

ANNUAL REPORT

To the Bonneville Power Administration

**Reporting Period:
April 2010- April 2011**

Prepared by:

**Northwest Fisheries Science Center
NOAA Fisheries,**

**Cooperative Institute for Marine Resources Studies
Oregon State University,**

and

**OGI School of Science & Engineering
Oregon Health Sciences University**

Summary of Activities April 2010 to April 2011;

We continue to make substantial progress toward our objectives outlined in our BPA supported proposal entitled “Columbia River Basin Juvenile Salmonids: Survival and Growth in the Columbia River Plume and northern California Current” which we report on herein. During 2010, we were able to successfully conduct 3 *mesoscale* cruises. We also were able to conduct 2 *predator* cruises, along with substantial shore-based visual observations of seabirds. Detailed results of the mesoscale cruises are available in the Cruise Reports and summarized in the next section.

We continue to take a proactive approach to getting the results of our research to fisheries managers and the general public. We have updated our annual predictions based on ocean conditions of the relative survival of juvenile coho and Chinook salmon well before they return as adults. This is based on both biological and physical indicators that we measure during our surveys or collect from outside data sources. Examples of our predictions for 2011 and 2012 are available on the following web site:

<http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm>

Juvenile Salmon Catches in Trawl Surveys -- Field sampling in 2010

May cruise - Thirty-six different station locations were sampled during the May 2010 cruise, including 39 trawls and bongo net hauls 36 vertical net tows, and 40 CTD casts as well as bird/mammal observations. A total of 291 Chinook salmon and 913 coho salmon were captured during the survey, representing 86.6% of the total salmonid catch numerically. The majority of salmon caught were juveniles: 97.6% of the Chinook salmon (those ≤ 450 mm FL) and 98.0% of the coho salmon (those ≤ 275 mm FL).

Only 3 subyearling (≤ 120 mm FL) Chinook salmon were caught during the cruise, on the Willapa Bay and Grays Harbor transect. Yearling Chinook (121 - 250 mm FL) and coho salmon (≤ 275 mm FL) were much more widespread and were generally high between the Columbia River, Grays Harbor and Queets River transects, and lower along the northernmost La Push and southernmost Cape Meares transects. Mixed-age juvenile Chinook salmon (251 - 450 mm FL) were found only along the Grays Harbor and Willapa Bay transects. In May 2010, catch per unit effort (CPUE, number per km trawled) of both yearling coho salmon and sockeye salmon was unusually high compared to other Mays (Fig.1). CPUE of coho salmon was three to four times the 12-year average and was two to three times the next highest year. CPUE of sockeye salmon was also three to four times the long-term average and was one of the highest of the time series. On the other hand, CPUEs of yearling Chinook salmon and of the other juvenile salmon were either below or close to their long-term averages. Among the years in which the latitudinal range of sampling in May was broad (1999 and 2006 - 2010) 2010 still stands out as a year of very high abundance of juvenile coho and sockeye salmon.

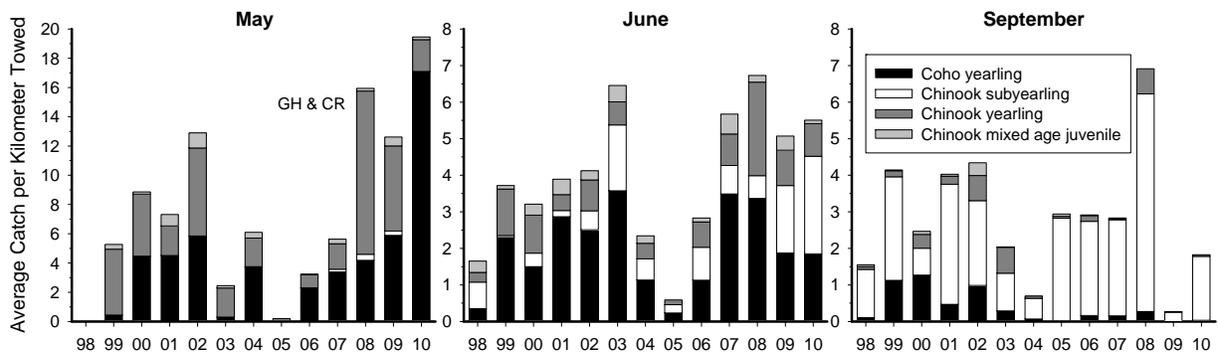


Figure 1. Catch of yearling coho and subyearling, yearling and mixed age juvenile Chinook salmon and yearling coho salmon during May, June, and September cruises. May data are from the two transects consistently sampled in all May cruises (Grays Harbor and Columbia River).

June cruise - Fifty-three different stations were sampled during the June 2010 cruise, including 55 trawls, 53 CTD casts and vertical net hauls, and 52 bongo net hauls, as well as bird/mammal observations. A total of 597 Chinook salmon and 411 coho salmon were captured during the cruise, representing 80.3% of the total salmonid catch numerically. The majority of salmon caught were juveniles: 98.3% of the Chinook salmon (those ≤ 450 mm FL) and 85.2% of the coho salmon (those ≤ 330 mm FL).

Subyearling (≤ 140 mm FL) Chinook salmon were most abundant from the Columbia River transect to the Grays Harbor transect and at the inshore stations further north. Yearling Chinook (141 - 280 mm FL) and coho salmon (≤ 330 mm FL) were much more widespread, but rare on the southernmost transects, and mixed-age juvenile Chinook (281 - 450 mm FL) were less abundant than other juveniles and found mostly from the Columbia River to Grays Harbor transects. The largest catches of juvenile coho and Chinook salmon were primarily from the Columbia River transect to the north. Juvenile chum salmon were found mostly from the Grays Harbor transect to the north, and sockeye salmon were found mostly from the Willapa Bay transect and to the north. CPUEs of subyearling Chinook salmon during this cruise was very high compared to the 12 previous June cruises 1998 - 2009, whereas CPUE of yearling Chinook and coho salmon were neither unusually high nor low (Fig. 1). June 2010 had the highest (out of 13) average CPUE of subyearling Chinook salmon, which was 45% higher than the next highest CPUE (June 2009), and was 3.7 times higher than the 1998 - 2009 June average. In June 2010, yearling Chinook salmon CPUE was ranked fifth highest of the 13 years of sampling, was 35% of the highest CPUE (June 2008), and was equal to the 1998 - 2009 June average. Mixed-age juvenile Chinook salmon CPUE was relatively low, 11 of 13 years, during the sampling period, was 18% of the highest CPUE (June 2007), and was 2.8 times lower than the 1998 - 2009 June average. Average CPUE of yearling coho salmon during June 2010 ranked eighth out of the thirteen years, was 52% of the highest abundance year (June 2003), and was equal to the twelve-year average. Abundance of yearling Chinook salmon during our June surveys has a significant and positive relationship to Spring Chinook jack counts at Bonneville the following spring (Fig. 2). Thus, our catches in June may be a good indicator of first year ocean mortality of yearling Chinook salmon. There were no relationships between our June catches of

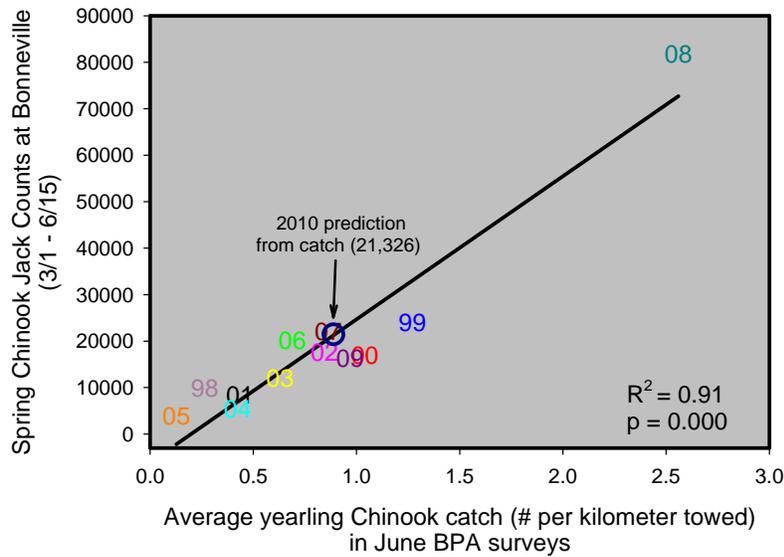


Figure 2. Average CPUE (Catch per Unit Effort, number per km towed) of yearling Chinook salmon caught during each of our June cruises, 1998 – 2009 versus Spring Chinook salmon jack counts at Bonneville Dam. The open point indicates the observed 2010 June CPUE (0.89) and predicted jack count from the regression (21,326).

subyearling Chinook or yearling coho salmon and Bonneville fall Chinook jack counts or coho smolt to adult survival. Based on our June 2010 catches of yearling Chinook salmon, jack counts at Bonneville in spring 2011 should be in the middle to the high side of the range seen during the survey years of 1998 - 2010 (Fig. 2).

September cruise - Fifty-one different stations were sampled during the September 2010

cruise, including 43 trawls, 51 CTD casts, 49 vertical net tows, and 48 bongo net tows. A total of 264 Chinook salmon and 10 coho salmon were captured during the cruise, representing 98.6% of the total salmonid catch. The majority of salmon caught were juveniles: 100% of the Chinook salmon (those ≤ 450 mm FL) and 50% of the coho salmon (those ≤ 330 mm FL). As was the case during previous September cruises, subyearling Chinook salmon were most abundant at the most inshore stations. Yearling Chinook salmon (251 - 400 mm FL) were much less abundant (n = 7) than subyearling fish, and all were caught inshore at the La Push, Grays Harbor and Cascade Head transects. Similar to the low catches in 2009, yearling coho salmon were not very abundant (n = 5)

Among the 13 September cruises, in 2010 the average CPUE of subyearling Chinook salmon was eighth highest overall, which was 33% higher than the next highest CPUE (September 1998), but 20% (1.2 times) lower than the 1998 – 2009 September average. In September 2010, yearling Chinook salmon CPUE was ranked eleventh highest of the 13 years of sampling, was 25% of the next highest CPUE (September 2005) and 85% less than the 1998 – 2009 September average (Fig. 1). CPUE of yearling coho salmon in September 2010 was tied with September 2005 for eleventh highest, was 57% less than the next highest abundance year

(September 2004), and 92% less than the 1998 – 2009 September average. Because we didn't catch any mixed-age juvenile Chinook in September 2010, we were tied for last overall with 2004, 2008 and 2009 for these fish. In general, salmonid CPUE values were up only slightly from 2009, when we recorded the lowest CPUE across all salmonid categories. (Fig. 1).

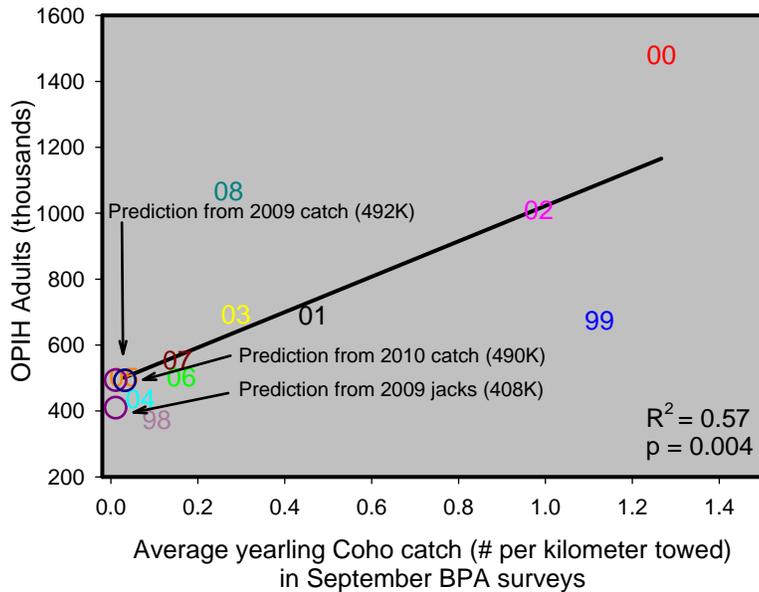


Figure 3. Regression of OPIH (Oregon Production Index Area Hatchery) adult coho salmon abundance on the average CPUE (Catch per Unit Effort, number per km towed) of juvenile coho salmon the previous September. The years indicated are for the catches of the juvenile fish. The predicted adult production from the 2010 smolt year based on jack returns is 490 thousand, (Pacific Fisheries Management Council). The observed 2009 September CPUE (0.01) predicts OPIH from the regression (492 thousand). Also shown are the predictions for the 2009 smolt year based on jack counts (408K) and based on our 2009 CPUE (492K).

CPUE of yearling coho salmon in our September catches (mixed stocks from Puget Sound to southern Oregon) appears to be a fairly good predictor of abundance of Oregon Production Index Area hatchery (OPIH) coho salmon (Fig. 3). The extremely low catches of juvenile coho salmon in our September 2010 catch suggest that adult production may be low in 2011.

This relationship between juvenile coho salmon abundance in September and adult production the following year indicates the importance of first summer ocean conditions to the survival of coho salmon in their first few months at sea.

Stock origins based on DNA Analysis

Columbia River coho salmon were an estimated 36% of our coho catches in June 2010 (Fig. 4). Only four coho salmon were genotyped from September trawls and all four were estimated to be from the Columbia River.

Columbia River Basin Chinook salmon were an estimated 100% and 99% of our catches of yearling

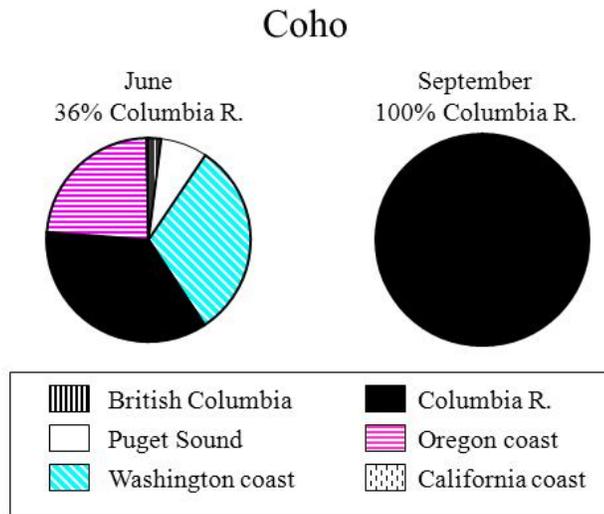


Figure 4. Stock proportions of juvenile coho salmon captured in the study area in 2010 based on microsatellite DNA analysis.

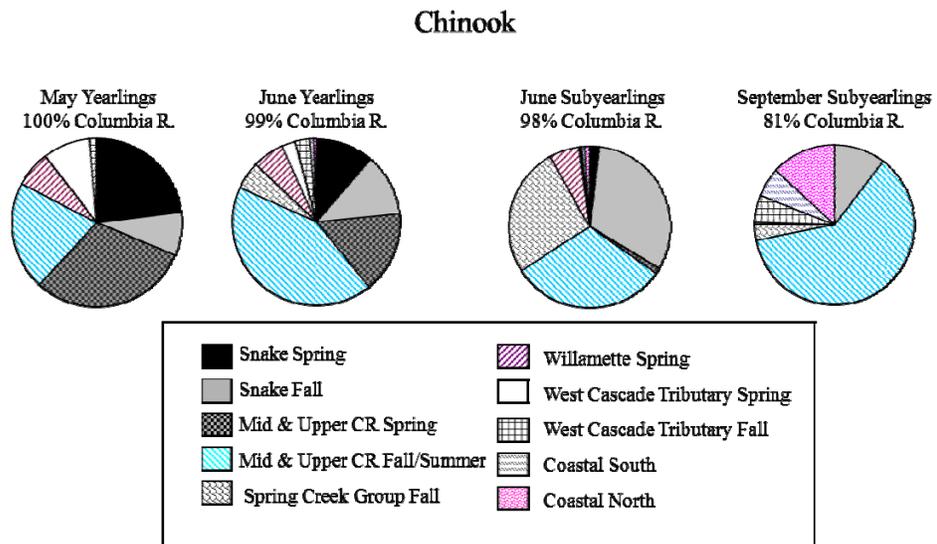


Figure 5. Stock proportions of juvenile Chinook salmon captured in the study area in 2010 based on microsatellite DNA analysis.

Chinook in May and June 2010, and 98% and 81% of our catches of subyearling

Chinook in June and September 2010 (Fig. 5). Spring Chinook salmon from the Snake River (23%), mid and upper CR (30%), West Cascade tributaries (9%) and Willamette River (6%) were predominate in May samples. The mid and upper CR summer/fall run (43%) and spring run (16%) stock groups were the largest contributors to our June yearling catches. Upper CR

summer and fall Chinook salmon were also a major contributor to subyearling (31%) June catches and the September subyearling catch (61%). Coastal stocks from north of the CR comprised an estimated 13% of the September subyearling catches. Snake River Fall Chinook salmon were caught in May (yearlings= 8%), June (yearlings = 12% and subyearlings = 32%) and in September

(subyearlings= 10%). We estimated 0.85 subyearling Snake River fall fish caught per km towed in June 2010, the highest density of the stock in the thirteen years of sampling (Fig. 6).

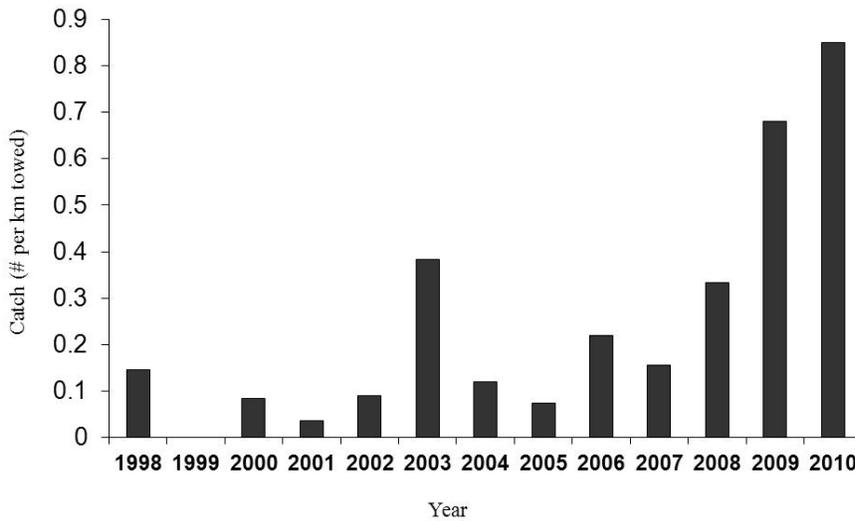


Figure 6. Densities (proportional estimate x CPUE) of Snake River Fall Chinook salmon subyearling juveniles caught in June trawls (1998-2010).

Summary of coded wire tagged (CWT) Chinook and coho salmon caught during the Columbia River Plume Study, 1998 – 2010.

During the Columbia River Plume study, 1998-2010, a total of 3,235 CWT Chinook and coho salmon which could be assigned to stock groups were collected (Table 1). Associated with some of these CWT groups were untagged fish released at the same size, location, and date as the tagged fish. Assuming that these untagged fish have similar ocean dispersal patterns as the tagged fish, we expanded the catch of CWT fish in each sample (tow) to account for the potential presence of untagged fish from the same release group. The expansions were constrained so as not to exceed the actual catch in the appropriate size/age range in each tow. Expanded catches totaled 7,377 fish (Table 1). The expansions based on CWT recoveries accounted for approximately 34%, 41%, and 23% of the total catch during the first ocean year of subyearling Chinook salmon, yearling Chinook salmon, and coho salmon, respectively.

Catch per unit effort (number per km towed) was calculated for expanded numbers of fish in each stock group in each tow. The CPUE in each tow was then averaged for all tows along each transect during each cruise. These month/transect-average CPUEs were then averaged across all years, yielding a grand average CPUE for each month and transect. The resulting CPUEs are presented in Figure 7 for the May, June and September cruises.

Several trends in ocean dispersal are apparent. Upper basin Columbia River Spring Chinook salmon and those from the Willamette river exit the study area to the north rapidly during May and June and are mainly absent by September (Fig. 7). Conversely, subyearling fall Chinook salmon, both from the Columbia River basin and from coastal streams, are most abundant in June and September, with yearling releases from the fall run fish also found in May. Lower Columbia River basin fall Chinook salmon (tule) have a distinctly more northerly distribution in September than do the upper Columbia River fall runs, although the Snake River fall run fish are also more abundant in the north in September, as are also the upper Columbia River summer run fish. Columbia River basin and coastal coho salmon decrease greatly in abundance between the May-June period and September, indicating that most had migrated to the north of the study area by September. A few Puget Sound (Salish Sea) coho salmon are found along the northern transects in September (Fig. 7).

Table 1. Total numbers of CWT and expanded numbers of associated coho and Chinook salmon caught during regular Columbia River Plume Study sampling, 1998 – 2010. Expansions accounted for untagged fish released with each CWT group, and were calculated separately for each sample (tow), and were also constrained so as not to exceed the total numbers of fish in the appropriate size/age range caught in each sample.

