134	9.58	<0.01	3	0.05	1.00

Figures

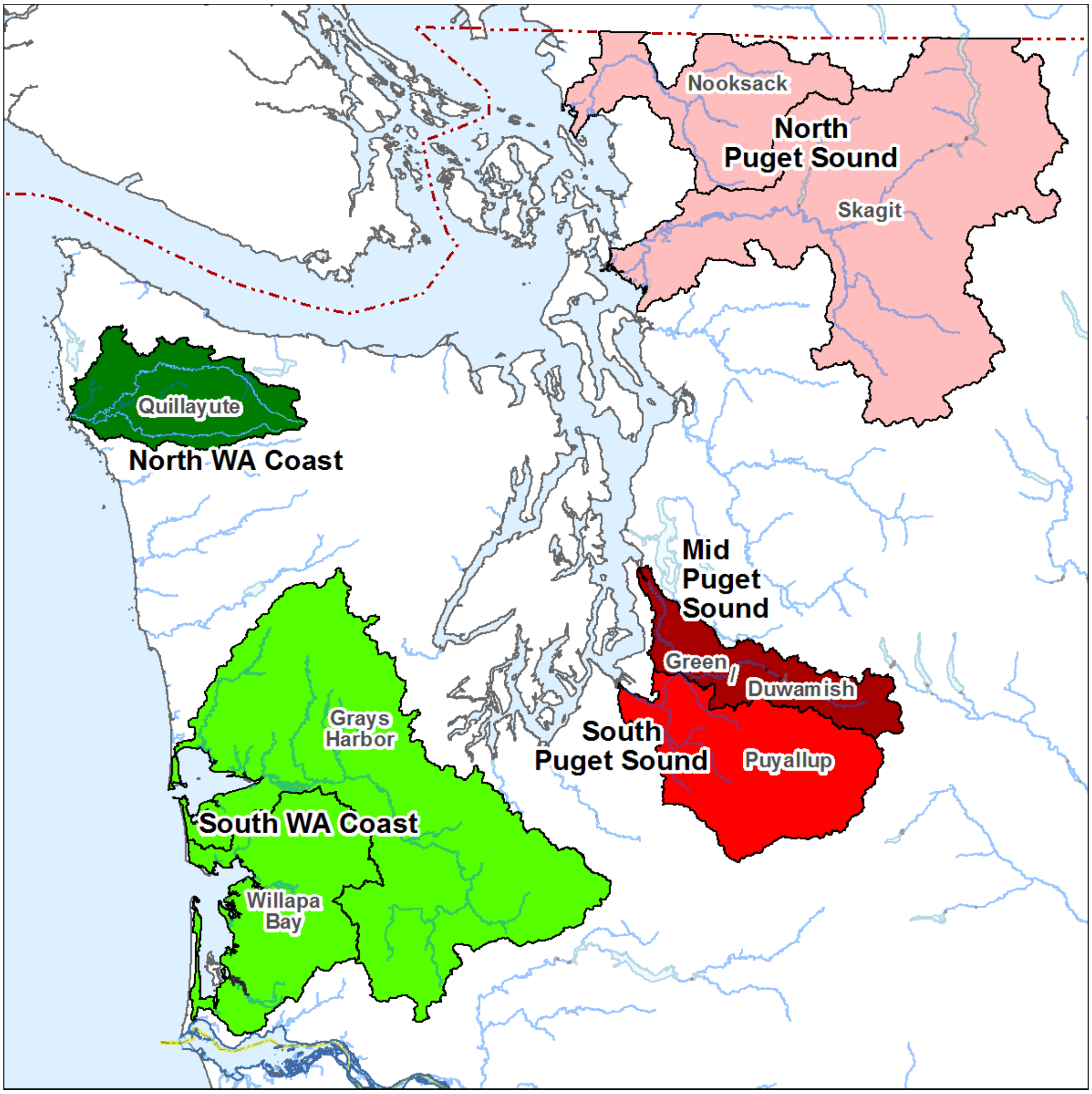

Figure 1. Map of the geographic areas and river basins where Chinook salmon used in this study were captured. Samples were taken from individuals captured in terminal gill net fisheries associated with each river system, Grays Harbor and Willapa Bay.