Stock group	First ocean year				Second ocean year			
	Subyearling (0.0)		Yearling (1.0)		0.1		1.1	
	n	exp. n	n	exp. n	n	exp. n	n	exp. n
<i>Chinook salmon:</i>								
Lower Col. R. fall tule	63	940	-	-	11	13		
Lower Col. R. spring	-	-	108	132	-	-	1	1
Mid-upper Col. R. fall	144	520	25	25	5	9	-	-
Snake R. fall	209	352	268	270	9	12	1	1
Upper Col. R. summer	34	40	718	725	1	2	3	3
Upper Willamette spring	-	-	96	435	-	-	-	-
Mid Col. R. spring	-	-	182	425	-	-	-	-
Upper Col. R. spring	-	-	209	340	-	-	-	-
Snake R. spring/summer	2	2	229	766	-	-	1	1
Coastal WA fall	52	97	-	-	1	1	-	-
Coastal OR (fall and spr.)	59	140	6	32	2	7	-	-
Puget Sound fall	2	2	-	-	13	22	-	-
Sacramento R. fall	2	4	1	1	4	8	-	-
Trinity R. fall	-	-	-	-	2	9	-	-
<i>Coho salmon:</i>								
Coastal OR	-	-	18	40				
Col. R.	-	-	511	1,544	-	-	1	-
Coastal WA	-	-	227	411	-	-	-	-
Puget Sound	-	-	12	40	-	-	2	-
West Vancouver Is.	-	-	1	5	-	-	-	-
Totals	567	2,097	2,611	5,191	48	83	9	6

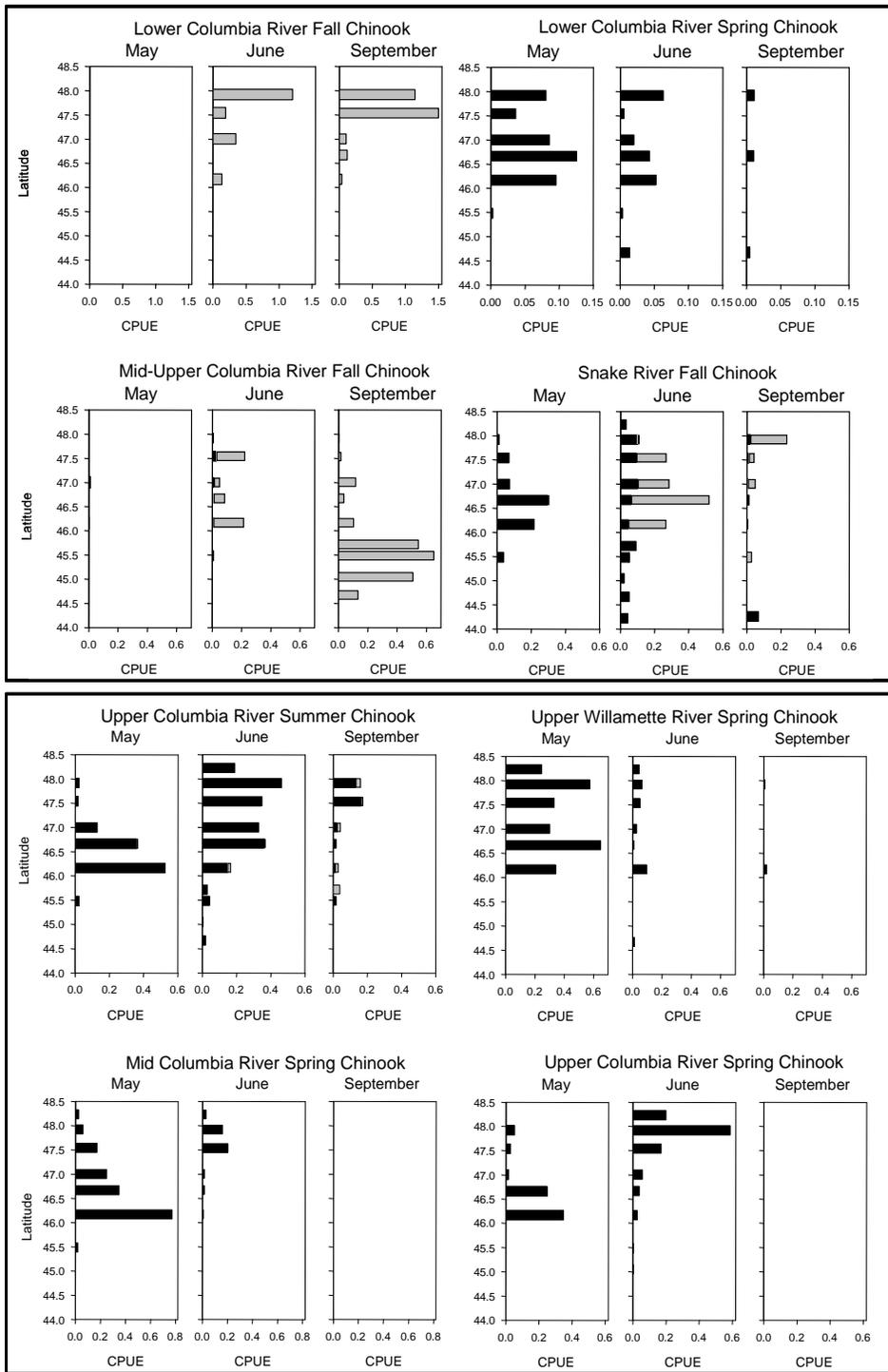


Figure 7. Average catch per unit effort of juvenile salmon associated with CST groups 188-2010 by month and transect. Note changes in scale between stock groups. Black: yearlings; Gray: subyearlings

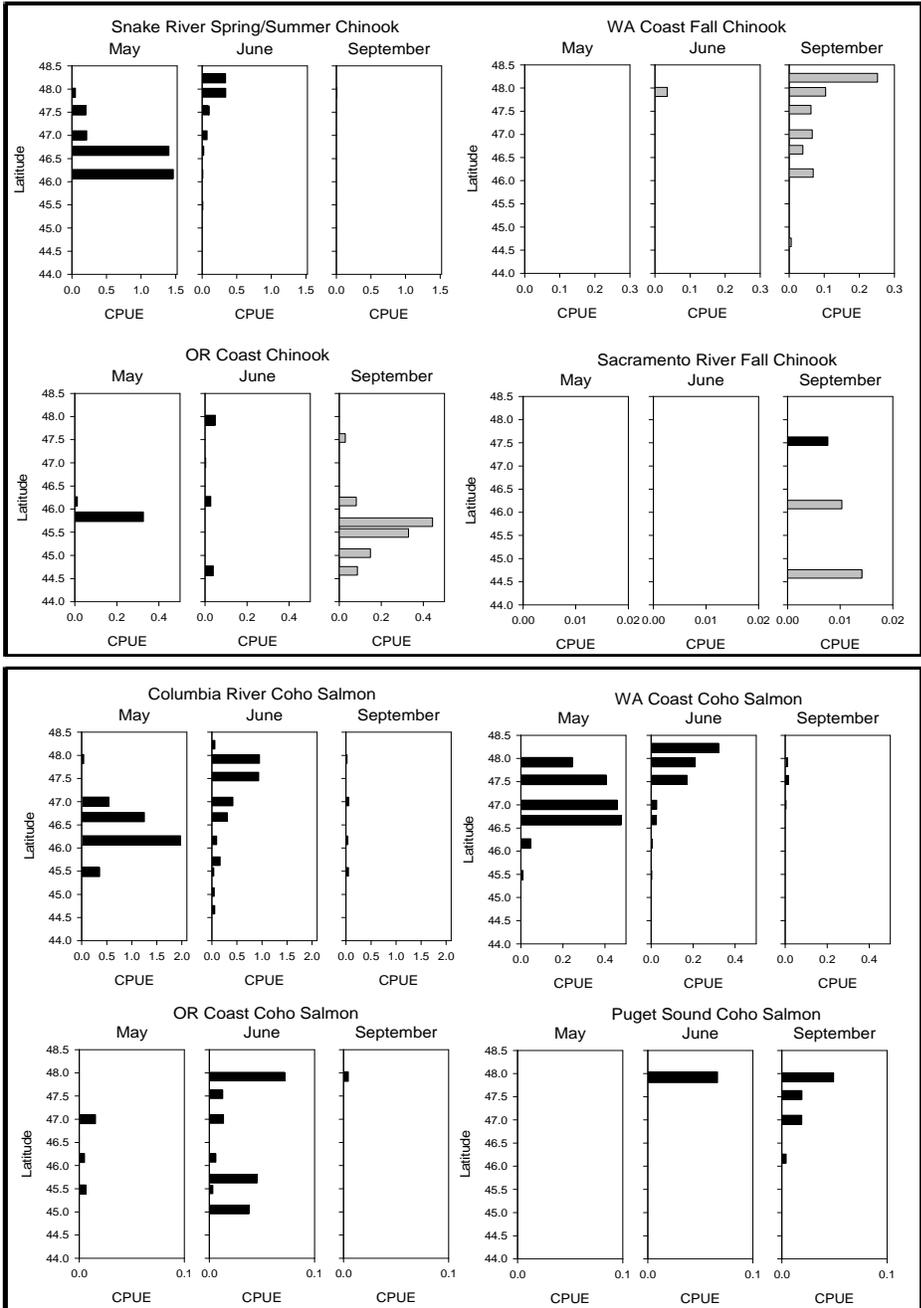


Figure 7 cont. Average catch per unit effort of juvenile salmon associated with CST groups 188-2010 by month and transect. Note changes in scale between stock groups. Black: yearlings; Gray: subyearlings

PROCESS STUDIES:

BOTTOM-UP PROCESSES AND AFFECTS ON SALMON GROWTH AND SURVIVAL

Prey Fields

Copepod community composition varies with ocean conditions (Fig. 8). The warm 1998 El Niño and the anomalously warm year of 2005 were dominated by warm water copepods, whereas the cold years of 1999 – 2002 & 2007 - 2009 were dominated by cold water copepods. The years of 2003, 2004, 2006, and 2010 were intermediate. This is expected because warm years are dominated by downwelling and onshore transport of warm, unproductive water, whereas cold years are dominated by upwelling of cold

nutrient rich productive water. As a result, community structure is a good proxy for ocean productivity.

This may explain why salmon catch and survival are related, with survival being higher during cold productive years and vice versa (Fig. 9). If this relation holds for future years, we can expect that salmon that entered the ocean in 2009 should result in relatively good adult returns.

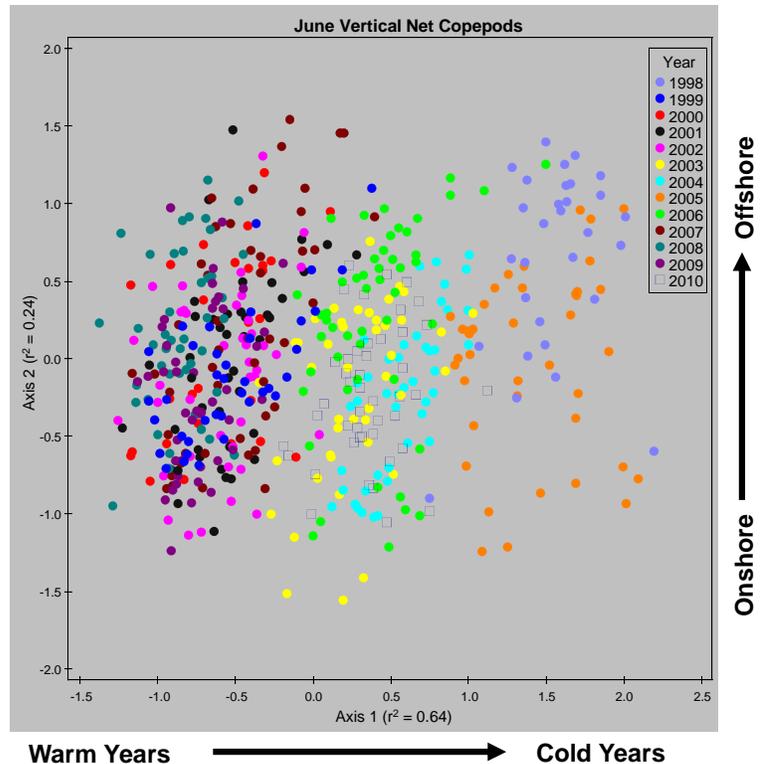


Figure 8. Non-metric multidimensional scaling ordination of copepod species. The closer two points (stations) are to each other, the more similar the copepod communities are between those stations.

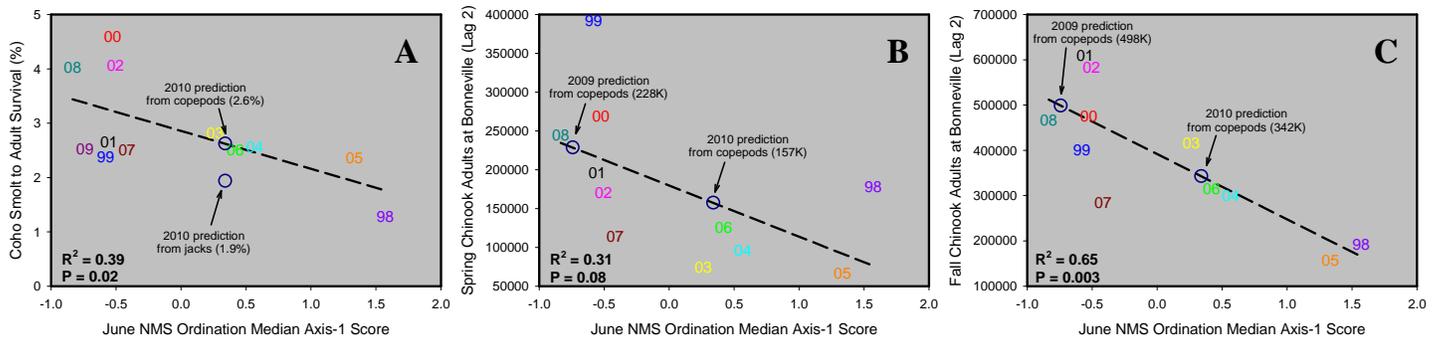


Figure 9: Median Axis 1 (warm vs. cold copepod community) score from Fig. 8 versus A) coho salmon smolt-to-adult survival. The open point on the line indicates the predicted coho survival from the regression (2.6%). The predicted survival from the 2010 smolt year based on jack returns is 1.9%, (PFMC). B) spring Chinook salmon adult returns at Bonneville Dam (lag 2 years). The open points on the line indicate the predicted adult returns from the 2009 (228K) and 2010 (157K) smolt years. C) fall Chinook salmon adult returns at Bonneville Dam (lag 2 years). The open points on the line indicate the predicted adult returns from the 2009 (498K) and 2010 (342K) smolt years.

References:

PFMC. 2011. Preseason Report I: Stock Abundance Analysis and Environmental Assessment Part 1 for 2011 Ocean Salmon Fishery Regulations. Pacific Fishery Management Council, Portland, Oregon.

Although we have no direct measure of the abundance or species composition of the prey field of salmonids (because it is difficult to sample adult krill and the juvenile fishes upon which salmon

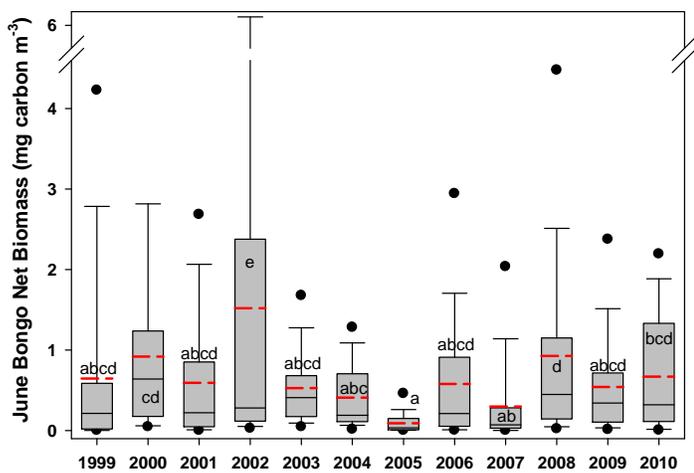


Figure 10. Box plots of June biomass (mg carbon m³) in the bongo net. Boxes range from the 25th to the 75th percentile; whiskers represent the 10th and 90th percentile, and circles the 5th and 95th percentile of the data. The median is shown as a black horizontal line and the mean as a dotted red line. Letters within the box indicate which years are significantly different from one another.

feed, we have developed indices of the prey field based upon catches of larval fish, decapods and krill larvae in Bongo net samples. We refer to this as the “potential prey field”. The potential prey field of juvenile salmon was estimated from the June bongo net samples from 1999 to 2010. The biomass of this salmon food index in June 2010 was not

statistically different from most years, lower than in 2002, and higher than 2005 (Fig. 10). In June, prey field biomass is related to mean plasma IGF-I levels measured in yearling

coho salmon (Fig. 11), as well as to their smolt-to-adult returns (SAR) or survival (Fig. 12). June prey field is also related to and fall Chinook salmon adult returns at Bonneville Dam (Fig. 13, lag 2 years). This suggests that food availability may be impacting juvenile salmon growth and ultimate survival.

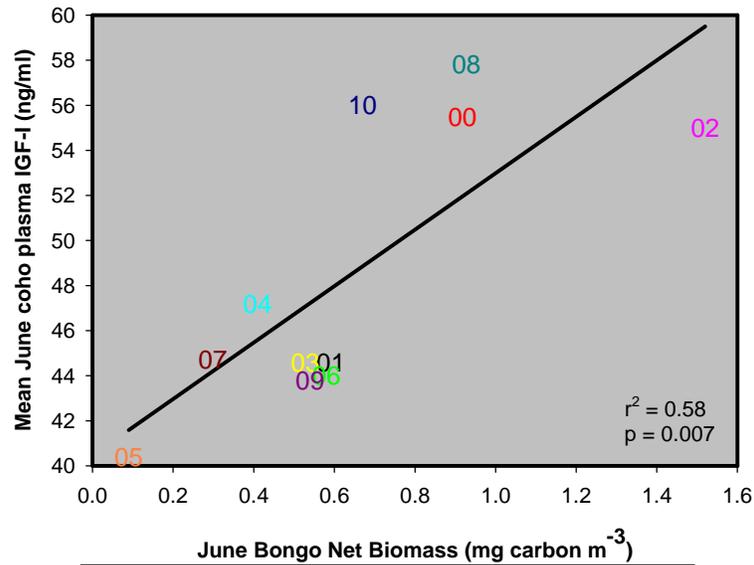


Figure 11. The relation between mean June prey field biomass from the bongo net in June and IGF-I measured in yearling coho salmon.

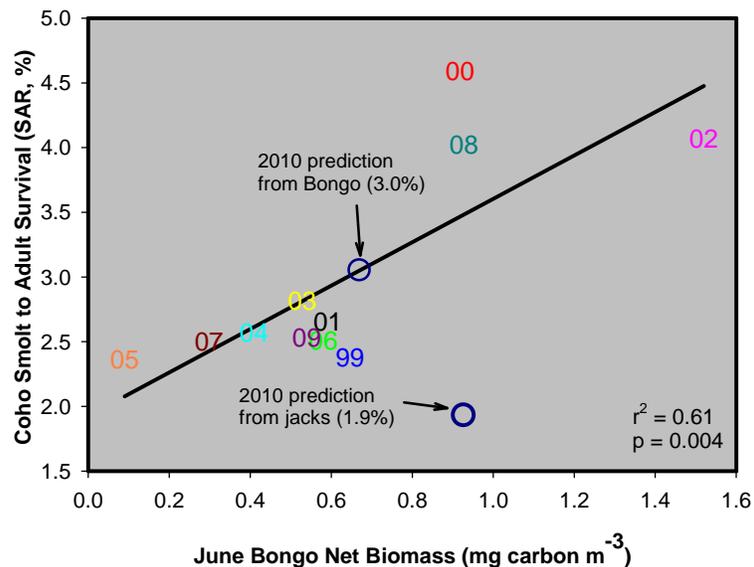


Figure 12. The relation between mean June prey field biomass from the bongo net in June and smolt-to-adult survival (SAR). The predicted SAR from the 2010 smolt year based on jack returns is 1.9%, (PFMC 2011). The observed 2010 June bongo net biomass predicts 3.0% survival from the regression.

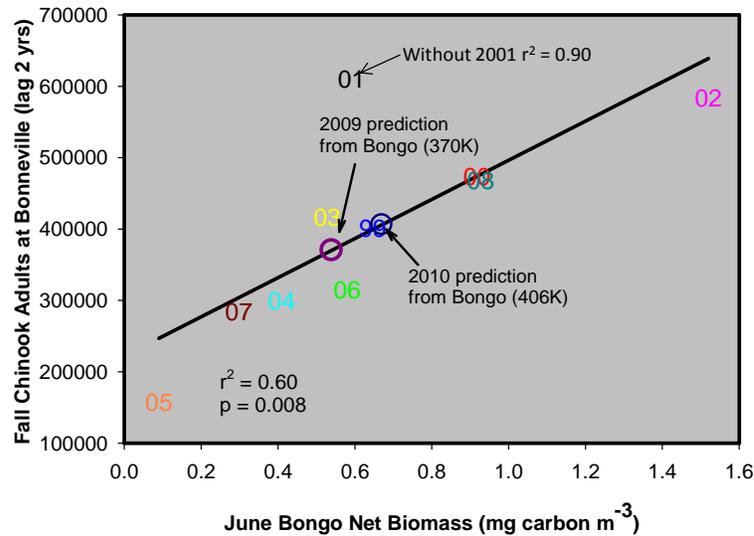


Figure 13. The relation between mean June prey field biomass from the bongo net in June and fall Chinook adult returns at Bonneville (lag 2 years). The predicted adult returns from the 2009 smolt year is 370K (2011 adult year) and 2010 smolt year is 406K (2012 adult year) from the regression.

Winter Ichthyoplankton Biomass: Predictor of Summer Prey Fields and Salmon Survival?

Summer diets of juvenile coho and Chinook salmon consist primarily of late-larval and early-juvenile winter-spawning fish taxa that are undersampled in plankton nets and large fish trawls, so we have measurements of the availability of these prey to juvenile salmon. We investigated whether the biomass of fish larvae in the winter and early spring could serve as a proxy for the spring-summer biomass of juveniles to create an index of food available to young salmon. We examined winter (January-March) ichthyoplankton abundance estimates from the Newport Oregon Hydrographic line from 1998-2010 as a potential indicator of future feeding conditions for young salmon in the marine environment. The proportion of the total

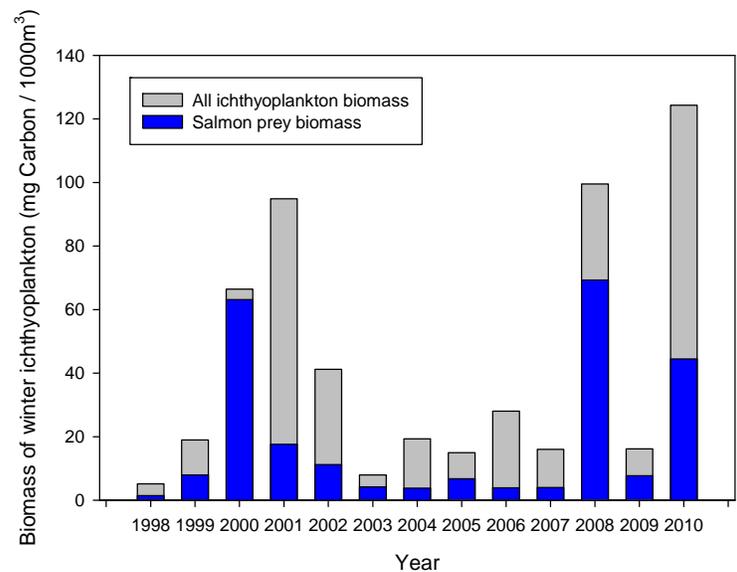


Figure 14. Total winter ichthyoplankton biomass from 1998 to present. Proportions composed of fish larvae considered prey items

ichthyoplankton biomass that are common salmon prey fluctuated from a low of 13.9% in 2006 to 95.0% in 2000 (Fig. 14). The relationship between the biomass of fish larvae in winter and subsequent coho salmon survival based on the Oregon production index (OPI) was found to be highly significant ($r^2 = 68.3$, $p = 0.0006$). This relationship was also highly significant for spring Chinook salmon ($r^2 = 84.8$, $p = 0.0003$; Fig. 15), with two outlier years of 1998 (El Niño) and 1999 (La Niña) removed. Finally, the relationship for fall Chinook salmon was positive and significant ($r^2 = 38.1$, $p = 0.03$). Annual winter larval fish composition showed high overlap with juvenile salmon summer diets during both May and June. Larval fishes appear to be a good indicator of ocean conditions and we believe they can be a useful and cost-effective performance indicator of future juvenile salmon survival, and can provide an early indicator of shifts in the availability of food resources for juvenile salmon.