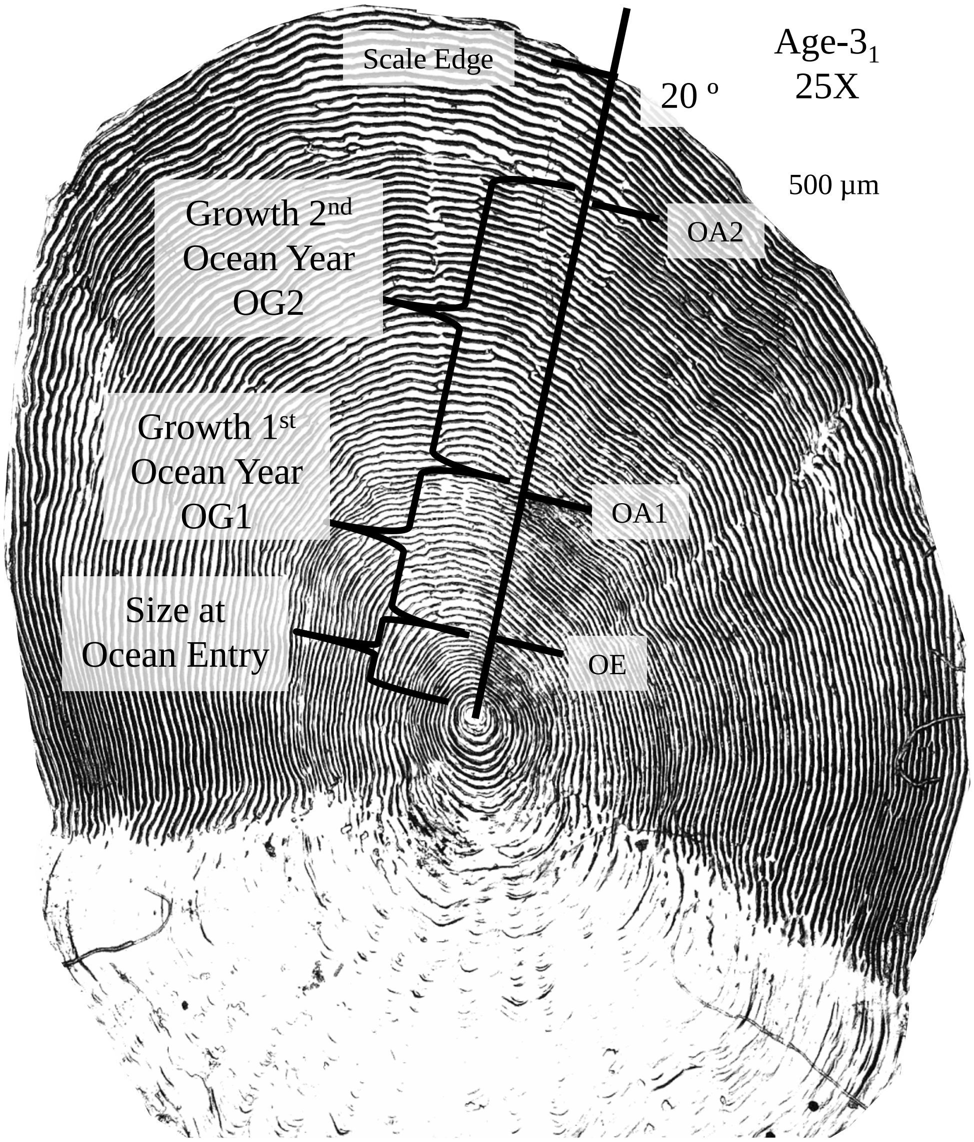

Figure 2 Image of an age 3_1 Chinook salmon scale from the Green/Duwamish River that was used in this study. Scale size at ocean entry (OE), ocean annuli 1 (OA1), ocean annuli 2 (OA2), growth during the 1st (OG1) and 2nd ocean year (OG2) and the scale edge are shown along the 20º dorsal axis used for measurements.