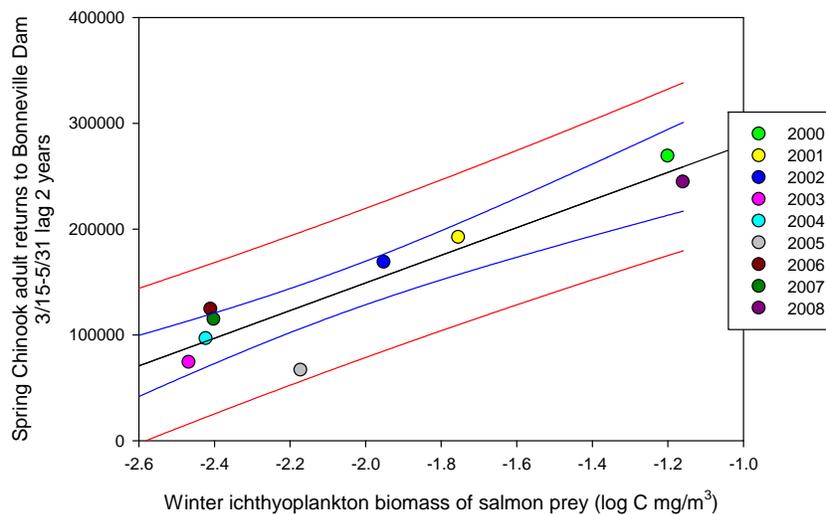


Figure 15. Regression of biomass of salmon prey with spring Chinook salmon adult returns to Bonneville dam (lag 2 years): $r^2 = 84.8$ $p = 0.0003$

Biochemical Measures of Salmon Growth

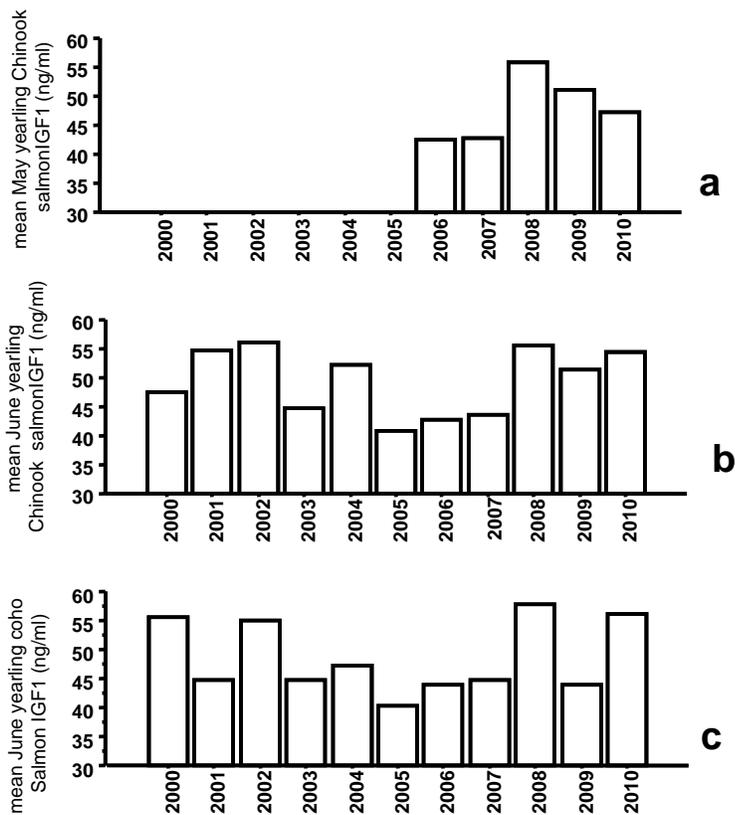


Figure 16. Mean IGF1 level yearling salmon caught off the Oregon/Washington Coast a). mean **May** IGF1 of yearling Chinook salmon b). mean **June** IGF1 of yearling Chinook salmon c). mean June IGF1 of yearling coho salmon.

Levels of the hormone insulin-like growth factor-I (IGF-I), an index of growth, were measured in Yearling Chinook salmon caught in the May 2010 cruise. These levels were greater than measured in 2006 or 2007 but less than found in 2008 or 2009 (Fig. 16a).

In contrast, mean June yearling Chinook salmon IGF1 was relatively high, similar to values found in 2000, 2004 and 2008 (Figure 16b). Mean

June IGF-I levels in coho salmon

were greater than found in 2009 and were similar to levels found in June 2000, 2002 and 2008 (Fig. 16c). Overall, IGF-I measures were intermediate in May 2010

for Chinook salmon and relatively high in June for both coho and Chinook salmon.

For the 1st time, population specific IGF1 values have been determined and assessed for yearling Spring Chinook salmon captured in both May and June. Population specific differences were evident, especially in May (Fig. 17). Values were higher in juveniles released from hatcheries below Bonneville Dam (Willamette River and West Cascade populations) and lower from fish released from the Upper Columbia and Snake Rivers. In June subtle differences between populations were also evident. It was also obvious that all populations had relatively low values in 2006 and 2007 and higher values in subsequent years.

This new analysis of yearling Chinook salmon data, divided among different populations, has allowed us to assess population specific relations in Chinook salmon between IGF1 levels and adult abundance. Positive and significant relations between mean IGF1 of up-river yearling

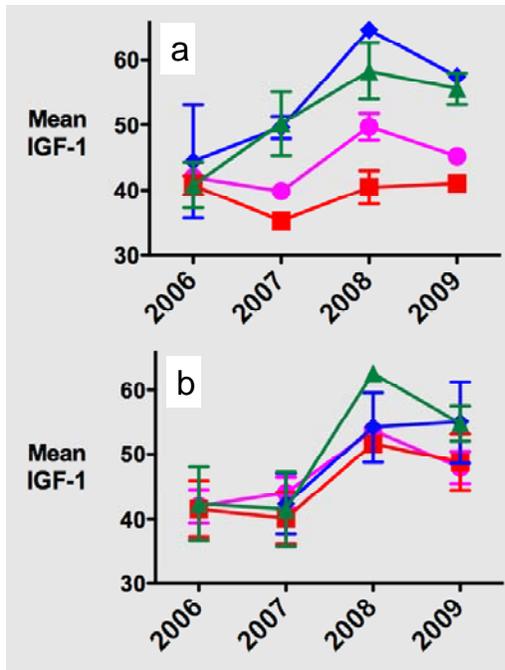


Figure 17. Mean a) May and b) June IGF1 of yearling spring Chinook salmon by population group (West Cascade (blue), Willamette River (green), Mid and Upper Columbia River (pink) and Snake River (Red)).

spring Chinook salmon (upper Columbia and Snake) caught in June and adult returns to Bonneville 2 years later were found (not shown) and smolt-to-adult survival (Fig. 18). At this point genetic analysis of Chinook salmon captured in 2010 is not yet complete. However, analysis of samples collected in 2009 suggests a relatively robust return of adult spring Chinook salmon to Bonneville in 2011.

Finally, a significant, positive relation has been found between June coho salmon IGF-I and adult returns the following year, as we have reported previously. If this relation holds for IGF-I levels

measured in 2010, the 2011 adult coho salmon return to the Columbia River will be similar to levels found in 2001, 2003 and 2009, with survival rates ranging between 4.0 and 5.0%.

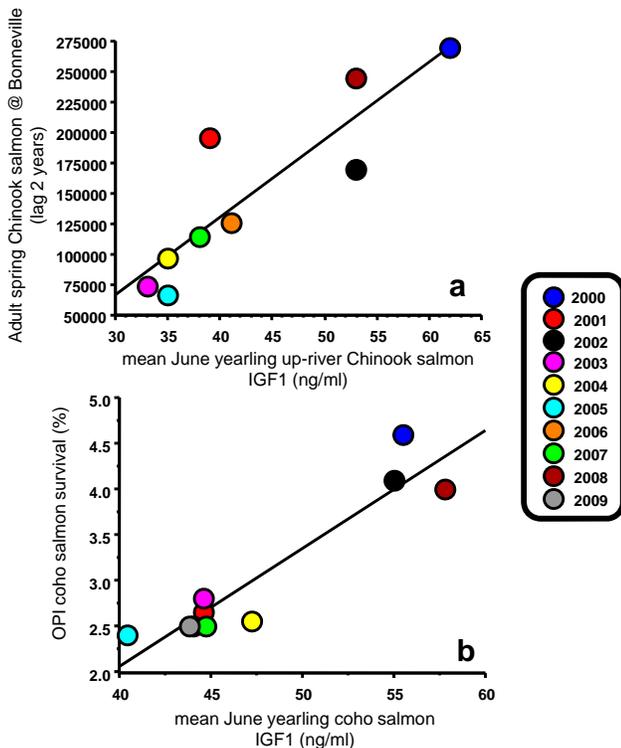


Figure 18. a) Relation of mean June IGF1 of yearling spring Chinook salmon to adult Spring Chinook salmon counted at Bonneville dam two years after ocean entry ($p < 0.01$, $r^2 = 0.78$). 3b). b) Relation of mean June IGF1 of yearling coho salmon to survival (%) of Oregon Production Index

Reconstructing migratory history of interior Columbia River spring Chinook salmon: the role of emigration timing, body size, and early marine growth

Over the last year, we completed analyses on juveniles from the mid-upper Columbia River (MUCRSp) and the Snake River (SNSp) spring Chinook stock groups. We included individuals that were genetically identified using the Genetic Analysis of Pacific Salmonids microsatellite baseline. Over 80% of the individuals were classified to either the MUCRSp or SNSp stock groups with a posterior probability of $\geq 75\%$. We included samples collected from 1999-2008, although 2001 and 2005 were excluded due to low sample sizes (< 20 individuals). Therefore, we were able to make comparisons between these two Interior Columbia Basin stock groups and address the following questions:

- Is there stock-specific variation in the size and timing of marine entry?
- Are size and timing of marine entry correlated with indices of future abundance?
- Is early marine growth correlated with indices of future abundance?
- Is early marine growth positively correlated with indices of marine productivity?

Initially, we validated our approach of using otolith chemical (Sr:Ca) and structural analyses to estimate the timing of juvenile emigration from freshwaters. After completing our analyses, we compared our results with tag, release, and interrogation data for 14 Snake River spring Chinook juveniles with PIT tags. For 12 fish, there were multiple tag detections within the hydropower system and our estimates of freshwater emigration were within 4 d of the final detection of those individuals at interrogation sites in the lower river, indicating a high level of temporal accuracy.

Size and timing of marine entry

Patterns of freshwater emigration varied among years but, on average, SNSp juveniles entered the marine environment almost two weeks later than MUCRSp juveniles (May 12th vs. April 29th, Fig. 1). This difference in timing was further demonstrated by the observation that 37% of the SNSp otoliths examined ($n = 85$) did not yet display an increase in Sr:Ca, which indicates that the juveniles had resided in brackish water for < 5 d (Miller, *accepted*). In contrast, $< 9\%$ of the MUCRSp juveniles failed to display an increase in otolith Sr:Ca. All but one of these

recent emigrants were collected during May. In all years, juvenile entry into the marine environment consistently occurred after the physical transition to predominantly upwelling conditions (mean date = Mar 23). However, there were no relationships between emigration timing and juvenile growth or future adult abundance observed in either stock group.

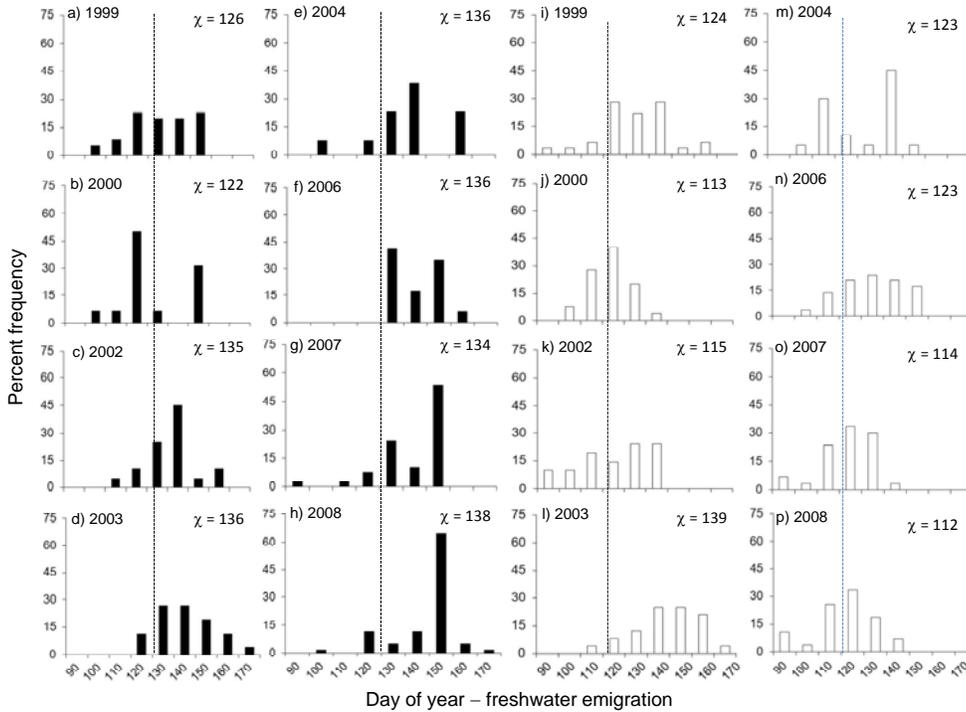


Figure 19. Timing of freshwater emigration for juvenile spring Chinook salmon. Percent frequency by day of year of freshwater emigration for juveniles from the Snake River (a–h) (n = 230) and mid-upper Columbia River (i–p) (n = 210). Year and mean day of year of emigration are included on each graph. Dotted lines represent overall mean date for Snake River (May 12 = 133) and mid-upper Columbia (April 29 = 120) River stock groups.

Marine migration rates

We observed differences in the marine migration rates between these two stocks, which may be related to their variable emigration timing combined with a trend toward faster migration rates later in the season. In both May and June, SNSp juveniles were migrating faster than juveniles from the

MUPSp stock (Fig. 20, $p < 0.01$). However, the mean migration rate for SNSp in May was similar

to MUPSp in June ($p > 0.20$). It is possible that the faster migrants from the MUPSp were already out of the sample area by the time of the May cruise, which resulted in a lower mean rate. However, there was also a consistent positive relationship between migration rate and date of marine entry, i.e., juveniles that entered the ocean later in the summer migrated north more rapidly. Therefore, the differences are likely related to both the variation in timing of marine entry between the two stocks and a seasonal increase in migration rate.

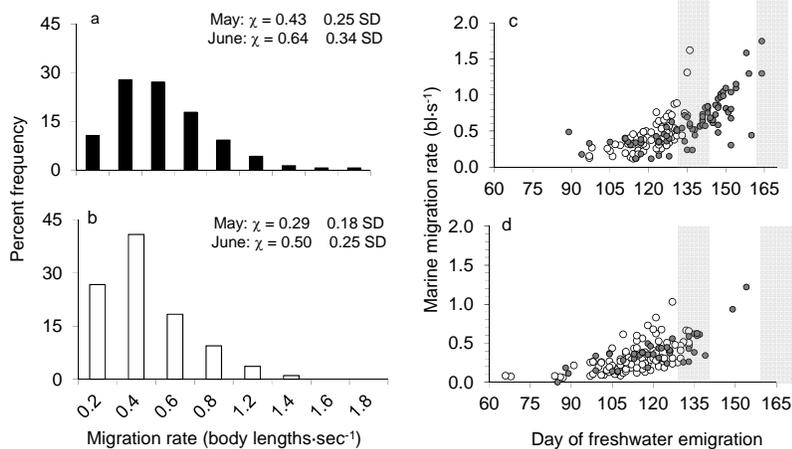


Figure 20. Estimated marine migration rates ($\text{bl}\cdot\text{s}^{-1}$) for juvenile spring Chinook salmon across all years. Percent frequency by rate for Snake River (a) ($n = 140$) and mid-upper Columbia River (b) ($n = 191$). Means ($\pm\text{SD}$) for May and June collections are included for each stock group in upper right corner of graph. Individual marine migration rates for Snake River (c) ($n = 140$) and mid-upper Columbia River (d) ($n = 191$) juveniles. Filled circles represent juveniles collected during May cruises and open circles represent juveniles collected during June cruises. Filled boxes indicate cruise dates.

Interannual variation in migration rate for both stock groups was correlated with indicators of ocean productivity. For the SNSp juveniles, mean migration rate increased during conditions of relatively poor ocean productivity, i.e., indicators of lipid-poor copepod community ($R^2 = 0.59$) and shorter

duration of upwelling season ($R^2 = 0.74$). Similarly MUPSp juveniles also migrated faster when the biomass of lipid-rich copepods was relatively low ($R^2 = 0.68$). These relationships may be influenced by the intensity of poleward alongshore flow. In other words, faster migration rates during years of low

productivity may be related, in part, to enhanced poleward flow during those years (Keister et al. 2011) that could promote northward movement of juveniles. However, regardless of the primary cause, the net result is that juveniles move northward faster in years of low production off Oregon’s coastal waters, which may result in movement to more productive feeding areas. There were negative correlations between migration rate and future adult returns, i.e., years when juveniles migrated faster, there were lower adult returns; however, these trends were not significant.

The two stock groups also differed in their pattern of residence in coastal waters of Washington and Oregon (Fig. 21), which is also likely related to the variation in timing of ocean entry and migration rate. Along the Columbia River transect, SNSp juveniles displayed relatively brief marine residence times (mean = 11 d) compared with MUPSp juveniles (mean = 26 d). At the more northerly transects, the distribution of residence times were more comparable between the stocks with the longest residence times occurring for fish collected in the northernmost transects (mean = 33 to 39 d). Overall, however, it is clear that some individuals (~20% of the individuals in this study) were present in coastal waters near the

mouth of the Columbia River >2 weeks after marine entry.

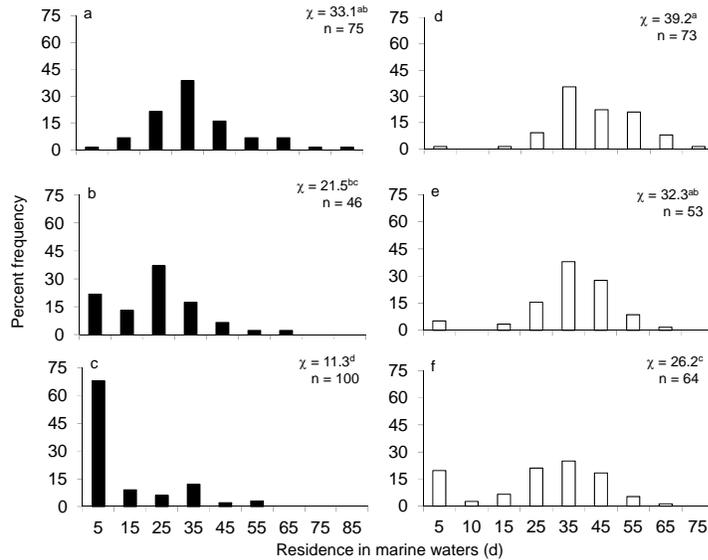


Figure 21. Estimated marine residence times for juvenile spring Chinook salmon across all years. Percent frequency in 10 d intervals for juveniles from the Snake River (a–c) and mid-upper Columbia River (d–f). Fish were grouped by geographic region and include transects north of Grays Harbor, Washington (a & d); off of Willapa Bay and Grays Harbor, Washington (b & e); and off the Columbia River (c & f). Mean residence time and sample size are included on each graph. Letters refer to statistically homogenous groups.

Early marine growth

Adult returns of spring/summer Chinook salmon to Ice Harbor Dam, which is the lowermost dam on the Snake River upstream of its confluence with the Columbia River, were positively related with Snake River spring/summer Chinook salmon SARs over 37 years ($R^2 = 0.82$, $p < 0.001$) (Scheuerell, et al. 2005). Furthermore, the majority of juveniles from these two stock groups emigrate as yearlings (>93% in this study) and return as 3-yr olds (Scheuerell et al., 2005; Fryer 2009). Therefore, we considered adult returns, lagged 2 years, an accessible and reliable, yet relative, indicator of survival. In this case, we used adult returns of spring Chinook salmon to Lower Granite Dam and to Priest Rapids Dam as proxies of survival for the Snake and mid-upper Columbia River spring runs, respectively.

We observed no relationship between interannual variation in mean size at freshwater emigration and indicators of survival. However, we observed significant, positive relationships between adult returns and size at capture and marine growth rates (Fig. 22). In this analysis, we included size at capture for all individuals collected from these two stocks ($n = 27$ to 199 individuals/yr) whereas, for marine growth rate estimates, we included only those fish for which marine growth was detected on the otoliths ($n = 10$ to 36 individuals /yr).

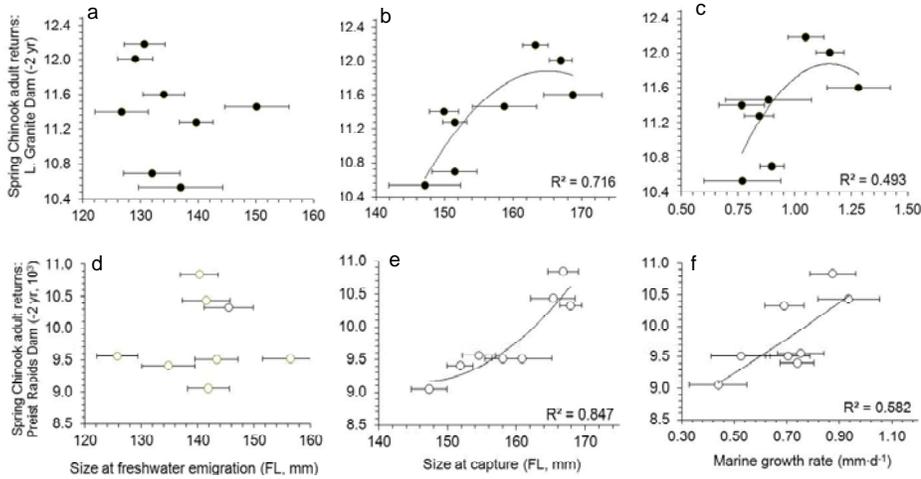


Figure 22. Relationship between adult returns and mean annual size and growth characteristics for spring Chinook salmon. Ln-transformed adult returns to Lower Granite Dam (-2 yr) versus Snake River mean (\pm SE) juvenile size at freshwater emigration (a), size at capture (b), and marine growth rate (c). Ln-transformed adult returns to Priest Rapids Dam (-2 yr) versus mid-upper Columbia River mean (\pm SE) juvenile size at freshwater emigration (d), size at capture (e), and marine growth rate (f). Lines represent linear or polynomial fit.

The strong, positive relationships between adult returns and juvenile size and growth rate after only 2-5 weeks of marine residence indicate that very early marine growth is important for survival. Therefore, we examined various indices of ocean productivity to determine if we could describe the observed variation in body size and/or early marine growth.

If, as proposed by Keister et al. (2011), copepod species composition can be as, or more, important than predators or prey quantity, then we should observe strong relationships between juvenile body size and growth and values of the CCSA indicative of the boreal, lipid-rich copepod community. We found strong support for this hypothesis. Size at capture for both stock groups was negatively correlated with the CCSA, which indicates that in years with a greater dominance of lipid-rich copepod communities, fish were larger at the time of capture (Fig. 23). For the SNSp stock, marine growth rate was also negatively correlated with the CCSA although no relationship was observed for the MUPSp stock (Fig. 23).

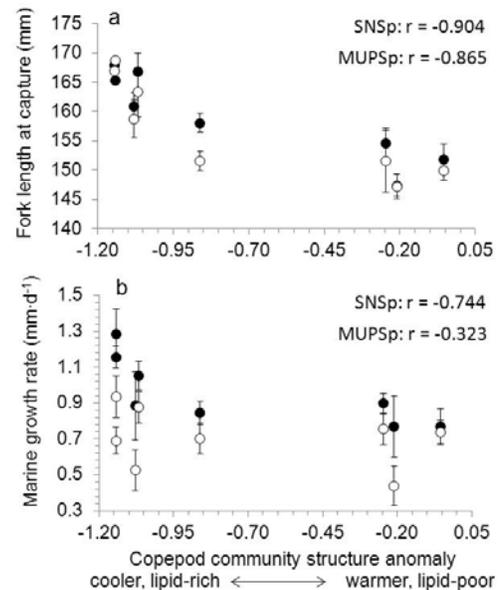


Figure 23. Relationships between mean (\pm SE) juvenile size at capture (a) and growth rate (b) versus the anomaly of copepod community composition in June. Filled circles indicate Snake River juveniles and open circles indicate mid-upper Columbia River juveniles.

Overall, we found no support for the hypothesis that size or timing of marine entry is related to future abundance but we detected strong evidence for the hypothesis that early marine growth and larger body size are important for survival of Interior Columbia River spring Chinook salmon populations comprised of predominantly yearling emigrants. We also determined that at least some individuals (20% in this study) reside in coastal waters for >2 wks. Finally, we were also able to detect relatively small scale differences in migratory patterns between stocks that are important for interpretation of field data.

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Individual-based model of salmon growth and coastal migration

We have completed construction of an individual-based model to make qualitative comparisons among various management options or estimate potential effects of climate change. With this tool, we can track virtual fish through the plume and nearshore environments, altering the location of each fish using one of several behavioral rules. These rules allow fish to dynamically respond to local environmental conditions such as temperature or ocean currents. We found that relatively minor differences in behaviors can result in dramatically different spatial distributions (Fig. 26). Fish performance is summarized in terms of spatial distribution and growth under various behavioral and management scenarios.

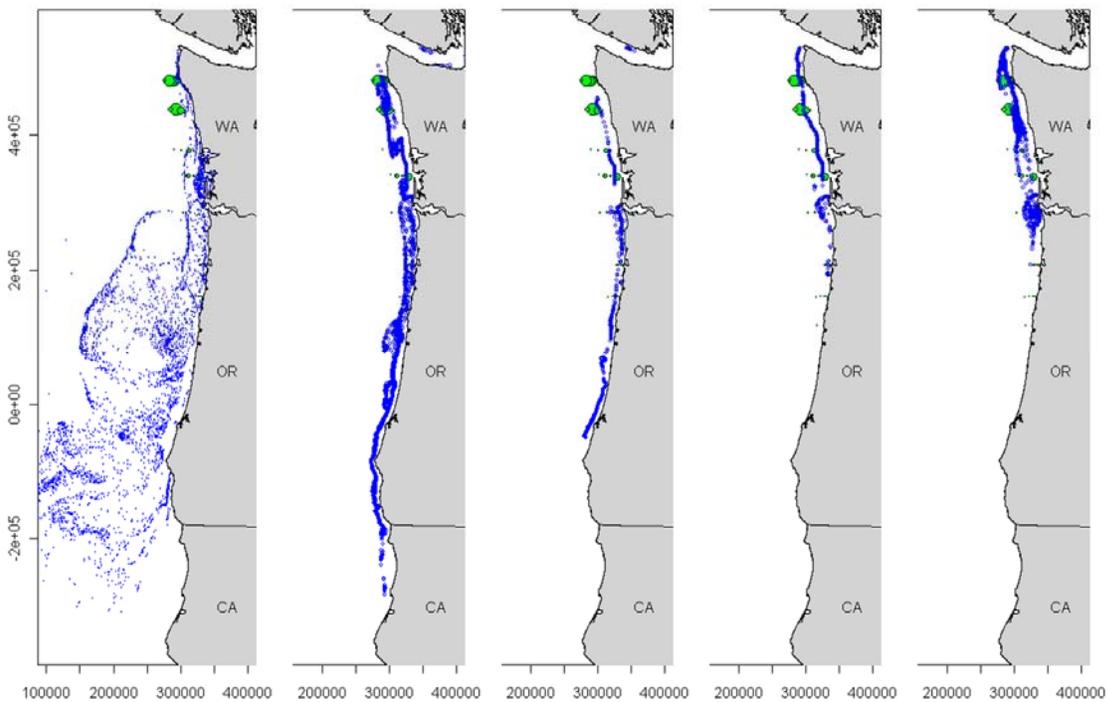


Figure 26. Locations of 10,000 simulated fish after a 60-day period ending 25 June, 2004 (all fish were released at the mouth of the Columbia River). Behaviors ranged from no behavior (passive particles, in the far left panel) to fish actively swimming north and optimizing water depth (far right panel).

Current efforts are also focused on drivers of behavioral decisions, such as temperature, secchi depth, and distance from shore. Through a set of Generalized Linear Models, we are determining the effects of the abiotic environment on CPUE of yearling Chinook salmon. We will then incorporate these findings into the IBM as drivers of migrational behavior rules. By comparing simple rules with those based on local conditions, we may be able to determine how fish are using local cues and conditions to make behavioral decisions about migration

Diet variation in September marine caught juvenile fall Chinook salmon off the coasts of Oregon and Washington

Juvenile subyearling Chinook salmon typically enter the marine environment mid-summer and by September we catch them throughout the entire latitude of our sampling grid, with almost all fish were found within 7 km of the shore. Subyearling Chinook average fork length in September was 175.7 (\pm 31.3) mm, and their diets showed a high dependency on juvenile northern anchovies and other juvenile forage fish prey such as clupeids (herring), and osmerids (smelts) (Fig. 27). Diets exhibited high interannual variability in both

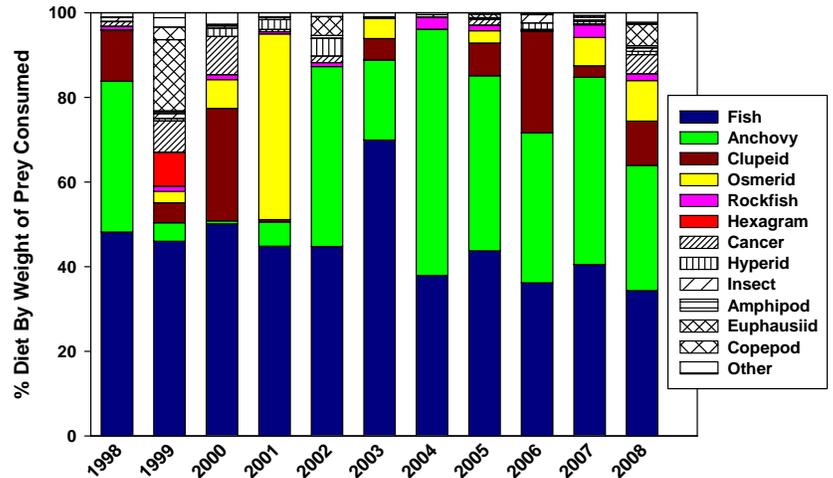


Figure 27. Diet by percent weight of prey eaten for subyearling Chinook juvenile salmon in September 1998-2008.

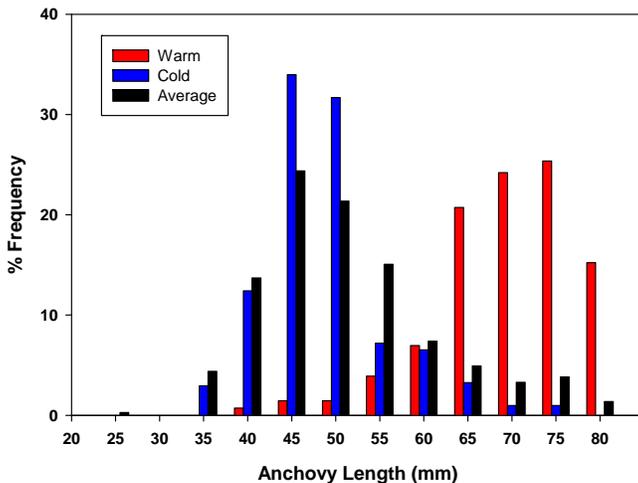


Figure 28. Length frequency of juvenile *Engraulis mordax* (< 80mm fl) collected in the environment during average, cold and warm years.

composition and feeding intensity, and there was a broad range of the percentage of fish that were caught with empty stomachs (2.5 - 29.3%). Regardless of ocean conditions, the average size of the juvenile northern anchovies eaten were approximately 45 mm which is also the average size of the juvenile northern anchovies that were sampled during cold to average ocean conditions (based on average annual sea surface

temperatures). During warmer ocean conditions, the average fork length of the juvenile northern anchovies sampled was 75 mm by September, which may be due to earlier spawning of the fish (Fig. 28). Prey/predator size mis-match may increasingly occur during warmer ocean conditions for subyearling Chinook salmon in that the size of their principal fish prey may be too large for the juvenile salmon during their first marine summer.

Diet and Distribution of Juvenile Steelhead (*Oncorhynchus mykiss*) in the Columbia River Estuary and off the Oregon and Washington Coasts

Juvenile steelhead have been collected in relatively consistent numbers each year off the Oregon and Washington coasts since 1999 and from the lower Columbia River estuary since 2007. The number of fish captured each year varied from zero in 2005 to 291 in 2006. The number of wild fish was estimated by dividing the number of adipose fin-clipped fish captured by a conservative estimate of the average annual clip rate from all Columbia River hatcheries and subtracting that value from the total number of fish captured. Clip rates ranged from 84 – 90% and averaged 87% across this period, with 2000 and 2007 having the highest proportions of wild fish at 84% and 57%, respectively. Of the data analyzed to date, 2007 had the highest feeding intensity and the lowest percentage of fish with empty stomachs (11%, range across years 11 – 17%). Dominant prey taxa by weight across all years were fishes (59.4%), euphausiids (19.2%), and crab larvae (16.6%; Fig. 29).

Based on our initial findings, we hypothesize that steelhead are generalist, opportunistic predators and will eat the highest quality prey available to them. Steelhead prefer surface waters and feed

on zooplankton and fish in the neustonic (upper 1 m) layer. Therefore, we expect steelhead diets to have a similar species

composition to the neustonic prey field, with the most nutritious components of that prey field (e.g., fish, euphausiids) selected more often by steelhead than lower quality prey items, such as barnacle larvae. We will test this hypothesis by comparing the diets of steelhead with available neuston and subsurface collections. By combining an improved understanding of steelhead diets

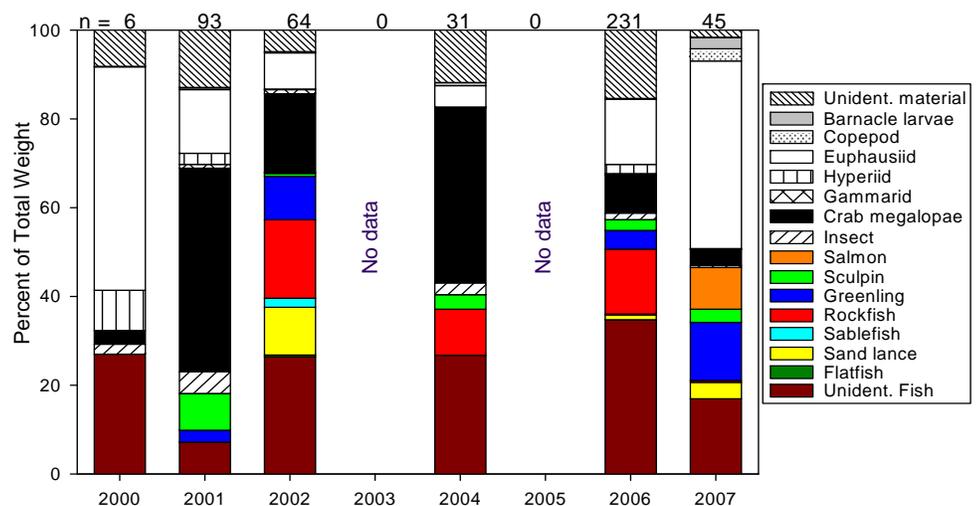


Figure 29. Marine diet composition (by % weight of prey) of juvenile Steelhead salmon in May. Fish prey are in color, and invertebrate prey are black and white pattern. No steelhead were captured in 2005 and too few were captured in 2003 to include in this analysis. (J.A. Scheurer, unpubl. data)

with ongoing research at the NWFSC on how climate variability may influence prey fields, we hope to gain more insight into how global climate change may affect listed steelhead populations.

Patterns of Macroparasite Infection in Juvenile Salmon

Trophically transmitted parasites have been shown to provide valuable information regarding the trophic interactions of juvenile salmon (Baldwin et al., 2008, Bertrand et al. 2008, Valtonen et al. 2010) beyond the 24-30 hour window that traditional diet analysis allows (Brodeur and Percy 1987). Macroparasites, such as nematodes, trematodes, and cestodes, often have complex life cycles using predator-prey interactions at many different levels in a food web for development and reproduction. These life history strategies make it possible to study macroparasites acquired by salmon through trophic interactions and gain information on an individual salmon's diet as well as the pelagic food web and environment.

Previous data suggested that opportunistic feeding strategies are important to the growth of Chinook and coho salmon during the first year of life (Losee et al. in review). In addition we have observed significant spatial variation in the parasite prevalences and intensities within our sampling region in all years examined to date (1999, 2002, 2003, 2004, 2005, and 2010). However, temporal variation among years of contrasting ocean conditions appears to be a more important driver of patterns of macroparasite infection observed in this study and may represent shifts in the food web from year to year.

Previously we observed significant differences in the marine parasite community of juvenile Chinook and coho salmon in “cold” ocean years, when the Pacific Decadal Oscillation (PDO) was negative, compared to “warm” ocean years. To control for differences in ocean migration and timing of entry into the marine environment between stocks we have selected yearling Chinook salmon from the Upper Columbia River Summer/Fall and Mid/Upper Columbia River Spring salmon stocks groups as well as Columbia River coho salmon to investigate these trends further. Recent findings suggest that the marine trophic interactions of yearling Chinook and coho salmon from these stocks groups captured in June vary interannually. This pattern is probably due to changes in the marine zooplankton community that these parasites use as intermediate hosts (Marcogliese 1995) as well as the proportion of fish in the diet (Pascual

et al. 1996, Petric 2011). While some parasites that were recovered in this study were present in all years many appear to correlate directly with local (i.e. SST) and basin scale indices (i.e. PDO) of ocean climate in yearling Chinook and coho salmon (Fig. 30). Because ocean conditions have been shown to relate closely to adult returns of Pacific salmon (Mantua et al. 1997) these findings may have implications regarding the prey quality of juvenile salmon in years of contrasting ocean conditions and salmon survival.

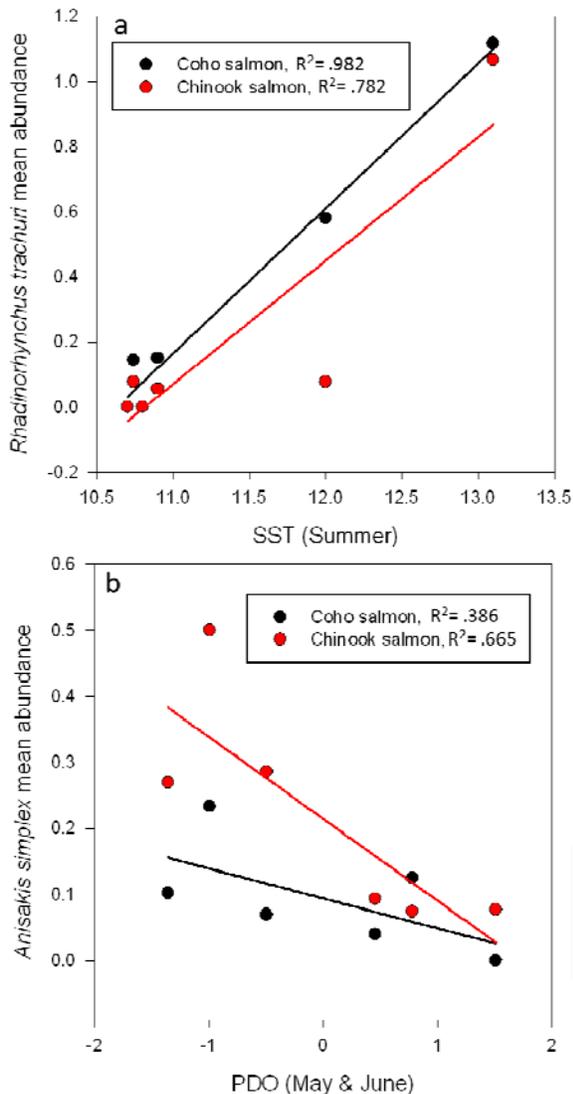


Figure 30. Relationship between a) *Rhadinorhynchus trachuri* and b) *Anisakis simplex* to mean values of

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Inter-annual variability in the Northern California Current food web structure: revealing trophic pressures upon juvenile salmon

Ecosystem productivity and food web structure within the Northern California Current (NCC) vary on seasonal to decadal time scales due to timing and strength of coastal upwelling, timing and abundance of migratory species entering the system, and forcing by climate-scale physical processes. Ocean survival of juvenile salmon correlates with lower trophic-level productivity (Nickelson, 1986; Fisher and Pearcy, 1988; Scarnecchia, 1981; Logerwell *et al.*, 2003; Scheuerell and Williams, 2005) and with the abundance of predatory fishes (Emmett *et al.*, 2006), showing that both bottom-up and top-down processes regulate juvenile salmon survival, though the strength and relative importance of these processes are expected to vary among years.

The first purpose of our ecosystem modeling effort is to examine how trophic network structure regulates juvenile salmon survival. Our primary hypothesis is that variability in trophic network structure has a substantial effect on the efficiency that energy is passed from phytoplankton to higher trophic levels. Observations of community structure made during BPA-sponsored mesoscale surveys of pelagic fishes, seabirds, and zooplankton were synthesized into a series of independent, mass-balanced food webs of years 2003 through 2007. From these

models we investigate the efficiency of energy transfer to juvenile salmon via direct and indirect pathways, and we develop an inter-annual predation index.

The second purpose of our modeling effort is to conduct alternate scenario investigations to analyze system sensitivity to variability in the strength of individual trophic pathways and their direct and indirect impacts upon juvenile salmon. End-to-end models describe the flow of production through the entire food web, from the input of nutrients to the production of top predators (Steele and Ruzicka, 2011). Because information flow within an end-to-end model is bottom-up, i.e., in the same direction as energy flow in the system, the model is inherently stable (Steele, 2009). A direct consequence of this is that the response of upper trophic levels to perturbations and/or energy flow rearrangements at lower trophic levels can readily be analyzed.

Bottom-up regulation: plankton production and food web efficiency

Phytoplankton production defines the maximum amount energy available to the entire system and was highest in 2006 and

2007 and lowest in 2004 and

2005 (Fig. 31). Grazing by

meso-zooplankton is the major pathway for transferring primary production to higher trophic levels, and the proportion of

primary production transferred to higher trophic levels (the

footprint, Fig. 32a) is highly variable between years (55-

80%). In turn, the predation footprint

upon meso-zooplankton by higher trophic levels also varies inter-annually (Fig. 32b). Thus not

only is system production variable, so is the efficiency of energy transfer at each trophic level.

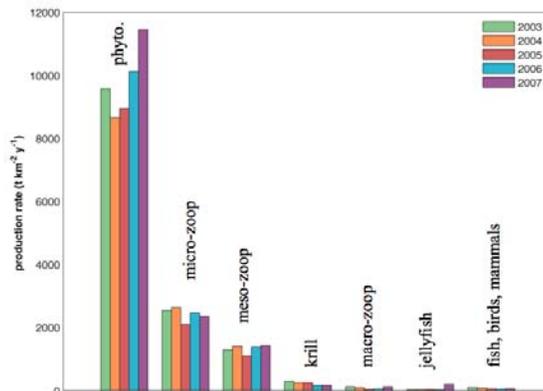


Fig. 31. Inter-annual comparison of production rates among aggregated pelagic functional groups as estimated by static, top-down balanced models.

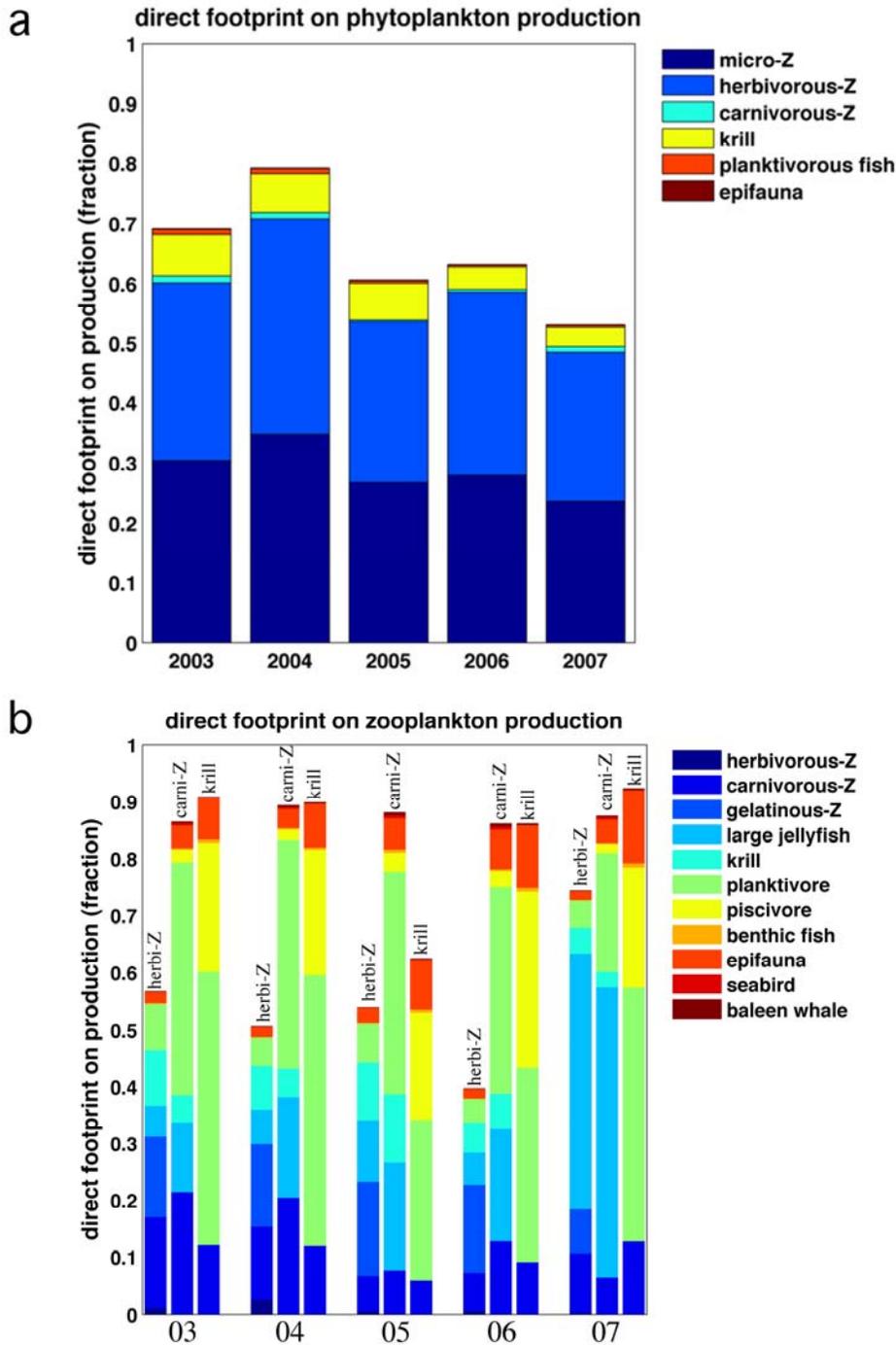
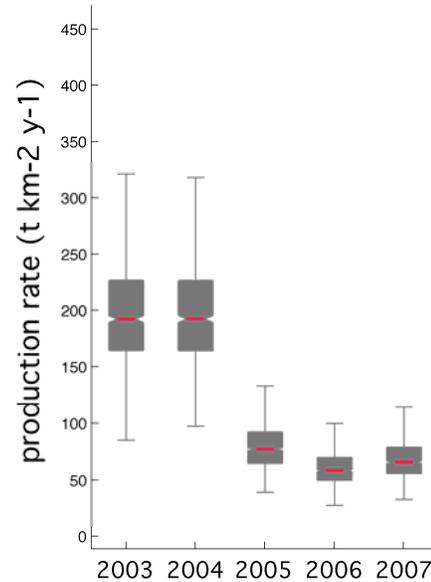


Fig. 32. Inter-annual comparison of total direct consumption pressure upon a) phytoplankton production and b) zooplankton production.

Inter-annual differences in the efficiency of the energy transfer chain from phytoplankton to small pelagic fishes (including juvenile salmon) are revealed by driving end-to-end models for each year under identical nitrate input rates (Fig. 33). In 2003 and 2004, this energy transfer

chain was much more efficient than in 2005, 2006, and

Figure 33. Inter-annual comparison of production rates of small pelagic fishes based on end-to-end models driven by identical nitrate input rates. Production differences indicate differences in the efficiency of the energy transfer chain from nitrate to small pelagic fishes. Inter-quartile range box plots represent the distribution of 1000 randomly drawn models where each term of the end-to-end production matrix was allowed to vary within $\pm 50\%$ from each year's base model.