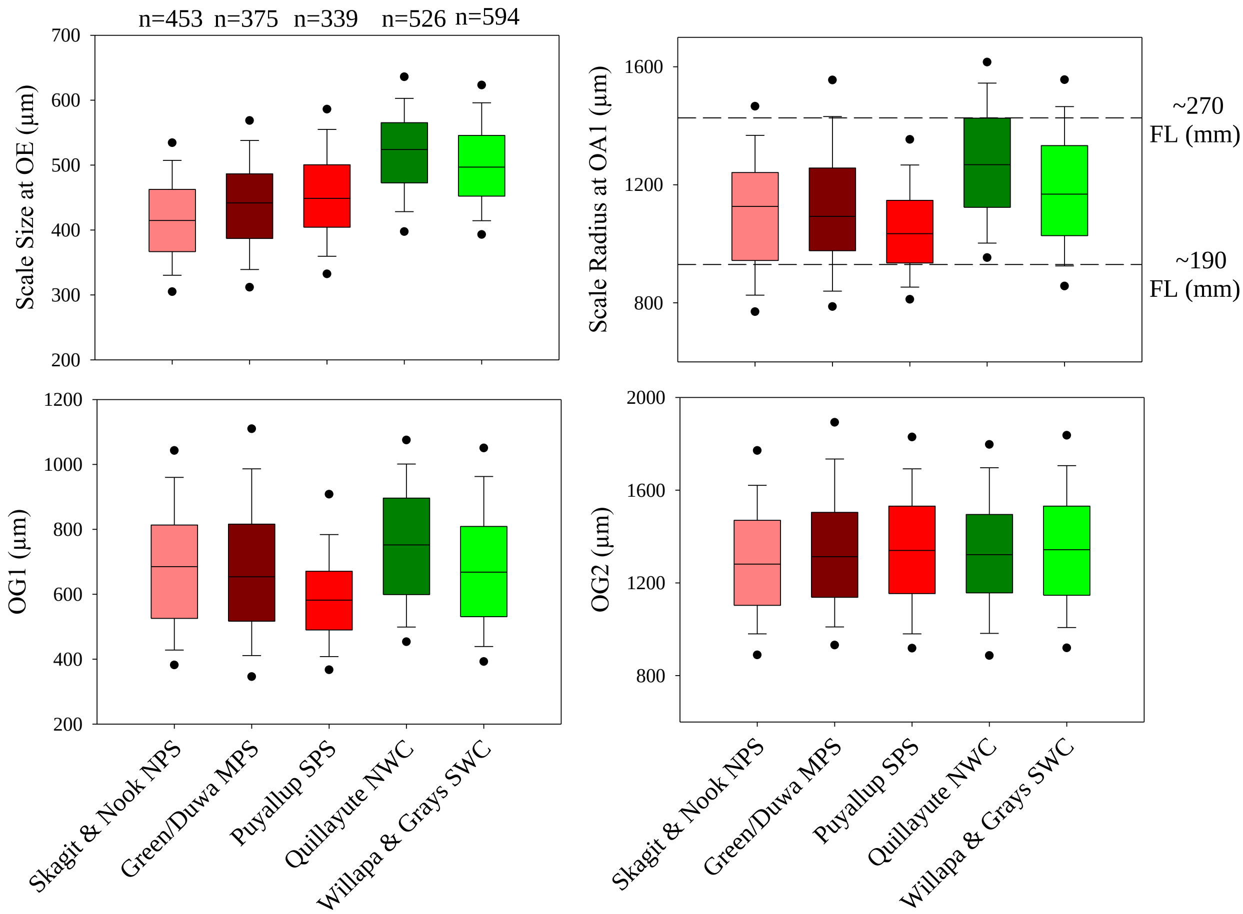

Figure 3 Box plots showing scale size at ocean entry (OE), ocean year-1 scale growth (OG1), ocean year-2 scale growth (OG2), and scale radius at the end of the first ocean year (OA1) for Chinook salmon from outmigration years 1992, 1998, 1999, 2002, 2005, and 2008. White and grey boxes indicate Puget Sound and coastal populations respectively. Line indicates median value.