2007. Despite high phytoplankton and meso-zooplankton production in 2006, our model analysis suggests that a disproportionately small fraction would ultimately be available to juvenile salmon and could explain the relatively low survival of coho that year (OPIH smolt-to-adult ratio = 0.25). In 2007, the large footprint on meso-zooplankton was due to unusually intense jellyfish grazing (Fig. 32b). Because jellies have few predators, they are a trophic dead end (Ruzicka *et al.*, 2007) and a pathway diverting much of the high meso-zooplankton production of 2007 from the pelagic system. We can only speculate that juvenile salmon survival would have been higher in 2007 if not for the unusually large jellyfish population that year. Similarly, we speculate that survival was relatively high in 2003 (OPIH smolt-to-adult ratio = 0.033) because of the greater energy transfer chain efficiency from phytoplankton to small pelagic fishes even though phytoplankton and meso-zooplankton production was comparatively low among the five model years.

Trophic network restructuring scenarios: Humboldt squid example

We are investigating the sensitivity of juvenile salmon to variability in trophic linkages across all trophic levels, and we are investigating the impact of specific suites of changes in food web structure. As one example, we have investigated the consequences across all functional groups of an increased abundance of the predatory Humboldt squid. Over most of the BPA mesoscale survey history, Humboldt squid have rarely been observed on the NCC continental

shelf. In 2009, large numbers of Humboldt squid were encountered off the mouth of the Columbia river (biomass density > 2 t/km²). Figure 34 shows the relative change in functional group productivity as Humboldt squid biomass is raised from a trace biomass to the high biomass observed in September 2009. For this purpose, we adopted squid diets from Field *et al.* (2007).

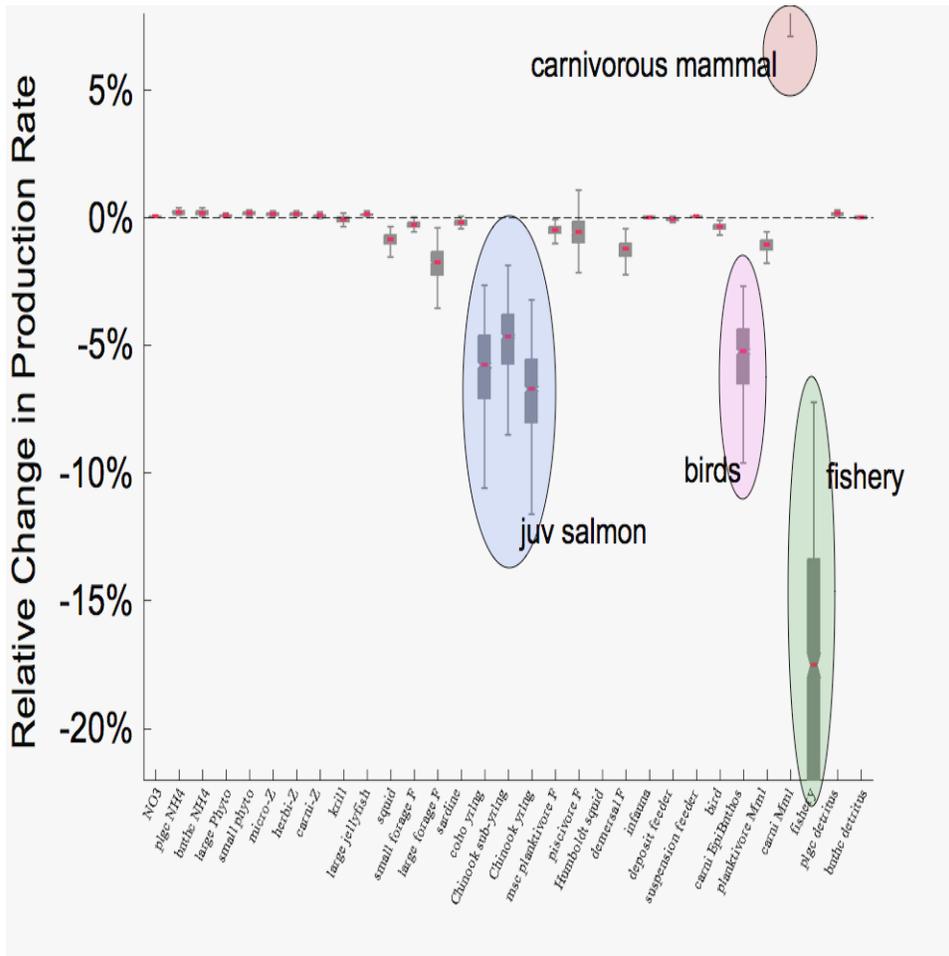


Figure 34. The relative change in functional group production caused by an increase in Humboldt squid biomass from a trace biomass density (0.01 t km⁻²) to biomass densities observed in September 2009 (2.5 t km⁻²). (Increase in carnivorous mammal production exceeds +15% and is off the scale of this graph.)

The negative impact upon juvenile salmon is much more severe than the impact upon other small pelagic fishes such as sardine because there is greater overlap between juvenile salmon and Humboldt squid diets; both are more piscivorous than forage fishes. Seabirds and fishery

production are also negatively impacted. Interestingly, predatory mammals may benefit from increased Humboldt squid abundance.

This scenario shows only the bottom-up effects of Humboldt squid competing for prey resources. If we assume that squid prey upon coho yearling in the same proportion to abundance as they do other small pelagic fishes. If we assumed that coho yearling contribute to squid diets in the same proportion to their biomass as do other small pelagic fishes (0.03% of the diet by weight), then we estimate that Humboldt squid directly consume 5-10% of the coho yearling production at the high squid densities observed in 2009.

Work in Progress

Work currently in progress includes:

1. improvement to the accuracy of inter-annual models through error-checking of biomass estimates derived from BPA-sponsored mesoscale surveys;
2. improvement of uncertainty analyses, particularly to the model rejection criteria in our Monte Carlo analyses to allow for observed biomass changes between early summer and late summer mesoscale surveys;
3. model validation using fatty acid tracer analyses of forage fish tissue composition (Litz *et al.*, 2010) and model derived estimates of inter-annual differences in relative diatom and dinoflagellate contribution to individual functional group production;
4. expansion of inter-annual coverage to run from 1998 through 2010;
5. and improvement of precision among time-dynamic food-web models by coupling them to a plankton model developed for the coastal NCC upwelling system (Ruzicka *et al.*, 2011).

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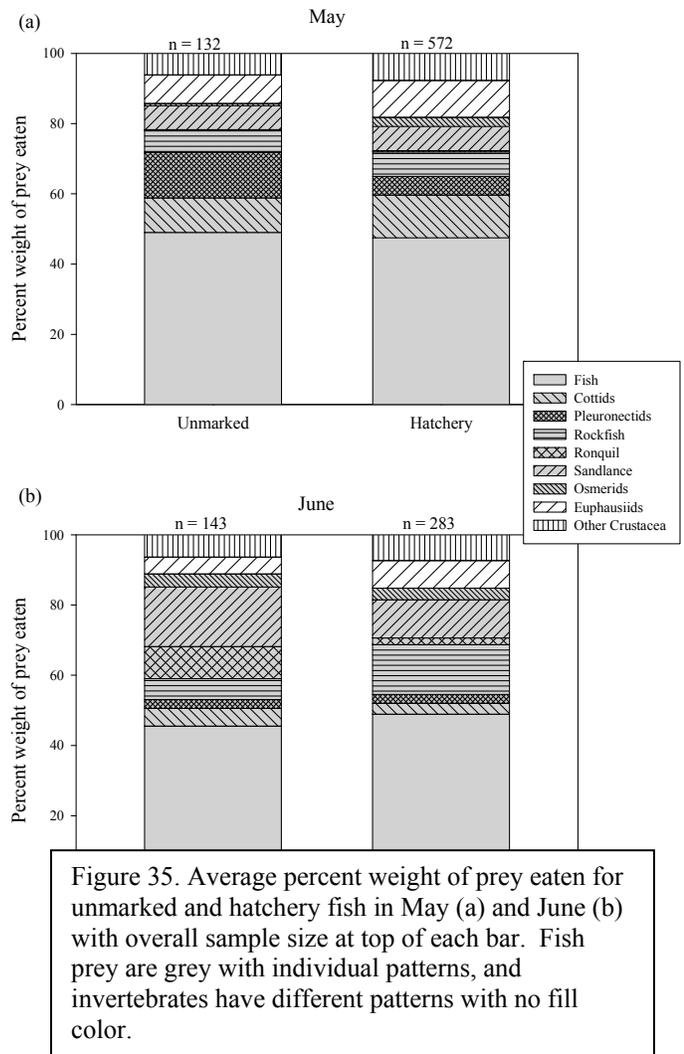
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Spatial and trophic overlap between hatchery and unmarked fish

Ecological interactions between natural and hatchery juvenile salmon during their early marine residence, a time of high mortality, have received little attention. These interactions may negatively influence survival and hamper the ability of natural populations to recover. We examined the spatial distributions and size differences of both marked (hatchery) and unmarked (a high proportion of which are natural) juvenile Chinook salmon in the coastal waters of Oregon and Washington from May to June 1999-

2009. We also explored potential trophic interactions and growth differences between unmarked and marked salmon. Overlap in spatial distribution between these groups was high, although catches of unmarked fish were low compared to those of marked hatchery salmon. Peak catches of hatchery fish occurred in May, while a prolonged migration of small unmarked salmon entered our study area toward the end of June. Hatchery salmon were consistently longer than unmarked Chinook salmon especially by June, but unmarked salmon had significantly greater body condition (based on length-weight residuals) for over half of the May sampling efforts. Both unmarked and marked fish ate similar types and amounts

of prey for small- (station) and large- (month, year) scale comparisons (Fig. 35). Feeding intensity and growth were not significantly different between the two groups. There were synchronous interannual fluctuations in catch, length, body condition, feeding intensity, and growth between unmarked and hatchery fish, suggesting that both groups were responding similarly to ocean conditions.



TOP-DOWN PROCESSES AND AFFECTS ON SALMON GROWTH AND SURVIVAL

Predator and Prey Field Studies

Annual catch of nekton

In 2010, Predator Study sampling for predatory and forage fishes was limited to one transect off Willapa Bay, WA, but also included a pilot salmonid prey field sampling component (Prey Field Study) to target juvenile fishes and invertebrates eaten by juvenile salmon as they first enter the ocean. Willapa Bay was selected as the sole sampling transect because of higher catches of pelagic fishes along this transect compared to the Columbia River transect in past years (1998-2009; Figs. 36 & 37). In 2010, we occupied 16 different stations and conducted 11 predator/forage fish trawls, 4 prey field trawls (2 during the day and 2 at night), and 12 CTD casts.

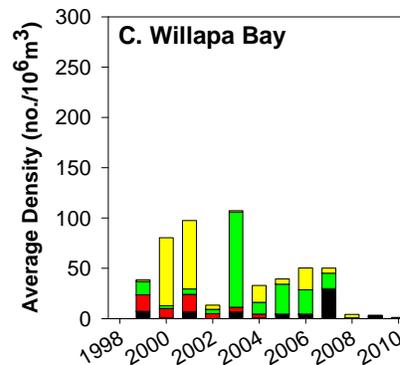
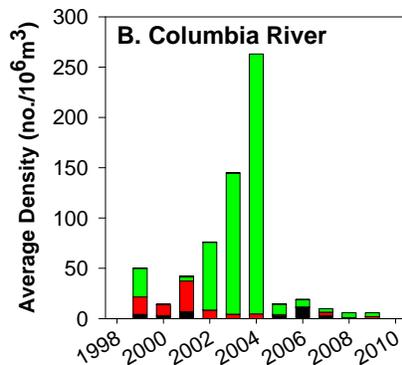
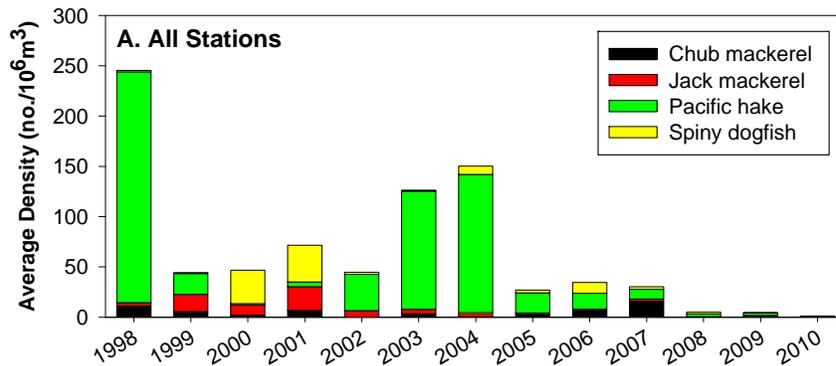
During the Predator Study, we collected a total of 20,009 jellyfish, 18,031 fishes, and 55 invertebrates. Numerically, the most abundant species was whitebait smelt (*Allosmerus elongatus*; n = 14,178), which comprised 50.5% of the total catch. The jellyfish *Chrysaora fuscescens* (n = 9,941; 35.4% of the total catch) was the next most abundant species captured. Pacific herring (*Clupea pallasii*) was the third most abundant species captured (n=1,388; 4.9% of the catch) followed by northern anchovy (*Engraulis mordax*; n = 1,347; 4.8% of total catch). The fifth most abundant species captured was juvenile (100-299 mm standard length) Pacific hake (*Merluccius productus*; 736; 2.6% of total catch). Combined together, these five species accounted for 98.2% of the total Predator Study numeric catch.

During the Prey Field Study, we collected a total of 182 cephalopods, 19,672 euphausiids, 1 crab megalope and 1,415 fishes. Numerically, by far the most abundant species was *Euphausia pacifica* (n=14,080) which comprised 66.2% of the total catch. *Thysanoessa spinifera* (n = 4,712; 22.2% of total catch) was the next most abundant species numerically, followed by euphausiids we were unable to identify to species (n = 880; 4.1% of total catch). The most abundant fish species was Pacific sardine (*Sardinops sagax*; n = 856) and contributed 4.0% to the total catch, followed by whitebait smelt (n = 413; 1.9% of the total catch). California market squid (*Loligo opalescens*) was the next most abundant species caught during the Prey Field Study (n=137), and comprised 0.6% of the total catch. All together, these species

accounted for 99.1% of the total Prey Field Study numeric catch, and overlapped with salmon diet contents in this area (G. Hutchinson, unpublished data).

Densities of predatory fishes

Annual average predatory fish densities caught during Predator Study cruises in 2010 were the lowest for all species observed during the 13 year study period (Fig. 36). Adult spiny dogfish (*Squalus acanthias*) was the most abundant piscivorous predatory fish captured, although the sample size for spiny dogfish (n = 3) and other predatory fish was small. For instance, we only caught 2 jack mackerel (*Trachurus symmetricus*), and 1 adult (300+ mm SL) Pacific hake, and for the first time in the 13-year time series, we captured no chub mackerel (*Scomber japonicus*). In addition, we recorded no catches of the predatory cephalopod species, Humboldt squid (*Dosidicus gigas*) in 2010, despite record densities of this species in 2009. Because of the



low catches of predatory fishes in 2010, we expect higher adult salmon returns to Bonneville as the result of lower predation pressure (see Fig. 39 below).

Densities of forage fishes

Annual average forage fish densities caught during Predator Study cruises in 2010

Figure 36. Annual average densities of predatory fish from (a) both Columbia River and Willapa Bay transects (1998-2010); (b) just the Columbia River transect (1998-2009); and (c) just the Willapa Bay transect (1998-2010).

were the highest since 2003 (Fig. 37). However, there was

considerable inter-specific variability. For example, average annual whitebait smelt and Pacific herring densities were the largest since 2003, while Pacific sardine densities were the lowest in

the 13-year time series, and northern anchovy densities were fourth lowest overall, lower than densities recorded since 2006. Nevertheless, overall forage fish densities were higher in 2010

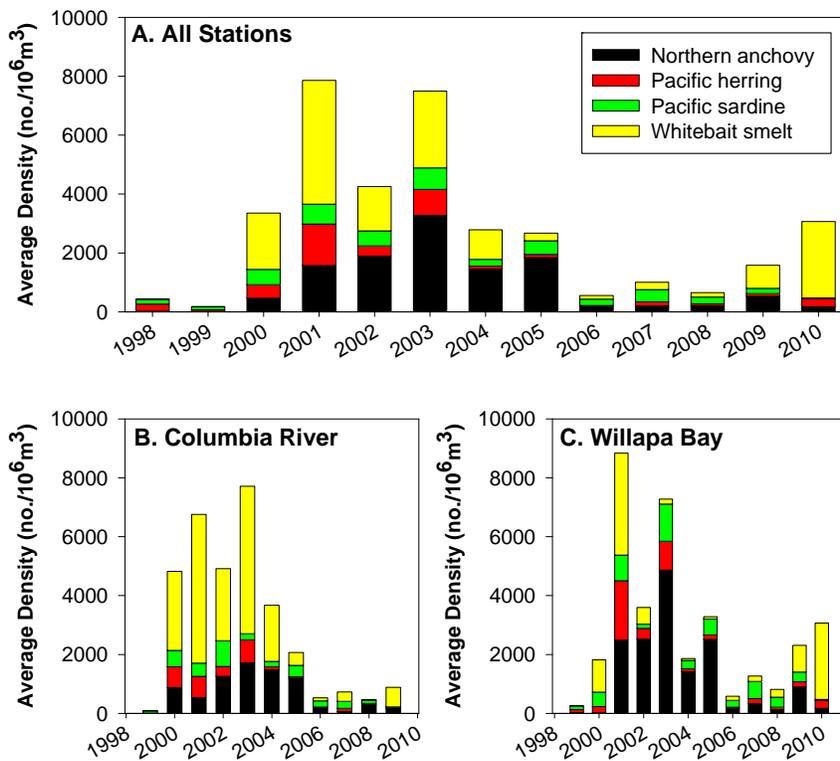


Figure 37. Annual average densities of predatory fish from (a) both Columbia River and Willapa Bay transects (1998-2010); (b) just the Columbia River transect (1998-2009); and (c) just the Willapa Bay transect (1998-2010).

than observed in 1998-1999, and 2004-2009, but still lower than their very high density years from 2000-2003 (Fig. 37).

Oceanographic conditions

Cold ocean sea surface temperatures (SSTs) are supportive of high primary and secondary productivity. Average ocean

second coldest in the 13-year Predator Study time series and associated with the transition of an El Niño to a La Niña (Fig. 38). In 1999-2001, and 2007-2008, during previous La Niña events, forage fish recruitment and survival of salmonid out-migrants was highly successful. The abundance of predator fish appears to be highly correlated to ocean temperatures with fewer

temperatures in 2010 were the

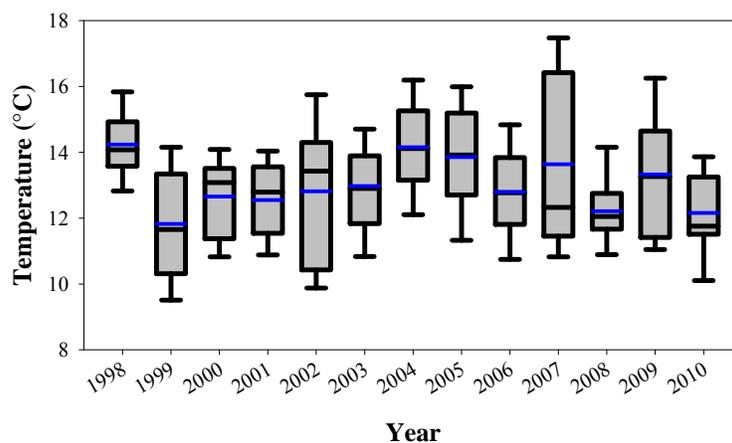


Figure 38. Annual sea surface (3 m) temperatures. The median is the line in each box. The box reflects the 75% quartile and the tails the range.

predators, particularly Pacific hake, found during cool oceanographic conditions (Emmett et al. 2006). As such, there appears to be a negative relationship between the abundance of Pacific hake and salmon returns to Bonneville Dam, and this relationship is being developed as a top-down indicator of salmon survival (Fig. 39).

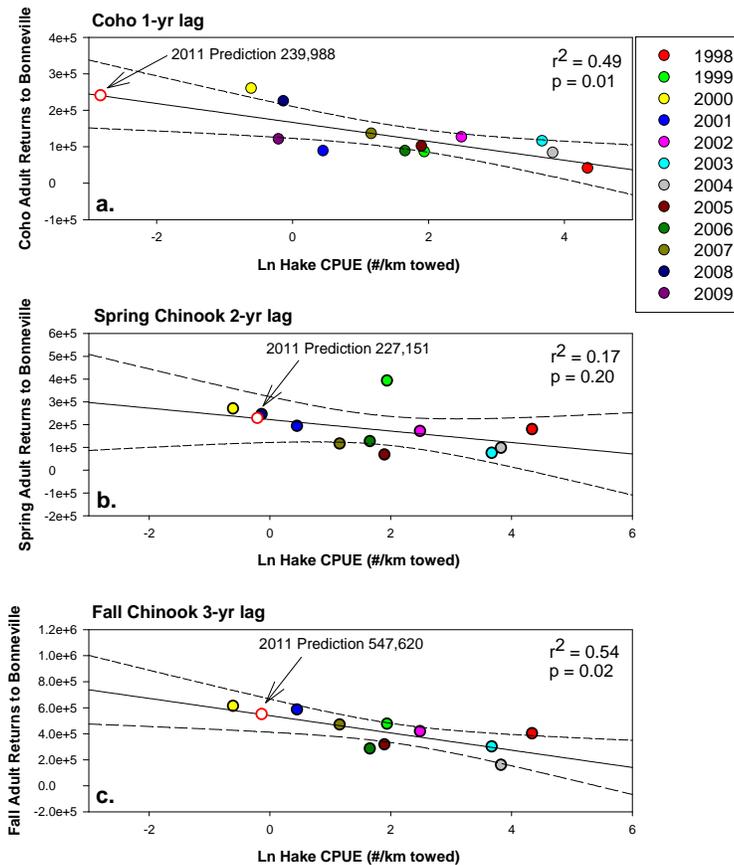


Figure 39. Regressions of adult returns to Bonneville Dam for coho (*Oncorhynchus kisutch*), Spring Chinook (*O. tshawytscha*), and Fall Chinook salmon on Pacific hake (*Merluccius productus*) catch-per-unit-effort (CPUE; number/km towed) during the period of salmon outmigration. Coho salmon adult returns are lagged by one year; Spring and Fall Chinook salmon adult returns are lagged by two and three years, respectively. Predictions for 2011 adult returns are also shown.

The marine survival of salmonids is almost certainly determined by two primary factors: predation on juvenile salmon (related to predator density) and growth rate of juvenile salmon (related to availability of food resources). During cool ocean conditions, which we observed in 2010, the number of predators was very low and juvenile salmon prey was abundant. We expect that juvenile salmonids that migrated to sea early (May-June) in 2010 grew rapidly and had low predation rates. Furthermore, if some forage fish

spawning and recruitment was as high (for anchovies and smelts), as we expect it was in 2010, then salmon predators (birds, mammals, fishes, and cephalopods) will have high numbers of alternative prey available to them in 2011.

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Pathogens of Juvenile salmon

Pathogens can have a significant affect on the survival of juvenile salmon during their outmigration and early marine residence (Fryer and Sanders 1981, Jacobson et al. 2008).

Renibacterium salmoninarum, the causative agent of bacterial kidney disease (BKD), has been the focal pathogen of our analysis for the past several years. Our data now span 12 years for the months of May and June (from 1999 through 2010). *R. salmoninarum* prevalence data exists for a total n= 10,246 salmon. Assayed by nested PCR (nPCR), which indicates only an infection, this past year were samples from 2009 (added n = 382 for a total n = 851) and 2010 (n = 1740). A total of 1,554 juvenile salmon (n=378 added this year) have been analyzed via a quantitative PCR (qPCR) of the *abc* gene of *R. salmoninarum* for samples from 1999-2010. This quantitative assay gives us an indication of the severity of infection. From the results of the two assays, we have identified four different infection levels 1) uninfected, 2) mildly infected, 3) moderately infected, and 4) severely infected.

Our long term prevalence data for the pathogen *R. salmoninarum* show that coho salmon survival and disease prevalence are related. Adding the 2009 data this year shows an apparent return to the original trend we saw through 2007 (for 1999-2009, $R^2 = 0.465$, $p=0.02$, Fig. 40), seeming to suggest that 2008 was an outlier for reasons that remain unclear. Overall, lower prevalences are apparent in both Chinook salmon and coho salmon since 2004.

Relating infection prevalence to stock specific evaluations was a focus of this year's effort. We see prevalence differences among stock groups in some of the later years, when focusing on three major stock groups of yearling Chinook salmon: Mid and Upper Columbia River Spring (Mid/UCR_Sp) , Snake Spring (Snake_Sp) and Upper Columbia River Summer/Fall (UCR_Su/F) (Fig. 41). While both spring stocks exhibit the same interannual trend of lower prevalence in later years, the UCR_Su/F stock group have shown an increase in prevalence again since 2006. UCR_Su/F had significantly higher total (1999-2009) *R. salmoninarum* prevalence than the other two stocks at 24.5% ($\chi^2 = 15.9$, $p<0.001$). Among the three stocks, UCR_Su/F had the highest prevalence in both 2006 and 2008 (2006: $\chi^2= 15.4$ $p<0.001$, 2008: $\chi^2= 8.3$ $p=0.016$) while Snake_Sp prevalence was highest in 2007 ($\chi^2= 8.4$, $p=0.015$). In 2006 and 2009, UCR_Su/F also had significantly higher prevalence of moderate infection (2006: $\chi^2= 26.2$ $p<0.001$, 2009: $\chi^2= 6.9$ $p=0.03$).

We further analyzed the UCR_Su/F stock group by age class for differences between yearling and subyearling fish within this genetic stock. Overall, for the years 1999-2009, yearling UCR_Su/F fish had higher *R. salmoninarum* prevalence ($\chi^2 = 24.1, p < 0.001$) and among

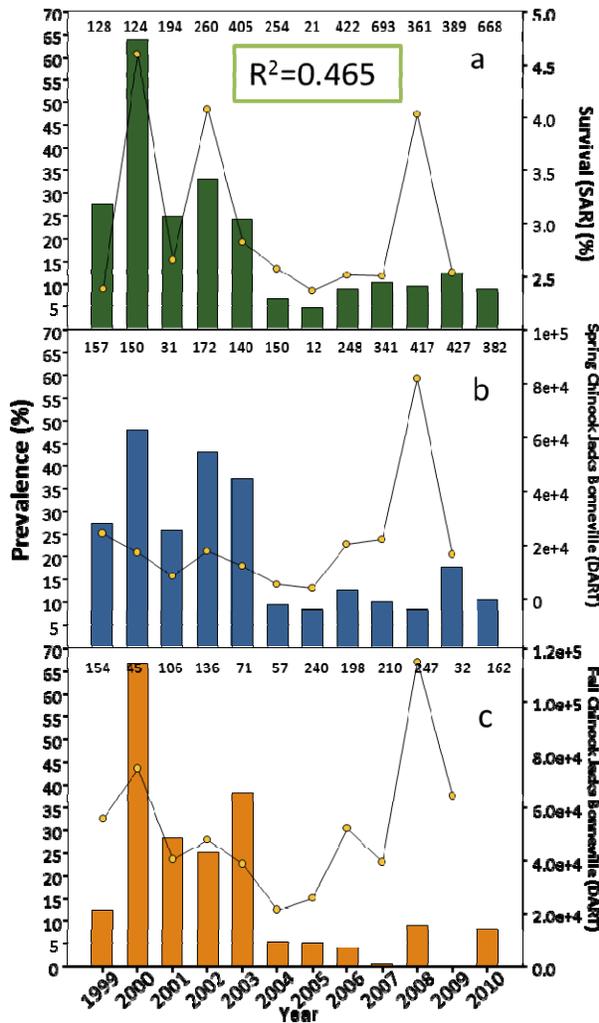


Figure 40. *R. salmoninarum* Infection Prevalence and Survival in a) yearling coho salmon in May and June vs. coho SAR, b) yearling Chinook salmon in May and June vs. spring Chinook jack returns to Bonneville Dam and c) subyearling Chinook salmon in June and September vs. fall Chinook jack returns to Bonneville Dam. Sample sizes are displayed above the graph.

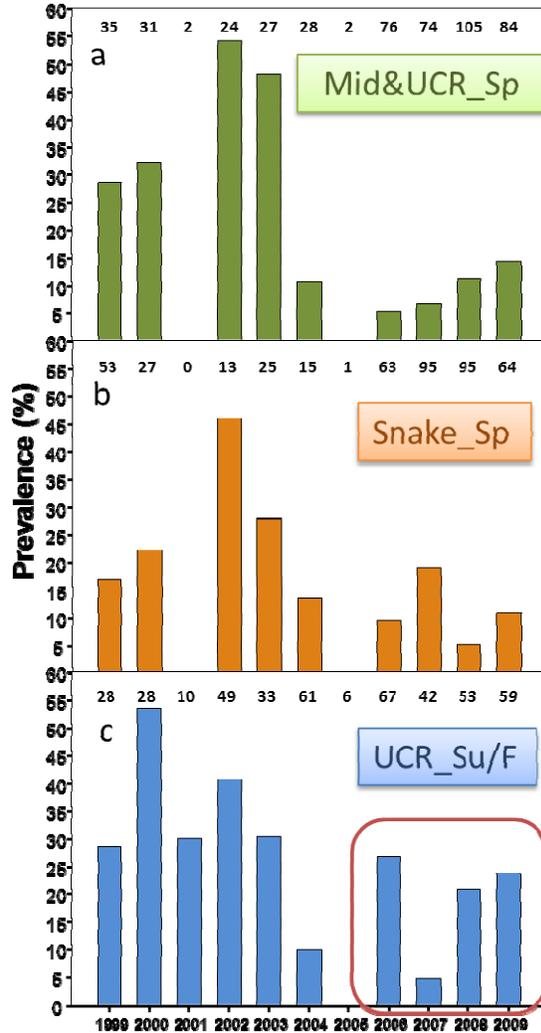


Figure 41. *R. salmoninarum* Infection Prevalence in yearling Chinook salmon in May and June from genetic stock groups a) Mid and Upper Columbia River Spring b) Snake Spring and c) Upper Columbia River Summer/Fall. Sample sizes are displayed above the graph.

individual years, yearlings had higher prevalences in each year from 2006-2009 ($p < 0.05$). Yearlings also had higher moderate infection prevalence in the same years, with statistical significance in 2006 and 2007 ($p < 0.05$).

Yearling coho salmon were analyzed by genetic stock group for the period of years from 1999-2009. The three major stock groups examined were Washington Coast (WC), Columbia River (CR) and Oregon Coast (OC) (Figure 3). Overall *R. salmoninarum* prevalence from 1999-2009 was significantly different among stocks with the CR stock group having the highest prevalence of 18.6% ($\chi^2=9.4$ $p=0.009$). CR coho have the highest combined-year prevalence (1999-2009) of moderate infections at 4.1% ($\chi^2= 13.65$, $p<0.001$). All three stocks appear to be following the aforementioned trend seen of decreased prevalence since 2004.

Renibacterium salmoninarum prevalence in juvenile salmon at Bonneville Dam bypass and in the lower Columbia River estuary are determined to provide upstream baseline data. Some notable results include significantly higher prevalence in UCR_Su/F yearling Chinook salmon in the CR estuary in 2009 (42.9%), as compared to other stock groups, and other years, as well as compared to the ocean-caught fish in 2009 (23.7%). At Bonneville Dam, yearling Chinook salmon had significantly higher prevalence of *R. salmoninarum* in 2009 than the ocean and estuary, at 44.6% ($p<0.001$, comparing among fish from stocks originating above Bonneville). The upstream data provided an enhanced perspective on what otherwise may have seemed an unremarkable prevalence level in the California Current in that year. Moreover, for subyearling Chinook salmon in 2009, a prevalence of 0% in the ocean-caught fish ($n=32$), compared to a prevalence at the dam of 48%, indicates that this pathogen may have had a significant impact on Fall Chinook salmon survival in 2009.

We began analyzing *R. salmoninarum* prevalence in sockeye ($n=194$) and steelhead ($n=45$) in 2010, and our preliminary results show that levels were comparable in these species to Chinook and coho salmon. Future efforts will aim to interpret more mechanistic explanations of the differences among stock group prevalences, continue to analyze upstream data to gain understanding of the bigger picture mechanisms influencing the long term interannual patterns of *R. salmoninarum* prevalence, and expand our knowledge on sockeye and steelhead.

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Abundance, Distribution, and Diet of Avian Predators

Immediately prior to conducting the salmon trawl surveys, marine bird surveys were completed along six transects in May 2010 and eight transects in June 2010. This provided information on the species, distribution, and abundance of potential salmon predators relative to salmon ocean distribution and ocean habitat. Stormy weather in May 2010 made observation through the bridge windows difficult, therefore half of all shearwaters seen could not be identified to species with certainty. However, given species composition observed in all prior years, it is reasonable to assume the unidentified dark shearwaters are all sooty shearwaters (*Puffinus griseus*). As in all prior years, the numerically dominant avian predators in both May and June 2010 were sooty shearwaters (55.8% and 46.3%, respectively) and common murre (*Uria aalge*, 33.3% and 43.5%; Fig. 42). Unlike in 2009, unusually large numbers of pink-footed shearwaters (*Puffinus creatopus*) were not seen again in 2010.

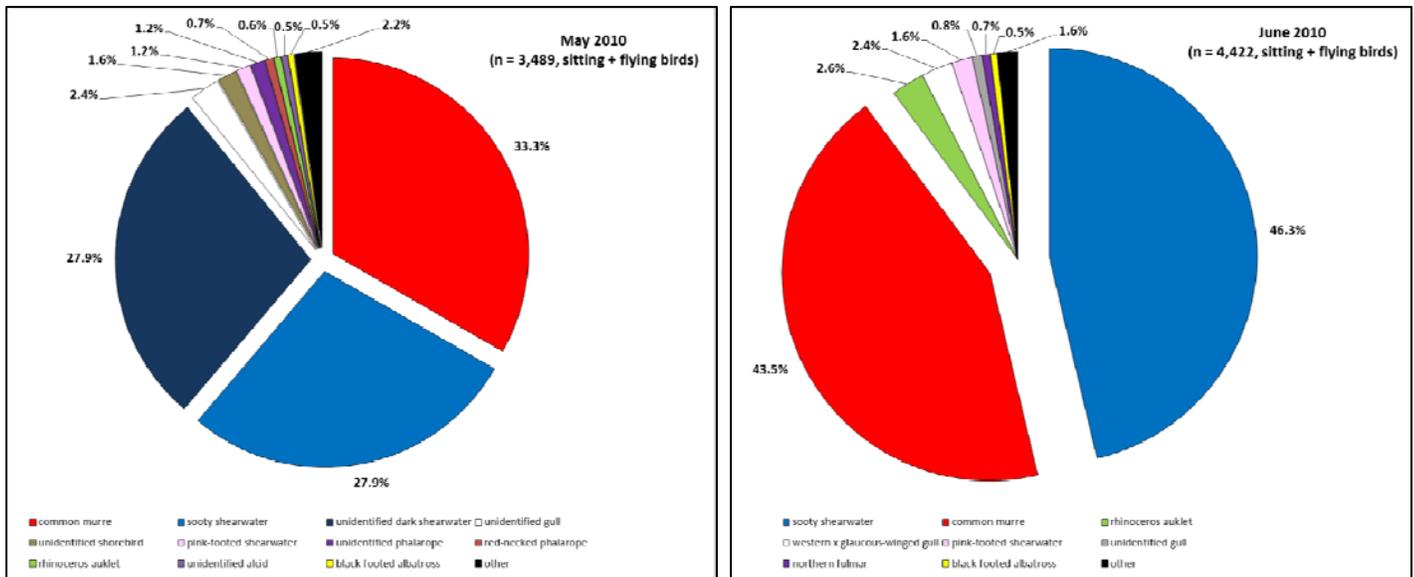


Figure 42. Species composition of avian predators in May and June 2010. Species that comprised <0.5% of the total were lumped together under the category “other”.

Over half of all avian predators seen on the water were near Columbia River mouth. In May and June of 2010, 58.9% and 53.5% of all birds were seen on the three transects bracketing the Columbia River mouth (Willapa Bay, Columbia River, and Cape Meares transects). These values are greater than what would be expected if avian predators were distributed uniformly in coastal waters over all transects: a uniform distribution would predict 49.7% and 36.8% of all birds seen to be found there in May and June, respectively. This means that predation pressure near the mouth of the river is higher than in other coastal areas (Zamon et al., in review).

When compared to previous years, total avian predator abundance per linear kilometer of survey in 2010 was the third lowest observed during May surveys (4.1 birds per km) but the highest of June surveys (12.55 birds per km)(Table 2). Low avian predator abundance in May followed by very high avian predator abundance in June 2010 could lead to differences in early marine survival for those Chinook and coho exiting the Columbia River in May versus June.

(A) MAY				(B) JUNE			
Year	Total birds per km	Common murre per km	Sooty shearwaters per km	Year	Total birds per km	Common murre per km	Sooty shearwaters per km
2003	4.96	1.39	2.21	2003	11.47	1.79	9.24
2004	6.83	2.82	3.81	2004	5.01	0.93	3.33
2005	8.57	1.78	6.43	2005	5.96	1.58	4.11
2006	10.33	0.72	8.08	2006	4.28	0.69	3.28
2007	2.38	0.22	1.61	2007	7.32	1.42	5.1
2008	2.42	0.38	1.73	2008	4.74	2.92	1.42
2009	7.06	1.07	5.7	2009	6.32	0.96	4.44
2010	4.1	3.3	0.6	2010	12.55	5.49	6.44

Table 2. Bird abundance per km of survey effort, May (A) and June (B) 2003-2010. To ensure comparisons of the same transects among different years, May data include only information from Grays Harbor and Columbia River transects. These calculations include only birds observed on the water; they do not include flying birds.

Data from monthly land-based marine bird and mammal surveys conducted at the North Head Lighthouse, 5.5 km north of the Columbia River entrance, demonstrate that dominant avian predators observed during ocean cruises in May and June also occur in high densities within 1.4 km of shore throughout the entire period in which Columbia River salmon smolts are entering the ocean (e.g. common murre, May-September, Fig. 43A). We also detected species of fish-eating birds in the very nearshore that are not typically observed during shipboard surveys (e.g. double-crested cormorants *Phalacrocorax auritus*, brown pelicans, *Pelecanus occidentalis*; Fig. 43B).

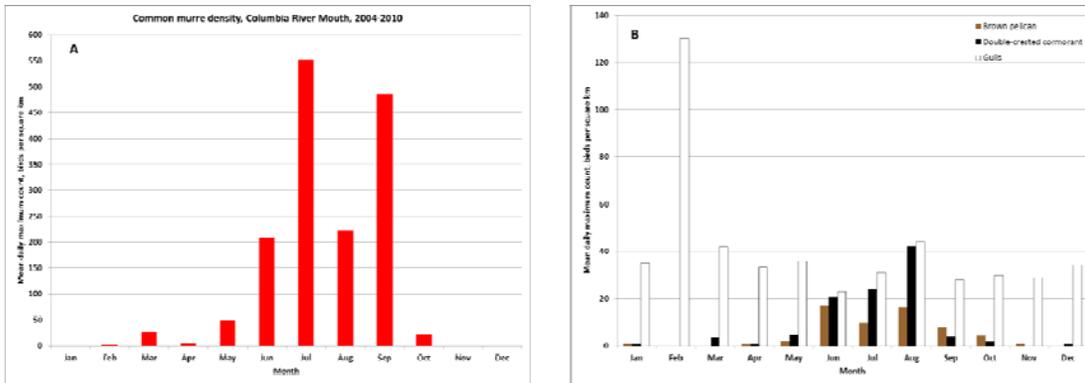


Figure 43. Bird densities vs. month of year. Data from land-based surveys 5.5 km north of the Columbia River entrance. (A) common murres (B) pelicans, cormorants, gulls.

Although we do not yet have diet samples from May or June, we have collected diet information from murres and shearwaters during July-September 2008-2010. Live capture of birds was followed by stomach lavage to obtain diet samples. Chinook salmon remains have been identified in murres. We have not yet detected salmon remains in shearwaters (Table 3). However, it should be noted that a Columbia River steelhead PIT tag was recovered from a shearwater attending its colony in New Zealand during 2007 (NOAA Press Release #NOAA07-R03). Our observed frequency of occurrence (8%) of salmonids in common murre diet is similar to results from Varoujean & Matthews (1983), who found 10.4% of 77 murres collected in the Columbia River plume area during May and June had consumed coho salmon smolts. Avian predators appear to be taking primarily northern anchovy (*Engraulis mordax*) during the July-September period, although herring, smelt, and other fishes are also occasionally taken (data not shown).

	Total number sampled for diet	Number with salmon remains	Percent occurrence of salmon	Number with anchovy remains	Percent occurrence of anchovy
Common murre	25	2	8%	20	80%
Sooty shearwater	32	0	0%	29	90%

Table 3. Salmon remains found in bird diet samples, July-September 2008-2010. Salmon tissue remains (soft or hard parts) were verified with genetic analysis techniques. Percent occurrence indicates presence/absence; it is not adjusted for the occurrence of multiple salmon in one sample.

There are now enough years of data to begin exploring relationships between avian predator abundance during juvenile salmon outmigration and variation in adult salmon returns.

Although our sample size is small ($n=7$), May data for coho salmon suggest an inverse relationship between avian predator abundance in May and adult returns and survival from the year class whose juvenile outmigration took place that same May (Fig. 44). Bird predation may therefore directly impact early marine survival of coho salmon. There is no apparent relationship between May bird abundance and spring Chinook returns (data not shown), although at this point we have only used five year classes (2003-2007) of Chinook return data in our analysis.

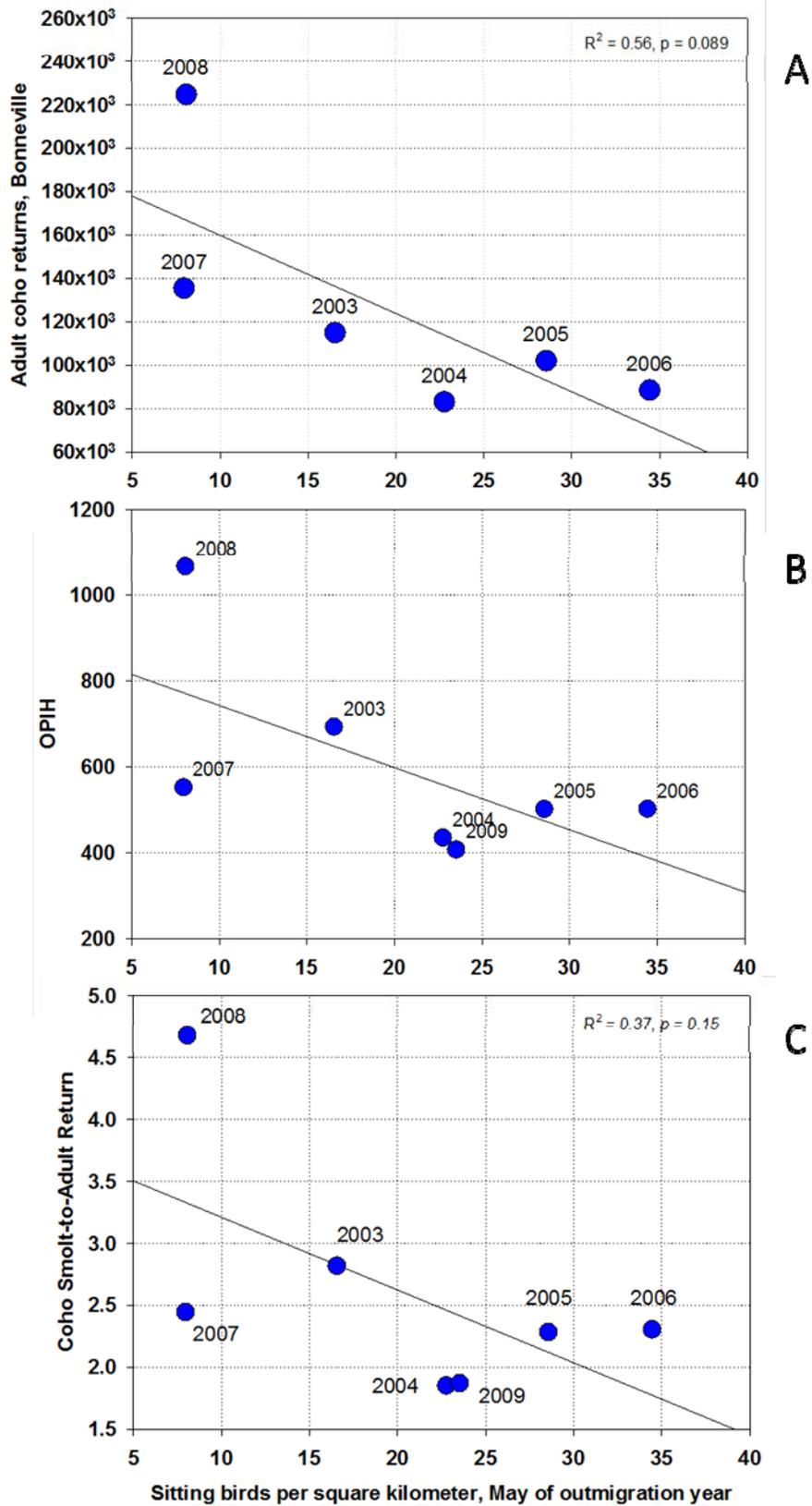


Figure 44. Bird abundance during May of ocean entry year vs: A) adult returns of coho salmon at Bonneville Dam, B) Oregon Production Index Area Hatchery coho salmon, and C) OPIH SAR. These linear regressions suggest a potential inverse relationship between abundance of bird predators and coho salmon survival and abundance.

June data showed no significant pattern for coho returns (data not shown). However, for Chinook salmon it appears outmigration years with high June bird predator numbers (e.g. 2003) have lower adult returns than years with low bird numbers (Fig. 45). This relationship may appear weak because in 2005, a year of low bird abundance, ocean temperatures were also extremely warm, and therefore salmon returns may have been affected by unfavorable ocean temperatures even though few bird predators were in the area. Bird predation pressure in June may therefore impact early marine survival of Chinook. It will be necessary to obtain additional years of data, however, before the statistical power of the regression is great enough to determine the likely biological significance of such a relationship.

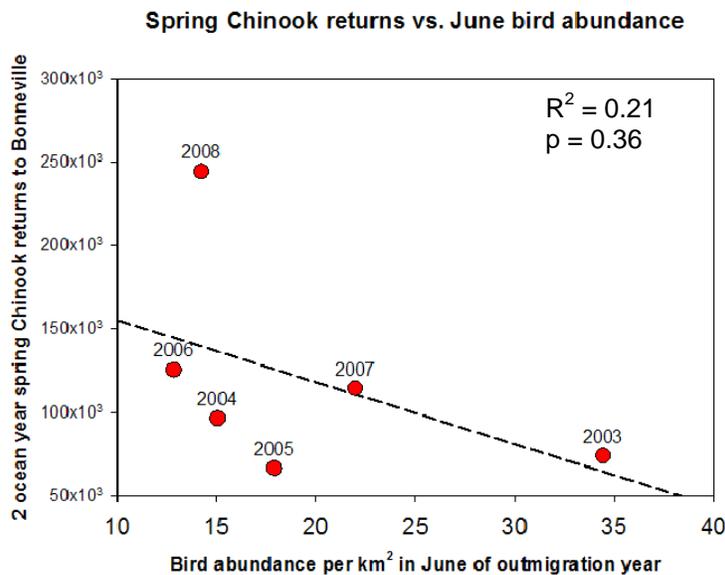


Figure 45. Adult returns of spring Chinook salmon vs. June bird abundance (sitting birds only).