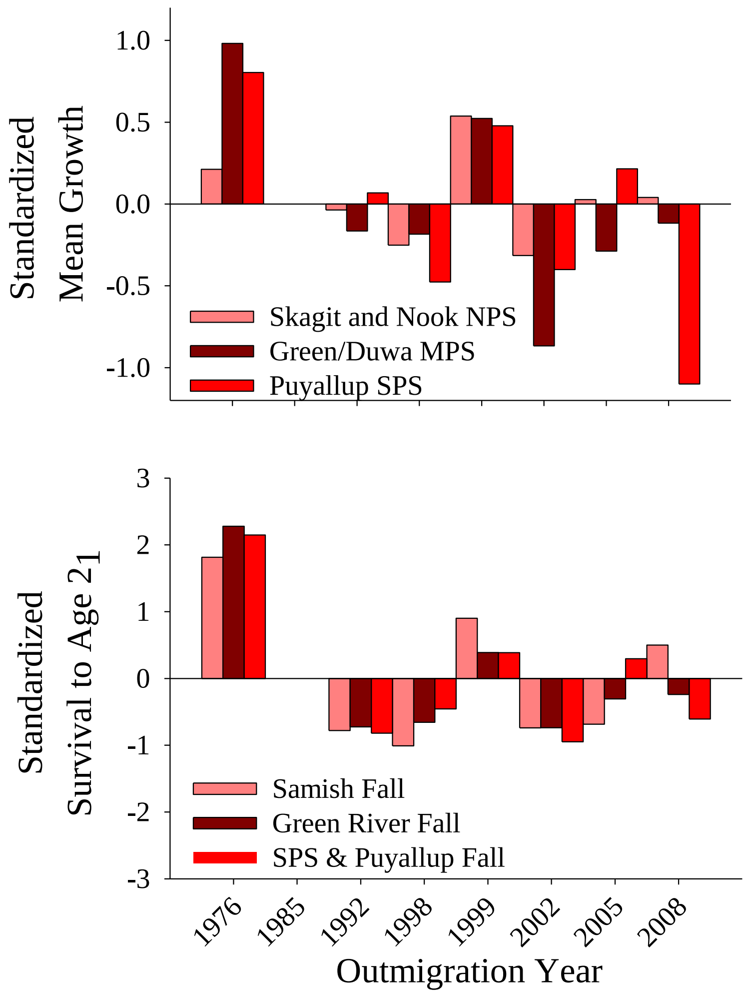

Figure 4. The top panel shows standardized growth during the first ocean year for Puget Sound Chinook salmon used in this study. The bottom panel shows standardized survival to age 2_1 from Ruff et al. (in review). Sample sizes can be seen in Table 1.