To assist with improving salmon forecasts, one of the new ocean indicators under development is an ocean avian predation index. This index ranks May and June of each year according to the density of avian predators found on our ocean surveys. It is reasonable to assume that higher bird densities results in higher predation risk for juvenile salmon. We have provided sample diagrams to show how this predation index is directly comparable to other indices developed as part of this project (Figure 46). This diagram clearly illustrates that predation pressure in May and June is not necessarily the same in a given year – as happened in 2010, it is possible to have low predation pressure in May but high predation pressure in June, as

well as vice versa. It is also a good way to visually see what years had low predation pressure in both months, a possible indicator of strong salmon returns for that year class.

		ALL BIRDS - SITTING + FLYING							
		2003	2004	2005	2006	2007	2008	2009	2010
May bird abundance, rank		4	3	8	7	1	2	5	6
June bird abundance, rank		4	1	2	6	8	5	3	7
May, birds per km ²		40.8	23.5	77.1	69.3	19.6	19.6	42.6	47.4
June, birds per km ²		45.5	32.3	34.0	53.8	61.5	50.8	38.5	57.8

		ALL BIRDS - SITTING ONLY							
		2003	2004	2005	2006	2007	2008	2009	2010
May sitting bird abundance, rank		4	3	7	8	2	1	5	6
June sitting bird abundance, rank		7	2	3	5	6	1	4	8
May, sitting birds per km ²		15.2	12.3	28.9	39.1	7.4	6.3	20.5	22.9
June, sitting birds per km ²		29.8	14.4	19.7	22.8	29.4	12.4	22.7	48.0

		ALL BIRDS - FLYING ONLY							
		2003	2004	2005	2006	2007	2008	2009	2010
May flying bird abundance, rank		6	1	8	7	2	3	4	5
June flying bird abundance, rank		5	6	1	8	7	3	4	2
May, flying birds per km ²		25.5	11.2	48.2	30.3	12.3	13.3	22.2	24.5
June, flying birds per km ²		15.7	17.9	14.4	31.0	32.1	38.4	15.8	9.8

Ranks 1-3	low bird density, least predation pressure
Ranks 4-6	moderate bird density, moderate predation pressure
Ranks 7-8	high bird density, most predation pressure

Figure 46. Sample Ocean Avian Predation Index.

In summary, although avian predator abundance was relatively low in May 2010, June 2010 predator abundance was the highest seen during the eight year time series. Birds aggregated near the Columbia River mouth in both May and June. Year-round land-based surveys demonstrate avian predators are present near the river mouth in high densities through the entire May-September period of smolt outmigration from the Columbia River. Murres consumed juvenile Chinook during the July-September period. Regression of adult salmon returns on bird abundance suggest that May bird abundance is inversely related to coho salmon returns, and June bird abundance is inversely related to Chinook salmon returns. Regression results suggest that incorporating an ocean avian predation index into ocean indicator forecasts for salmon will be useful. However, to develop estimates of marine mortality caused by avian predators in the ocean, quantitative information on the occurrence of salmon in bird diet will be required, especially during May and June when alternative prey such as anchovy are less likely to be available to birds.

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- Varoujean DH, Matthews DR . 1983. Distribution, abundance, and feeding habits of seabirds off the Columbia River, May-June, 1982. Report No. OIMB 83-1, University of Oregon Institute of Marine Biology, Charleston, OR.
- Zamon JE, Phillips EM, Guy TJ. In review. Marine bird aggregation at tidally-driven plume fronts of the Columbia River. Deep Sea Research II.

Top-down regulation: a predation pressure index

Predation pressure is a function of the abundance of predators, primary prey, and alternate prey, all of which are incorporated into the food web models. In order to address the cumulative uncertainty about all model parameters in the final model and predation index, we performed a Monte Carlo analysis of viable food web structures. For each model year, random models were drawn from the set of all potential models within 1 standard deviation of each observed functional group biomass and within $\pm 20\%$ of each element of the base diet matrix. Models in which predation pressure on any prey group exceeded its production rate were rejected.

Predation takes between 75-90% of juvenile coho production (Fig. 47). 2005, 2006, and 2007 were the years of heaviest predation pressure. Predation is not significantly correlated with the OPIH smolt-to-adult ratio. However, we cannot take this as strong evidence that top-down pressures are not important regulators of salmon survival. Over the five years so far modeled, the OPIH values have very limited range (0.025 – 0.033). Also note that 2006, though a high plankton production year, was also high predation year and this may be reflected in the low estimated survival in 2006 (OPIH smolt-to-adult ratio = 0.025).

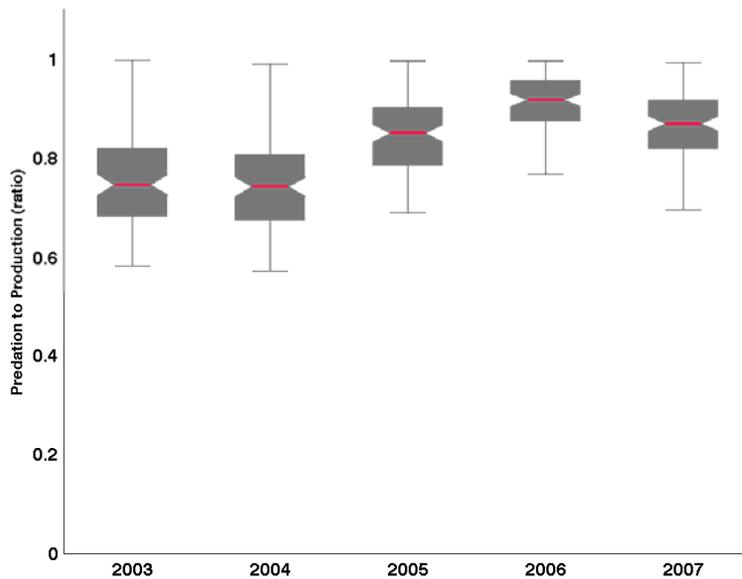


Figure 47. Inter-annual predation pressure upon coho yearling. Predation pressure is normalized to coho yearling production rates. Box plots represent the distribution of 1000 valid models drawn from the set of all potential models within ± 1 SD of each observed functional group biomass and within $\pm 20\%$ of each element of the base diet matrix.

Characterizing juvenile salmon in the Columbia River estuary

To better understand factors affecting juvenile salmon survival in both the Columbia River and the Pacific Ocean, we have now completed a fourth year of sampling juvenile salmon in the Columbia River estuary as they make the critical transition between riverine and marine environments. This program is based on the premise that knowing both *when* various groups of salmon reach the estuary and *what* their characteristics are (e.g., size,

parasite and pathogen prevalence, food habitats, hatchery-wild origins), will be informative to studies of salmon in both the Columbia River and the ocean.

Sampling in 2010, like that in 2007-2009, focused on the spring outmigration period of coho, yearling Chinook, and steelhead, with cruises every other week from mid April to late June. Like 2009, we also sampled monthly from July through October to document migration patterns and characteristics of subyearling Chinook salmon, which reach peak abundances in July. We continued to use the same two stations (North Channel and Trestle Bay) on the Washington and Oregon sides of the lower estuary, respectively, adjacent to the two deep channels using a 500 ft-long (154 m) purse seine.

In 2010 we made a total of 110 sets, capturing an estimated 558,878 fish (of which 553,100 were northern anchovy), including 1,867 juvenile salmonids (762 subyearling Chinook, 386 yearling Chinook, 210 coho, 83 chum, and 31 sockeye salmon and 395 steelhead). Unique to 2010, we surgically implanted 100 juvenile steelhead with acoustic tags. The objectives of this pilot project were to 1) determine the feasibility of tagging fish caught in the purse seine, and 2) begin to understand steelhead ocean migration patterns which are poorly understood. We are waiting to learn if any of these tags were detected in the ocean.

We observed similar timing of peak abundances of juvenile salmon in the estuary in 2010 compared to earlier years, suggesting a predictable peak in abundance in mid May for yearling Chinook and coho salmon and steelhead (Fig. 48), and a peak in July or early August for subyearling Chinook salmon. The year 2010 was notable for having higher abundance peaks for both yearling Chinook and steelhead than had been observed previously. Like previous year, the presence of adipose fin clips in 2010 indicated that most (>90%) juvenile coho, yearling Chinook and steelhead salmon were of hatchery origin.

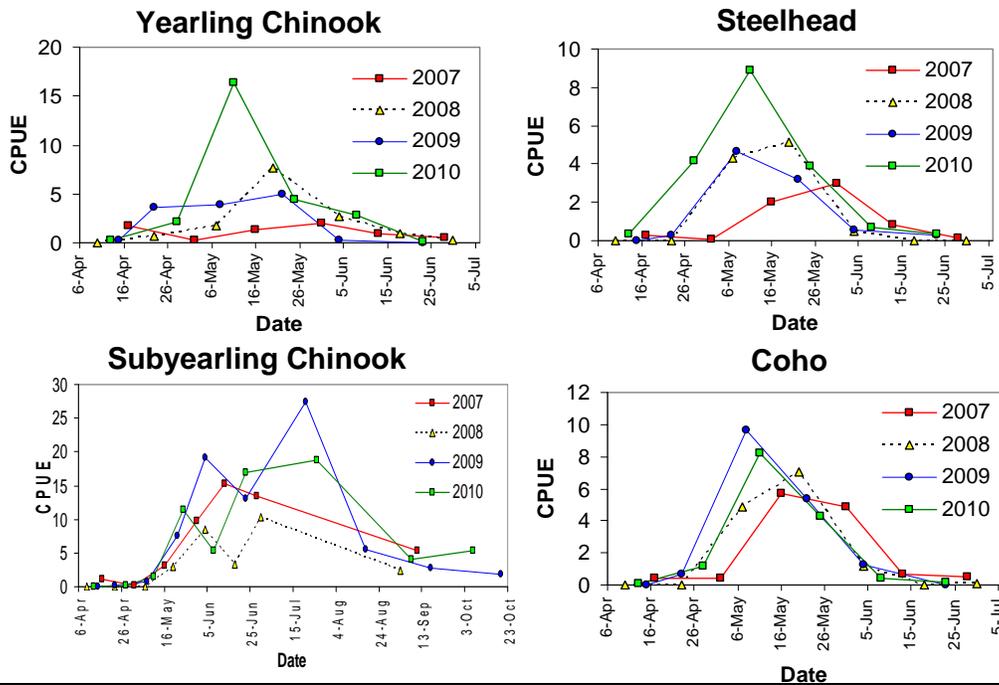


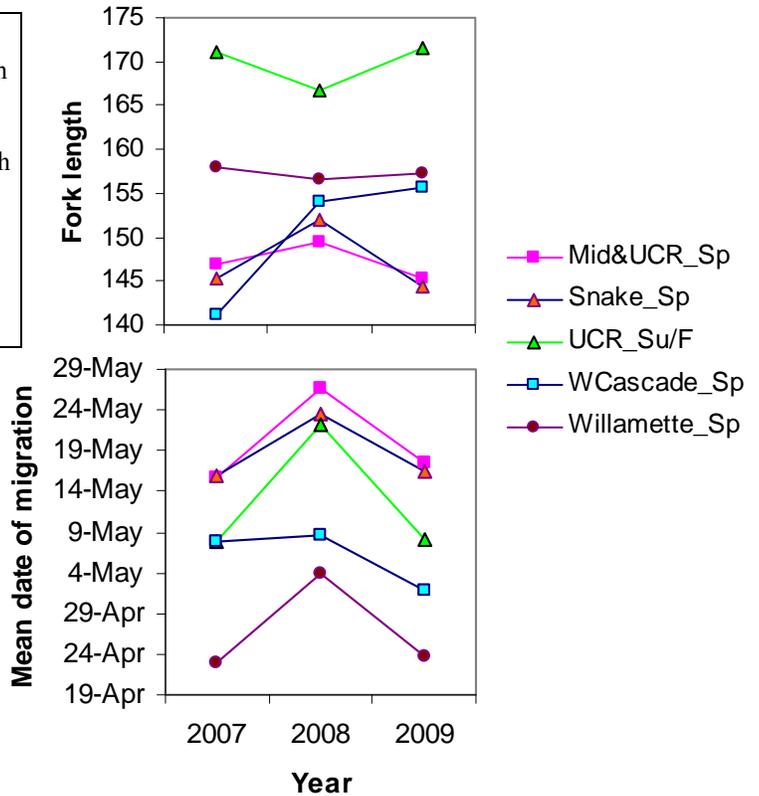
Figure 48. Abundance (fish per haul) of juvenile coho and Chinook salmon and steelhead in the Columbia River estuary during 2007-2010. Note the extended time scale for subyearling Chinook salmon.

From the four years of sampling, we have release information from 501 coded wire tags (CWTs) and 38 passive integrated transponder (PIT) tags. This tag information and genetic stock analysis of Chinook salmon and steelhead [new in 2010] indicates that the juvenile salmon caught by the study originate from all parts the Columbia River basin.

Because a primary goal of the estuary study is to understand salmon ecology during the critical transition to marine environments, we have begun to compare juvenile salmon caught in the estuary with those in the ocean. For example, we used genetic stock information for yearling Chinook salmon to examine both the size and timing of different groups in the estuary during years 2007-2009 (Fig. 49). This analysis indicates stock-specific size and arrival time in the estuary, with upper Columbia summer/fall and Willamette Spring Chinook having the largest mean size, while Willamette and West Cascade spring Chinook salmon were the earliest migrants in the estuary, with upper river stocks (e.g., Upper Columbia and Snake River springs) arriving up to a month later. We then compared the sizes of fish in these groups caught in the estuary with those in the ocean in May and found differences in the resulting growth rates that were consistent with the ocean entry timing: stock groups that entered the ocean earlier had higher growth rates (1.2

– 2.2 mm/d) than those that entered later (0.2 -0.7 mm/d). We also determined that the relative abundance of yearling Chinook salmon and especially steelhead in the estuary was a reasonable predictor of ocean abundances (i.e., years in which estuarine catches are high correspond to high catches in the ocean). We are continuing these estuary-ocean comparisons as we accumulate enough years of data to make such comparisons.

Figure 49. Mean fork length (top) and date of migration (bottom) for five yearling Chinook salmon stocks in the Columbia River estuary during years 2007-2009. Stock groups were determined by genetic analysis. All groups are Spring run (Sp) with the exception of the upper Columbia (UCR) summer/fall (Su/F) group (yearling migrants only). The West Cascade (WCascade) group is of lower river origin.



Linking hydrographic conditions with 3-dimensional salmon tracking in the Columbia River estuary

This is a new task, responsive to the concern that depletion of oxygen in the estuary might be reaching levels of concern for salmon (Roegner et al. [8]).

In this task, the NOAA-led team will concurrently measure the 3-dimensional migration pattern of juvenile salmonids relative to the hydrography of the CRE. We hypothesize that the vertical position and location of salmonids is altered when high salinity and low DO are present in the

estuary. Specifically, we predict salmon will hold or move upstream in response to encountering intruding seawater and shoal when encountering low DO. During ebb tides, when water is fresher and normoxic, we expect continued migration and deeper depth distribution.

OHSU is contributing to this task through characterization, prediction and analysis of the underlying circulation and DO dynamics. We rely extensively on observational, modeling and analyses efforts that we are conducting under core NSF funding of the Science and Technology Center for Coastal Margin Observation and Prediction (CMOP). BPA funding is used primarily to create the bridge between NSF-funded research on bottom-up processes and NOAA-led research on salmon survival.

Progress in 2010/2011: We have begun establishing a robust observational and modeling framework to characterize oxygen conditions at time of “ocean entry”. We focus on a highly inter-connected, cross-scale region that includes (a) the estuary downstream of the Astoria-Megler Bridge, where there is strong ocean influence; (b) the tidally-influenced plume, which we view as an extension of the estuary into the shelf; and (c) the continental shelf under the extended, longer-term, influence of the Columbia River freshwater.

Elements of our strategy include:

- A. Observation and analysis of DO and contextual physical and biogeochemical variables, across the estuary-shelf continuum.

Figure 50 shows relevant stations of CMOP’s SATURN observation network.

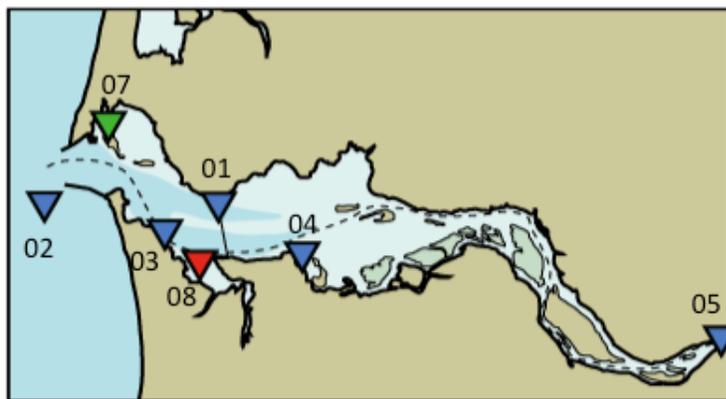


Figure 50: Blue markers denote biogeochemical stations of CMOP’s SATURN observation network that currently measure DO in the estuary (01, 03-04), plume (02), and tidal freshwater (05). All DO measurements have started recently (typically 2010 or 2011; 2009 in the case of SATURN-05). Also shown in red and green are future stations in ocean-influenced lateral bays: 07, in Baker Bay, planned for deployment in 2011; and 08, in Youngs Bay, under consideration for deployment in 2012. Station 05 is courtesy of Dr. Joe Needoba, at OHSU. Other stations are maintained under Baptista’s direction. Data from all SATURN stations is available at http://www.stccmop.org/datamart/observation_network/dataexplorer

Early data from recently deployed DO sensors

exemplifies the severity of the oxygen depletion in the estuary. In particular, oxygen levels measured at SATURN-03 in the summer of 2010 (Fig. 51) frequently crossed the threshold of

4.3 ml/l (incipient response [9]) and occasionally crossed the threshold of 2.1 ml/l (acute mortality [10]).

Low oxygen can be traced, via simple salinity-DO mixing diagrams (e.g., inset in Figure 51), to an oceanic source, which is consistent with the findings of Roegner et al. [8]. That oxygen levels of concern for salmon survival were detected in the estuary in 2010 (when the shelf was exceptionally well oxygenated relative to the recent norm, Figure 52), raises the question of what to expect during years of severe shelf hypoxia.

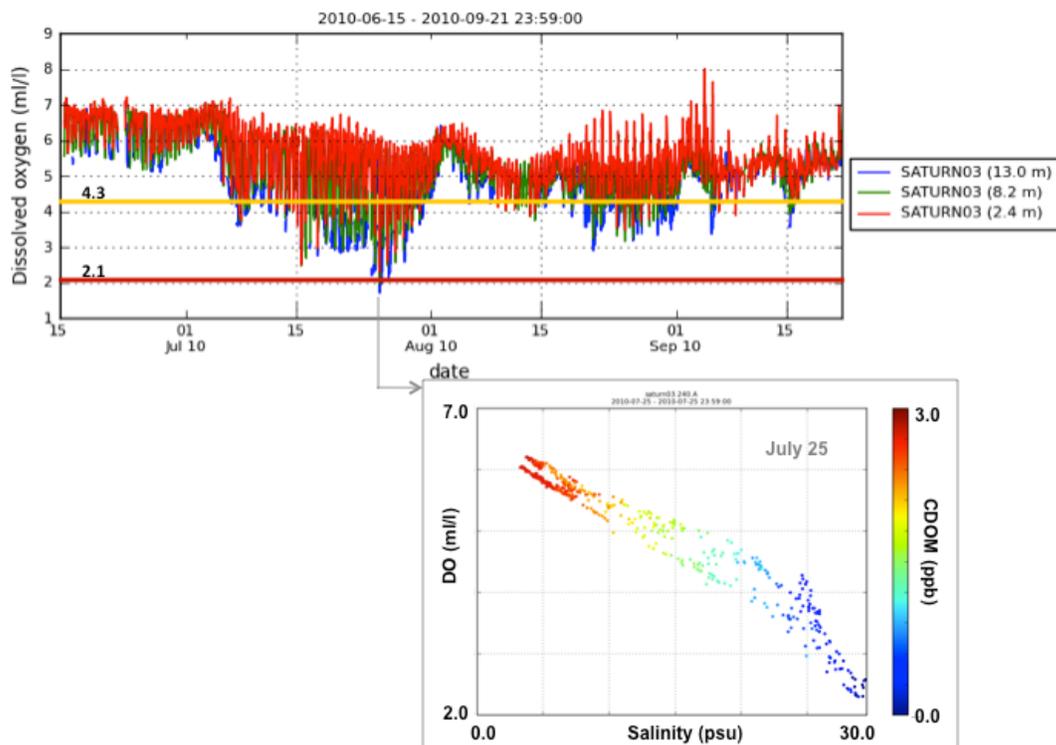
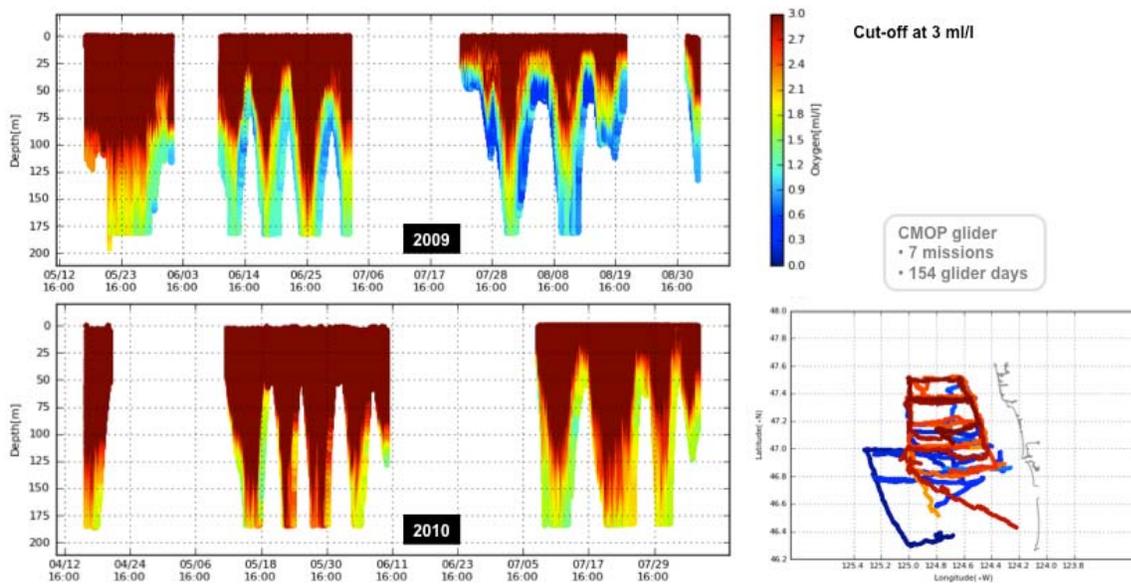


Figure 51: Time series of dissolved oxygen at three depths, at the SATURN-03 station in the South Channel of the estuary. First deployed on June 1, the DO sensor captured, from July through September, multiple violations of two salmon-relevant ecological thresholds (4.4 and, rarely, 2.1; see text for explanation of thresholds). Also captured, in August and September, are spikes of oxygenation associated with blooms of *M. rubra* (supporting evidence not shown). The inset shows, via a mixing diagram, that the source of low oxygenated waters is oceanic.

Long-term observations of DO in SATURN endurance stations (Fig. 50) and gliders (Fig. 52) are essential to address questions of seasonal and inter-annual variability. For instance, measurements at SATURN-02 (Fig. 53), initiated in April 2011 to better understand the linkages between oxygen in the estuary and shelf, illustrate the onset of low oxygen levels this year. Correlation with estuarine oxygen levels, wind regimes, tides and river discharges will be further investigated in 2011-2012.



http://www.stccmop.org/datamart/observation_network/glider

Figure 52: CMAP glider data off the Washington coast shows that oxygen levels in the shelf were substantially higher in 2010 than in 2009. Contrary to the norm over the last decade (separate data), no severe hypoxia events were detected in 2010. Glider tracks are shown in the inset.

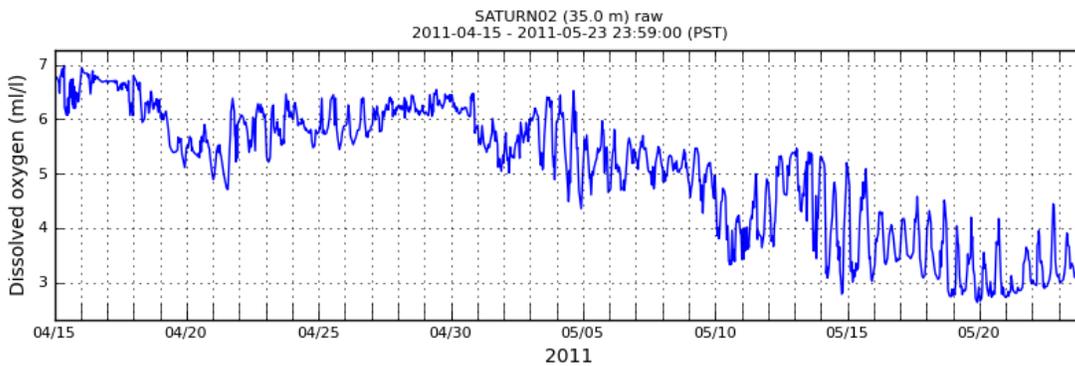


Figure 53: Time series of DO at SATURN-02 shows a trend of increased depletion, through the early stages of the 2011 upwelling season.

B. Detailed modeling of the vertical structure of salinity in the lower estuary

The unambiguously oceanic nature of the source of low oxygen to the estuary suggests that salmon-relevant modeling of oxygen dynamics in the estuary requires highly skilled modeling of

3D circulation processes, and in particular salinity intrusion, vertical structure and salinity retention in the North and South Channels. Although the CMOP simulation databases and forecasts for circulation, developed over the last decade and addressed below, have substantial process- and system-wide skill for the Columbia River, that skill is insufficient to meet the new requirements. As an example, the existing models miss details of the retention of salt in the North Channel during ebb (Fig. 54). A sensitivity analysis—involving parameters ranging from time step (Fig. 54), grid resolution, ocean forcing, and turbulence closure—is in progress to enable the necessary additional refinements (Lopez, Baptista, et al, in progress).

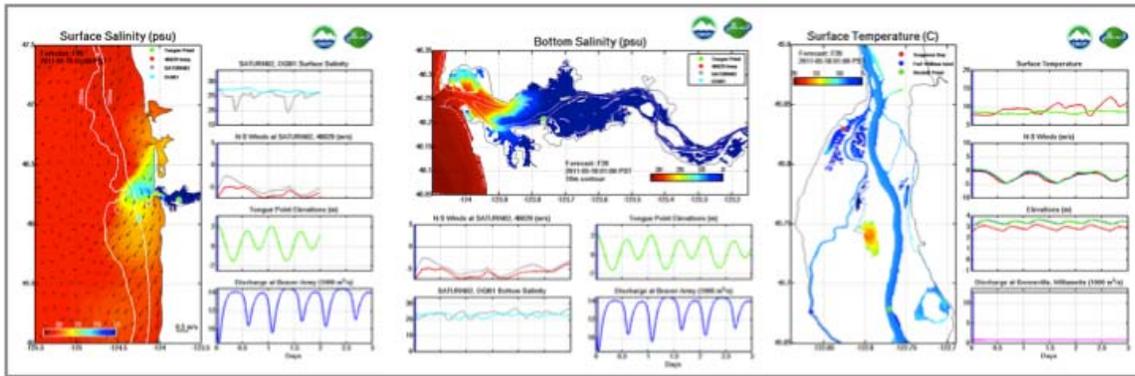


Figure 54: The most recent of the daily forecasts of circulation (F26) covers the Columbia River coastal margin from Bonneville Dam and Willamette Falls to the continental shelves of Oregon and Washington. This contrasts with the other forecast (F22, not shown), which upstream boundary is at Beaver Army Terminal. Panels show snapshots of F26 circulation in multiple parts of the system. From left to right: (a) surface salinity in the plume ; (b) bottom salinity in the estuary; and (c) surface temperature near the confluence of the Columbia and Willamette rivers.

C. Modeling of oxygen dynamics

Although oxygen in the estuary tracks well at high level salinity and temperatures, direct modeling of oxygen involving biological factors is necessary to explain the prevailing dynamics. Although we will not show here the details, this assertion is—for instance—supported by Figure 51: the dissolved oxygen spikes observed in August are traceable to primary productivity (in this case, blooms of *M. rubra*). With (among others) the motivation to support salmon survival studies, efforts are under way to develop a NAPDZ model for the estuary (Welle, Baptista, Spitz, et al). The acronym NAPDZ indicates that the model includes representation of nitrate, ammonia, phytoplankton, detritus and zooplankton. These efforts are made meaningful by the

emergence of the extensive network of SATURN endurance biogeochemical stations (Fig. 51) and glider (Fig. 53), each with an extensive set of inter-disciplinary sensors—and several with capability to characterize the vertical structure of the water column.

Physical Circulation.

The SATURN circulation modeling system, also known as the *virtual Columbia River* (<http://www.stccmop.org/datamart/virtualcolumbiariver>), constitutes important infrastructure for the overall NOAA-led project.

The *Virtual Columbia River* relies on the application [1, 2] of numerical models [3, 4] to create and skill-assess multiple representations of circulation processes, variability and change across river-to-shelf scales. Circulation includes water levels, salinity, temperature, and velocities.

Simulations of circulation have been shown to provide important practical insights into the factors that control salmon survival. For instance, (a) we have established a positive correlation between plume size at time of ocean entry and smolt-to-adults ratios for steelhead [7], and (b) we have shown that over 40% of the contemporary variability of plume characteristics is explained by river discharge, and over 20% by shelf winds [6]. Together, the two findings suggest that timing the release of steelhead smolt relative to predictable characteristics of the plume (hence, weather and hydropower operation) might be an effective management strategy.

Progress in 2010/2011: OHSU has continued to maintain, expand, assess and enhance the Virtual Columbia River infrastructure, with synergistic funding leveraged across multiple projects (BPA, US Army Corps of Engineers, and NSF). In particular,

- We routinely maintain two 2-day ahead daily forecasts of river-to-shelf Columbia River circulation (F26, featured in Fig. 54; and F22, not featured). Both forecast use the same circulation code and the same general modeling approach, but each differs in important details of domain, spatial detail, and parameterization. That the circulation outputs are different between forecasts is an important reminder of the need to account for uncertainty, when using model results for decision making.

For each forecast, both computational cost and error and uncertainty grow with the duration of the forecast. Yet, the findings of [6] and [7] suggest that forecasts might offer valuable input into the management of the timing of release of steelhead smolts, if they the forecast horizon is longer. We are thus cautiously exploring strategies to extend the length of one of the forecasts to 14 days.

- We are maintaining diverse simulation databases of river-to-ocean Columbia River circulation. The reference simulation database is DB22, which we are maintaining from 1999 to “present” (currently, 2010). However, DB14, the previous reference (maintained from 1999 through 2009), is still kept on archive, as neither database has yet been demonstrated to be superior to the other on all relevant accounts. We have also begun the development of a newer circulation database (DB26, with the same expanded domain as forecast F26), which skill and cost-performance will be systematically contrasted against DB14 and DB22.

Each database is processed to compute salmon-relevant estuary and plume metrics that are incorporated in a Virtual Columbia River Climatological Atlas. These metrics are beginning to be used for a range of empirical correlations with fisheries data, in many cases by non-modelers. An exciting example is the analysis that suggests that 3-year ahead predictions of returns of some salmon stocks can be made using plume volumes combined with cormorant data (Jessica Miller, private communication). Miller’s analysis raises the need to develop clear guidance on what simulation database leads to the most reliable plume metrics, for what type of application. Addressing this challenge is a priority for 2011-2012.

- We also plan to explore in 2011-2012 the extent to which empirical correlations (e.g., as in Bruland et al. 2008) observed from or with data of the SATURN observation network can be coupled with circulation simulations to create 4D surrogate representations of ecological variables. The initial focus will be on dissolved oxygen. The NAPDZ model referred earlier will be used as a reference, to offer insight on whether empirical

correlations might be sufficient to describe and predict salmon-relevant aspects of oxygen dynamics.

Characterizing Ocean Entry Conditions and their Implications on Adult Returns.

Physical, chemical and biological conditions experienced by salmon at ocean entry play a significant but incompletely understood role in overall survival. Identifying what metrics offer the best ability to predict salmon returns is a high priority effort for the NOAA-led team.

Progress in 2010/2011: Jessica Miller's results (described elsewhere in the NOAA progress report) suggests that predictions of Chinook subyearling salmon returns are possible, with significant level of reliability, using only:

- plume metrics computed from CMOP's Virtual Columbia River simulation databases
- Cormorant population data

If confirmed, those finding might be the first evidence of the ability to predict salmon survival years ahead, from plume physical characteristics. These findings would validate and substantially expand the ideas introduced by [7] on the use of plume metrics advance management of salmon stocks.

Engage, advise and inform managers.

Research described in the NOAA-led proposal is designed to identify mechanisms that link climate and ocean variability with salmon survival through modeling and statistical analysis of our decade-long time series. We are just now beginning to see the value of this work given our rudimentary attempts to provide

qualitative forecasts of salmon returns. Our work has shown the power of variations in ocean conditions to determine salmon survival and has clearly shown that large basin-scale climate and oceanographic factors such as PDO cycles, and ENSO events, as well as local-scale factors (such as interannual variations in winds, upwelling, snow pack, river discharge and size of the Columbia River plume) have dramatic impacts on salmon.

Progress in 2010/2011: We have created a test version of a 7-days ahead forecast for time of release of steelhead smolt, based on the analysis of Burla et al. [7], and are exploring forms of extending the forecast horizon (to 14 days ahead). We are considering the logistics associated to a limited release of those forecasts this year, for internal feedback.

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Indicators of ocean conditions

Table 4 is a chart showing our “stoplight approach” of summarizing physical and biological oceanographic conditions within a given year. The table shows the ranks of the key indicators that have been measured since the inception of the BPA-funded field program in 1998, a 13-year period.

Table 4. Ocean conditions for a variety of physical and biological variables related to salmon growth and survival.

<i>Environmental Variables</i>	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
PDO (December-March)	12	4	2	8	5	13	7	11	9	6	3	1	10
PDO (May-September)	7	2	4	3	8	12	11	13	9	10	1	6	5
MEI Annual	13	1	3	6	12	11	10	7	8	5	2	9	4
MEI Jan-June	13	1	3	4	9	10	8	11	5	7	2	6	12
SST at 46050 (May-Sept)	11	8	3	4	1	7	13	10	5	12	2	9	6
SST at NH 05 (May-Sept)	8	4	1	6	2	5	13	10	7	12	3	11	9
SST winter before (Nov-Mar)	13	10	3	5	6	9	11	8	7	2	1	4	12
Physical Spring Trans (UI Based)	3	6	12	11	4	8	10	13	8	1	5	2	7
Upwelling Anomaly (Apr-May)	7	1	12	3	6	10	9	13	7	2	4	5	11
Length of upwelling season (UI Bas	6	2	12	9	1	10	8	13	5	3	7	3	11
Deep Temperature at NH 05	13	4	6	3	1	9	10	11	12	5	2	8	7
Deep Salinity at NH05	13	3	6	2	5	11	12	8	7	1	4	9	10
Copepod Richness Anomaly	13	2	1	5	3	9	8	12	10	6	4	7	11
N.Copepod Anomaly	13	10	3	7	2	11	8	12	9	6	1	5	4
Biological Transition	13	7	5	3	6	11	9	12	10	4	1	2	8
Copepod Community structure	13	3	4	6	1	9	10	12	11	7	2	5	8
Winter Ichthyoplankton	13	6	2	4	5	9	12	8	11	10	1	7	3
Catches of salmon in surveys													
June-Chinook Catches	12	2	3	10	7	9	11	13	8	6	1	4	5
Sept-Coho Catches	9	2	1	4	3	5	10	12	7	8	6	13	11
Mean of Ranks of Environmental D	10.8	4.1	4.5	5.4	4.6	9.4	10.0	11.0	8.2	5.9	2.7	6.1	8.1
RANK of the mean rank	12	2	3	5	4	10	11	13	9	6	1	7	8

The color coding is based on the ranks: low, intermediate, and high rank numbers indicating good (green) for the lower rank numbers, intermediate (yellow) for the intermediate

ranks, and poor (red) ocean conditions for the higher rank numbers. The last row of the chart, "RANK of the mean rank" in Table 4 summarizes ocean conditions in each year as a composite. Four years had the best ocean conditions (green: 1999, 2000, 2002 and 2008, five years had intermediate ocean conditions (yellow), and four years had poor ocean conditions (red): 1998, 2003, 2004, and 2005. A full description of each of the variables that contribute to the "stoplight table" is available on our web site. <http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm>.

A noteworthy feature of the stoplight table is that the 4-year period of cold ocean conditions observed from 1999-2002 resulted in good returns of Chinook salmon whereas the warm ocean conditions which followed, from 2003-2005, have resulted in declining returns. Ocean conditions improved through 2007 and especially in 2008, with the result that coho salmon returns in fall 2009 were the second highest on record for counts at Bonneville Dam (190,000 fish) and the highest OPIH number since 1990 at 4.0% returns. Similarly, returns of spring Chinook salmon (2-ocean fish) were high in spring 2010, being third highest on record. We anticipate high returns of fall Chinook (3-ocean fish) in fall 2011.

However, ocean conditions began to deteriorate in mid-2009 due to the development of an El Niño event. The PDO became positive in May 2009 and remained so through May 2010. Due to the El Niño event, the ocean off Oregon and Washington warmed significantly, with anomalies in sea surface temperatures at about + 1.0°C throughout the latter half of 2009 and through April 2010.

We suspect that this warming event that persisted for one year, from May 2009-April 2010, may have lead to detrimental changes in the pelagic food web and likely high mortality of juvenile salmon in the northern California Current. That is, copepod species richness was very high (a negative indicator) with a rank of 11 of 13, the copepod community structure index ranked 8 of 13 indicating that a "warm water community" was present in coastal waters, and the "biological spring transition" also ranked 8 of 13.

On the other hand, two other biological indicators suggest that the summer of 2010 was not so bad: both the "northern copepod index" and a new index, "winter ichthyoplankton" were ranked 3 of 13 and 4 of 13 respectively.

Taken as a whole, even though 2010 began as a “warm year”, the ocean began to cool in May, and by July, the ocean was the coldest observed in recent years. Thus we had very mixed signals in 2010 making it difficult to offer any reliable outlooks in returns of coho salmon in 2011 and Chinook salmon in 2012. We blame this on the pronounced El Niño/La Niña cycle which gave us “the best of times” and “the worst of times”. Here we discuss each of our indicators in the context of how our measurements in 2010 compare to those made by our research team since 1998.

Analysis of anticipated returns for Chinook and coho that went to sea in 2010.

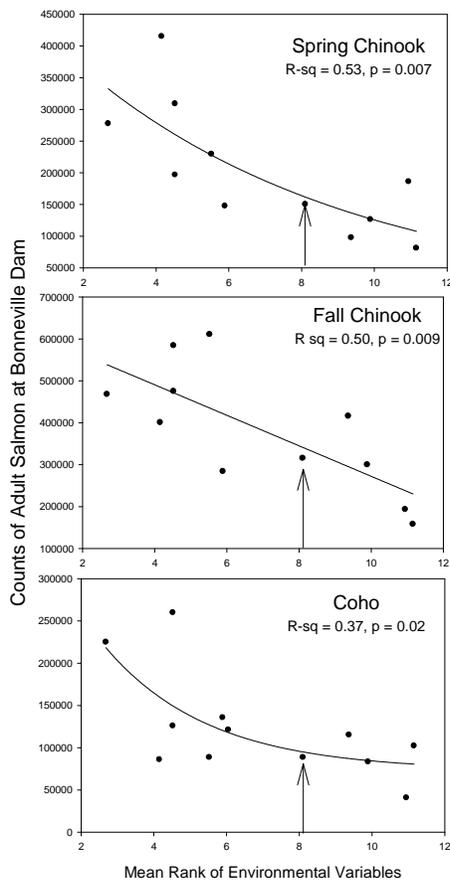


Figure 55. Ocean condition rank vs. salmon counts at Bonneville Dam

Forecasts of returns of adult salmon to Bonneville Dam for fish that went to sea in 2010, based on the “Mean of Ranks of Environmental Data” listed in Table 4 (see the second line from the bottom of the Table 4), are shown in Figure 55. The plot assumes that spring Chinook salmon passing Bonneville Dam spend two years at sea, and coho one year. Thus, spring Chinook salmon that went to sea last spring (in 2010, when ocean conditions had a mean rank of 8.1) should return at low levels in spring 2012 (indicated by the vertical arrow); the graph (and vertical arrows) would suggest numbers 160,000 spring Chinook (in 2012) and 95,000 Coho (in 2011). For fish returning this year (2011), spring Chinook that went to sea in 2009 when our environmental indicators showed a mean rank of 6.1, could return on the order of 200,000 fish by early June 2011; coho that went to sea in 2010 and which will return

in fall 2011 could return in relatively low numbers, on the order of 95,000 fish. For fall Chinook that went to sea in 2010, we would expect about 350,000 fish in 2013 based on a mean rank of environmental indicators of 8.1.

We have also analyzed the indicator data using two other (and more sophisticated) statistical analyses. One is Maximum Covariance Analysis (MCA), which is mathematically identical to Principle Components Analysis (PCA), but differs from PCA in that we apply it to the covariance matrix between two datasets rather than the variance/covariance matrix of a single dataset. Normally, one could get several components (linear combinations of the indicators) that describe the covariance between the indicators and salmon returns. However, one can only calculate as many components as the number of columns in the smallest dataset; since we use only one return dataset (e.g., spring Chinook salmon at Bonneville), we can only calculate one principle component. In MCA, the components are called Expansion Factors, and are weighted averages of the indicators (so one value for each year). The weights are determined by the

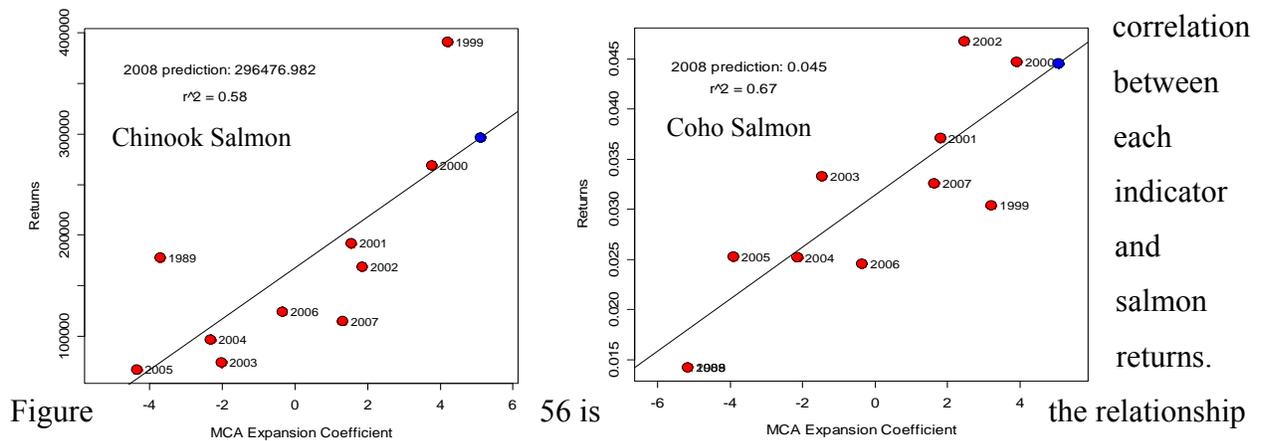


Figure 56. Relationship between the integrated suite of ocean indicators and adult return of yearling Chinook and coho salmon using maximum covariance analysis

Expansion Factor (weighted average indicator) and returns of coho and spring Chinook salmon. For the spring Chinook salmon, the expectation for returns in 2010 (fish that went to sea in spring 2008) is 296,477 fish counted at Bonneville. For OPIH coho, the expectation for 2009 is 4.5% (for fish that went to sea in 2008) Figure 5.

The second method is an extension to the first and is called Partial Least Squares Regression (PLSR). It starts out the same (MCA analysis on the covariance matrix to get a set of expansion factors, although PLSR calls them scores). It then calculates loadings, which, mathematically, is the score (good year/bad year) times the indicator values, summed over the years (i.e., the loading is just the covariance between the scores and each indicator).

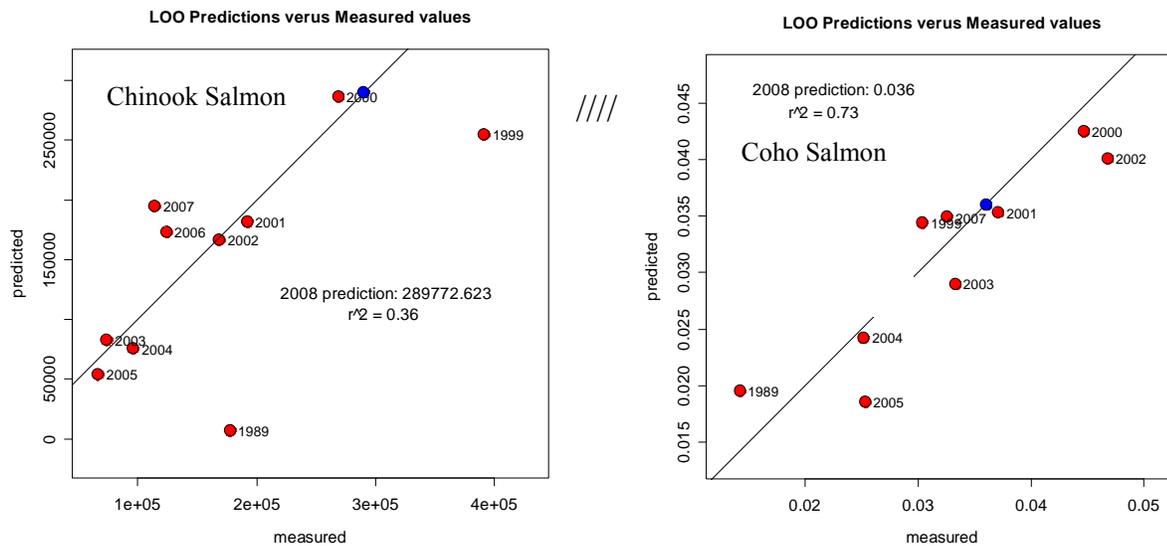


Figure 57. Relationship between the integrated suite of ocean indicators and adult return of yearling Chinook and coho salmon using partial least squares analysis leading to a forecast for future adult returns.

We then run a linear regression between the scores and the return data and proceed to an iterative process of taking the residuals from that linear model and running MCA on them to get a second set of weights and scores. Then a third - in essence, we are maximizing the covariance between the indicators (or the residuals of the indicators) and the return data (or the residuals of the return data) through a linear combination of indicators (i.e., by weighting the indicators). Because this is a regression approach (not a correlation approach, as MCA is), we can legitimately use it to predict future returns (Figures 56 and 57). Each data point is the prediction of that year, *if the indicators for that year were left out of the model*. This “Leave One Out” approach is one way to validate the model. It would not be fair to compare the R² from these to the R² from MCA, since MCA uses all of the data to estimate the correlation. The PLSR approach predicts somewhat lower returns than the MCA method: 289,772 fish past Bonneville for spring Chinook and 3.6% for OPIH coho survival.

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