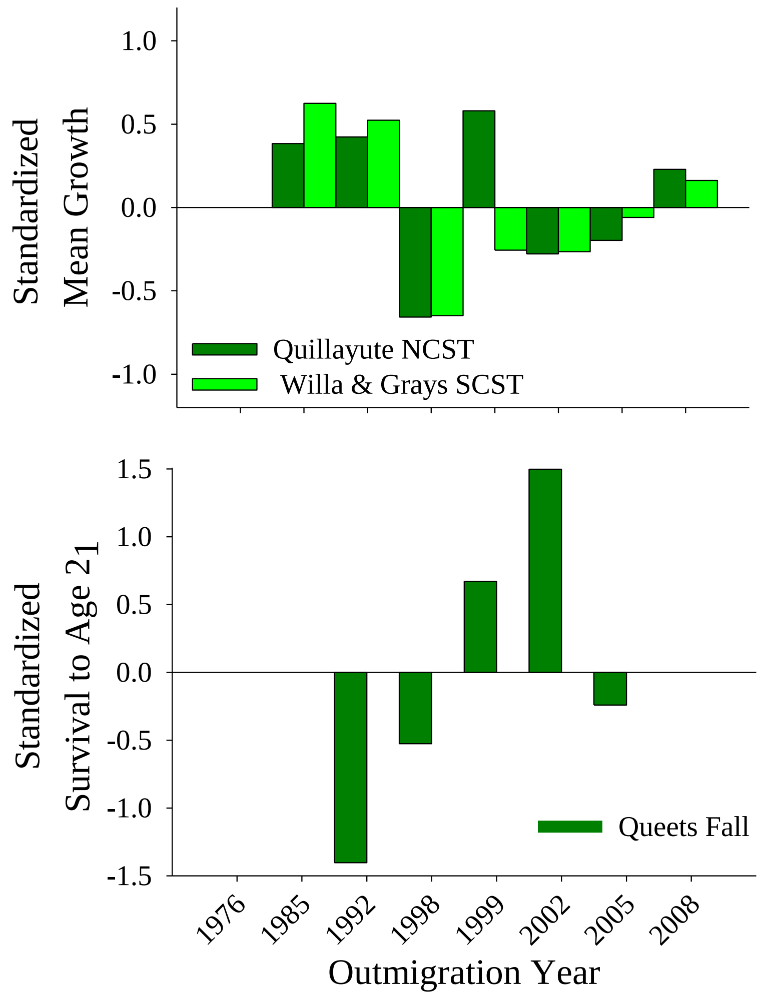

Figure 5 The top panel shows standardized growth during the first ocean year for coastal Chinook salmon used in this study. The bottom panel shows standardized survival to age 2_1 from Ruff et al. (in review). Sample sizes can be seen in Table 2.

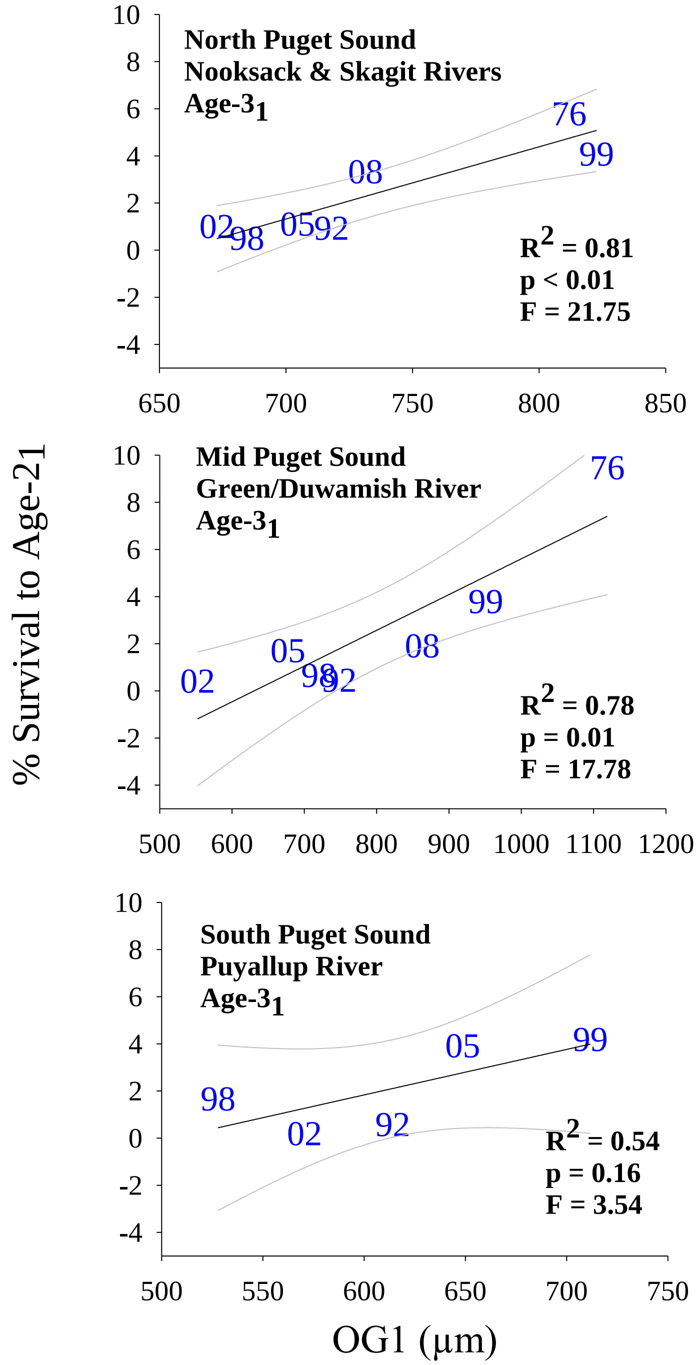

Figure 6 Plots and linear regressions showing scale growth during the first ocean year (OG1) of age 3_1 fish predicting percent survival to age 2_1 of an entire cohort for north, mid, and south Puget Sound Chinook salmon.